NUCLEAR TRAINING COURSE

COURSE 125

1 - Level
2 - Science Fundamentals
5 - HEAT & THERMODYNAMICS

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HEAT & THERMODYNAMICS

MODULE B.7

COURSE PROCEDURES (READ FIRST)

PERSONAL PROGRESS SUMMARY

MODULE		DATE ACHIEVED	SIGNOFF INITIALS
B.6	Basics		
B.5	Steam Tables		
B.4.2	Mollier Diagram		
B.4.1	Turbine		
B.3.2	Feedheater		
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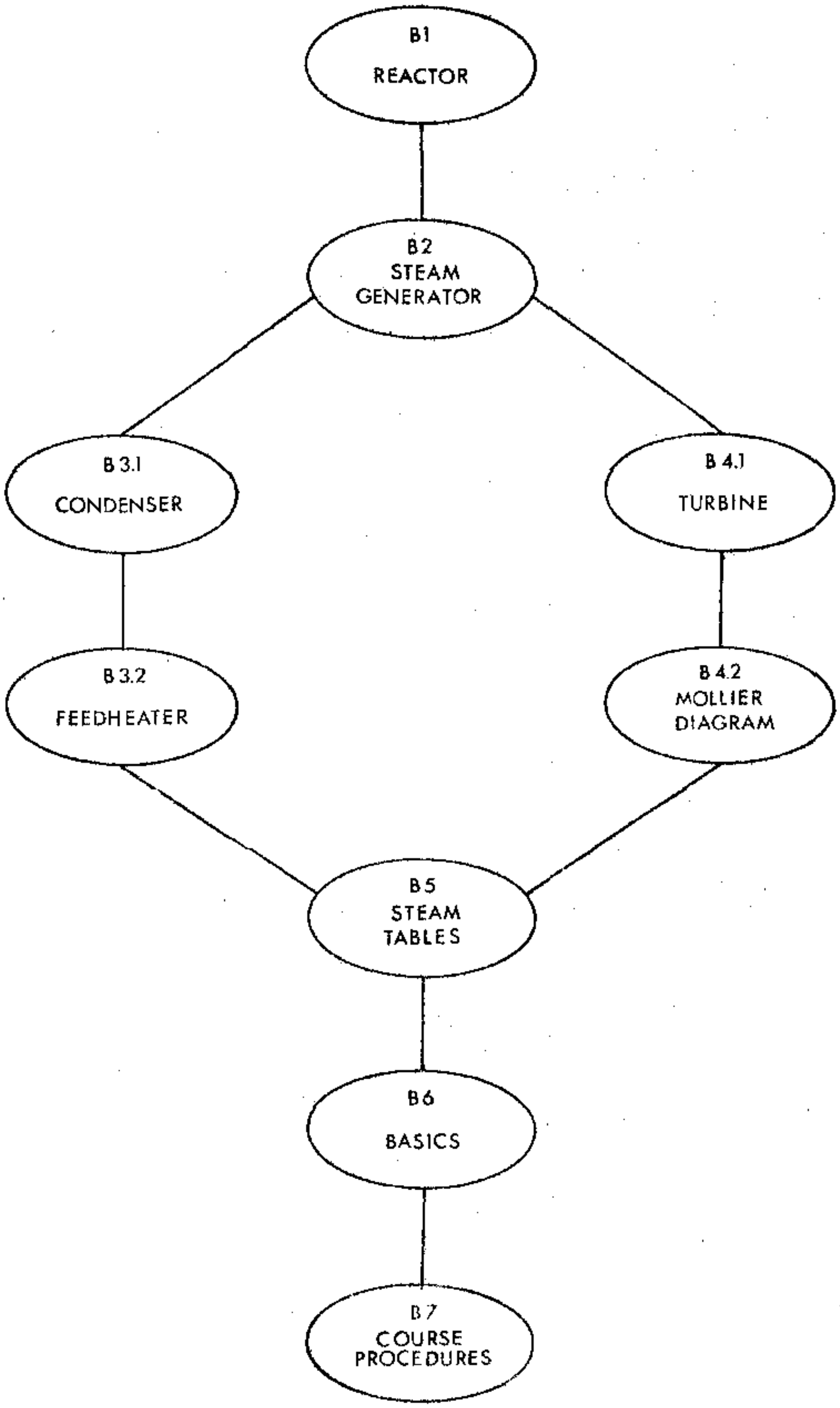
B.2	Steam Generator		
B.1	Reactor		

COURSE MAP


B1
REACTOR
B2
STEAM
GENERATOR
B 3.1
CONDENSER
B 4.1
TURBINE
B 3.2
FEEDHEATER
B 4.2
MOLLIER
DIAGRAM
B5
STEAM
TABLES
B6
BASICS
B7
COURSE
PROCEDURES

COURSE PROCEDURES

Description of the Course

This course is designed for a training program using the resource of at least one Course Manager. It is also designed so that you may proceed at the pace which best satisfies your needs.

There is no final checkout. Each lesson or module has its own test which has to be completed to the satisfaction of both the student and the Course Manager before you proceed to the next module.

There are 8 sections or modules in this course and they are numbered as follows:

B.7 - Course Procedures
B.6 - Basics
B.5 - Steam Tables
B.4.2 - Mollier Diagram
B.4.1 - Turbine
B.3.2 - Feedheater
B.3.1 - Condenser
B.2 - Steam Generator
B.1 - Reactor

It is suggested that you proceed according to the course map upwards. Thus the first lesson module is B.6, then B.5. When you have completed Module B.5, you have a choice of doing Module B.4.2 or B.3.2. You should not do Module B.2 until all the modules below, on the course map have been completed.

Description of a Module

A module is a complete section of training material. All modules have the same format as follows:

1. Objectives

   These tell you exactly the performance needed to pass the criterion test at the end of the module. There are two types of objectives:

   a) Course Objectives which have been selected to improve your performance as a Shift Supervisor and describe exactly the desired performance which is needed to pass the course.

b) Enabling Objectives which describe those skills which may be needed so that you can satisfy the course objectives. The enabling objectives should make desired performance in the course objectives easier and that is why we test both 'course' and 'enabling' objectives.

2. Module Training Material

This provides the instruction for the module. It contains many questions which provide reinforcement of the concepts for the student. The answers to all the questions are included at the end of the module.

3. Criterion Test

This is a test which tests those objectives stated at the beginning of the module - no more and no less.

4. Self Evaluation Sheet

This provides a guide to the main points and rationale that you should have covered when you wrote the criterion test.

What are the advantages of this type of presentation?

1. The course objectives are selected only because they can improve your performance as a Shift Supervisor.

2. You don't have to waste time going through material you already know. You can take the criterion test when you feel you are ready.

3. You don't have to wait for the rest of the class to proceed. Equally, you don't have to be rushed through an area with which you are unfamiliar. You work through at your own pace.

4. If you need to ask questions, the Course Manager is there all the time to help you with any problems you have with the course.

These are some of the advantages. You'll find more as you progress through the course.

PROCEDURE

1. Read Module B.7 - Course Procedures.

2. Select your first lesson, Module B.6 - Basics.

3. Make sure you have a calculator and a set of Steam Tables.

4. Read the objectives for the module.

5. Read the course material and answer the questions contained in the material as you proceed. Check your answers at the back of the module.

6. When you have completed the lesson material, re-read the objectives.

7. When you are ready for the Criterion Test, ask for it from the Course Manager.

8. When you have written the test, select the self evaluation sheet and compare with your answers.

9. Discuss your test with the Course Manager when you have compared your test and the self evaluation sheet.

0. If there are areas that need to be reinforced, return and practice before trying the test again.

1. If you are both satisfied with the results, have the Course Manager sign off your Personal Progress Summary.

2. Proceed to the next module.

3. When you have completed Module B.1, please complete the course evaluation form so that we may improve your training.

This is not a race - no prizes for being first finished. Work at your own pace and make the best use of the program to clarify any problem areas you may have.

J. Irwin-Childs

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HEAT & THERMODYNAMICS

MODULE B.6

BASICS

Heat & Thermodynamics

MODULE B.6

BASICS

Course Objectives

1. You will be able to define the following and state the units from memory:

   (a) Temperature.
   (b) Heat.

2. You will be able to explain the following terms in your own words from memory, when applied to the various states of water:

   (a) Saturation Temperature.
   (b) Subcooled Liquid.
   (c) Wet Steam.
   (d) Saturated Steam.
   (e) Superheated Steam.

3. You will be able to explain the following heat transfer mechanisms, in your own words and give an example of each mechanism:

   (a) Conduction.
   (b) Natural convection.
   (c) Forced convection.
   (d) Radiation.

4. You will be able to state that a compressor will raise both the pressure and temperature of a gas and explain that an aftercooler is used to reduce the volume of the receiver.

5. You will be able to state that the effect of heating a closed volume of gas is to raise its pressure and illustrate this principle with a gas "feed and bleed" example from the station.

6. You will be able to explain why it is important to know when a gas cylinder is effectively empty and state the test for this condition when the cylinder contains:

   (a) Liquid Gas.
   (b) Compressed Gas.

7. You will be able to explain why high energy in a compressed gas makes it dangerous for pressue testing purposes.

Enabling Objectives

1. You will be able to explain the following terms in your own words from memory, when applied to the various states of water:

   (a) Sensible Heat.
   (b) Latent Heat of Vapourization.
   (c) Saturated Liquid.

2. You will be able to draw a graph of temperature against enthalpy as heat is added at constant pressure and complete the graph by doing the following from memory:

   (a) Label the areas.
   (b) Indicate sensible heat region.
   (c) Indicate latent heat region.
   (d) Mark the saturation temperature.
   (e) Indicate the subcooled region.
   (f) Mark the point for saturated liquid.
   (g) Mark the point for saturated steam.
   (h) Indicate the superheated region.

BASICS

One of the most common problems from which we all suffer at some time or other, is that we try to rationalize a situation without returning to basic concepts. Although when we start to look, in detail, at some thermodynamic processes life can become complex, the majority of thermodynamic processes, with which we are familiar in our station, may be readily understood and explained using basic principles.

Before we can progress to look at some of the thermodynamic problems, it is essential that the basic items and concepts be understood if confusion is to be avoided.

Temperature

Temperature is a measure of the intensity of heat of a substance. It indicates the ability of one substance to gain or lose heat with respect to another substance.

Thus TEMPERATURE is a measure of quality or grade of heat. Temperature should NOT be confused with the quantity of heat.

There are many temperature measurement scales used to compare the temperatures, but today we generally only use the Celsius scale. As we know from previous experience the Celsius scale uses the freezing point and boiling point of water, at atmospheric pressure, as the lower and upper reference points of the scale. There are 100 divisions on this scale and thus the freezing point is at 0°C and the boiling point is at 100°C.

A point to note is that in symbol form, using S.I., a temperature of 10 degrees Celsius and a temperature rise of 10 degrees Celsius are BOTH shown as 10°C and obviously we need to take extra care to determine whether the given information is a point on a temperature scale, eg, 40°C or an interval eg, the difference between 90°C and 50°C is also 40°C.

HEAT

Heat is a Form of Energy

The heat in a substance is associated with the motion of its molecules. The hotter the substance the more vigorous the vibration and motion of its molecules. If heat is applied continuously to a solid it relaxes the cohesion of the molecules, and a point is reached at which the vibration of the molecules is such that the solid changes into a liquid in which the molecules can move about more freely. On further addition of heat to the liquid the motion of the molecules is increased still more and a point is reached at which the liquid begins to change into vapour and then a gas. The heat applied dissociates the molecules of liquid from one another so that they fly apart and remain separate in the gaseous state.

The pressure exerted by a gas or vapour, in a vessel, is due to the impact of the molecules on the walls of the vessel. The hotter the gas, the greater the pressure, because the more violent is the motion of the molecules which, by molecular impact, cause a bigger force on the sides of the vessel. With these ideas in mind, as to the nature of heat, it is easier to imagine the molecular condition of the water and steam in the interior of a boiler.

The Measurement of Heat

The quantity of heat that a substance contains is by no means obvious. If you were to see a block of steel in a foundry that had to be heated to 300°C you could not readily determine how much heat energy would be required. The rate at which the temperature of a material changes with the change of heat energy depends upon two factors as we shall see later: (a) the quantity of material involved (b) the nature of the material ie, how much heat is absorbed by a unit mass of the material for a unit rise in temperature.

All energy forms are measured in JOULES.
The symbol for heat energy is 'Q'.

Thus HEAT is the quality of energy that a body possesses due to its temperature and depending upon the material.

Specific Heat

Specific Heat may be simply defined as: The amount of heat energy required to change the temperature, of one kilogram of the material, one degree Celsius.

Thus the units are:

kiloJoules per kilogram per degree Celsius.

Symbol - kJ/kg°C.

The symbol for specific heat is 'C'.

We may now relate heat and specific heat. We have already seen that the amount of heat a body requires to realize a particular temperature change depends upon the mass of the body, the material of which it is composed, and the stated temperature change. Thus:

$$Q = M \times C \times \Delta T$$

$$kJ = kg \times kJ/kg°C \times °C.$$

Where 'Q' is the quantity of heat required to produce a temperature change of 'ΔT' degrees Celsius in material with a mass 'm' having a specific heat 'C'.

Example

Given 14 kg of water at 30°C. How much heat must be added to raise the temperature to 64°C if C for the water is 4.18 kJ/Kg°C. By simply substituting into $Q = mC\Delta T$ we may determine the value of Q.

Thus $Q = 14 \times 4.18 \times (64 - 30)$ k.Joules

kg x kJ/kg°C x °C

$= 14 \times 4.18 \times 34$

$= 1989.7$ kJ.

Try this next example for yourself; you will find the answer at the end of the module.

B.6.1

In a 600 MW unit 1300×10^6 Joules of energy per second are rejected to the condenser cooling water system. If the temperature rise of the cooling water is 11°C and the specific heat of the cooling water is 4.18 kJ/kg°C determine how much cooling water is needed every second.

Enthalpy

For water, enthalpy is the total heat value of fluid measured from 0°C. This is an arbitrary temperature that is convenient for reference such that fluid at 0°C has zero enthalpy.

The symbol for enthalpy is h.

The units are in kiloJoules/kilogram.

The values of enthalpy are laid out in the steam tables as we shall see later.

Before we progress to look at water, it would be an ideal point for you to re-read the previous notes and if you feel you have understood them, try and write down the definitions for:

Temperature
Heat

When you are satisfied that you know the definitions continue with the next section.

WATER

This remarkable fluid is used so widely for so many purposes that a lot of its characteristics are hardly recognized. We use water as a heat transfer fluid because it is cheap, easily purified and has an exceptional heat capacity.

When we speak of water we tend to think of it in its most familiar form, as a liquid and do not immediately register that it could also be a solid, vapour or gas. We are continually heating this substance in one part of the system and cooling it in another part. It is not surprising that we should pay a lot of attention to the behaviour of water when it is being heated and when it is being cooled.

What happens to water when it is heated - get's hotter? Not necessarily so! When water is turning from liquid into steam the temperature, which measures the hotness, remains constant. Alright, if we heat water as a liquid the temperature may rise. What else happens when water is heated? A change of state may take place, eg, the liquid may become vapour. What else happens? The enthalpy of the fluid increases. Can you think of anything else? What happens to the volume of the fluid? Right, it usually increases.

The same rationale may be applied to the cooling of the fluid. How do all these changes affect the rest of the fluid system? Very significantly - each change produces its own particular problem and unless we have knowledge as to how the fluid is behaving in the process, we have very little chance of being able to diagnose the cause of abnormal operation or produce a rationale for a particular event.

At a given pressure, the amount of enthalpy that the steam possesses will determine its state. Consequently, if we know either the state or the enthalpy of the fluid we can determine the other characteristic without too much problem.

To visualize a process we often use an aid and one of the most useful aids is the graph of temperature of the water, at constant pressure, which is plotted against the enthalpy of the fluid.

This graph is shown below and we will be referring to this on many occasions.

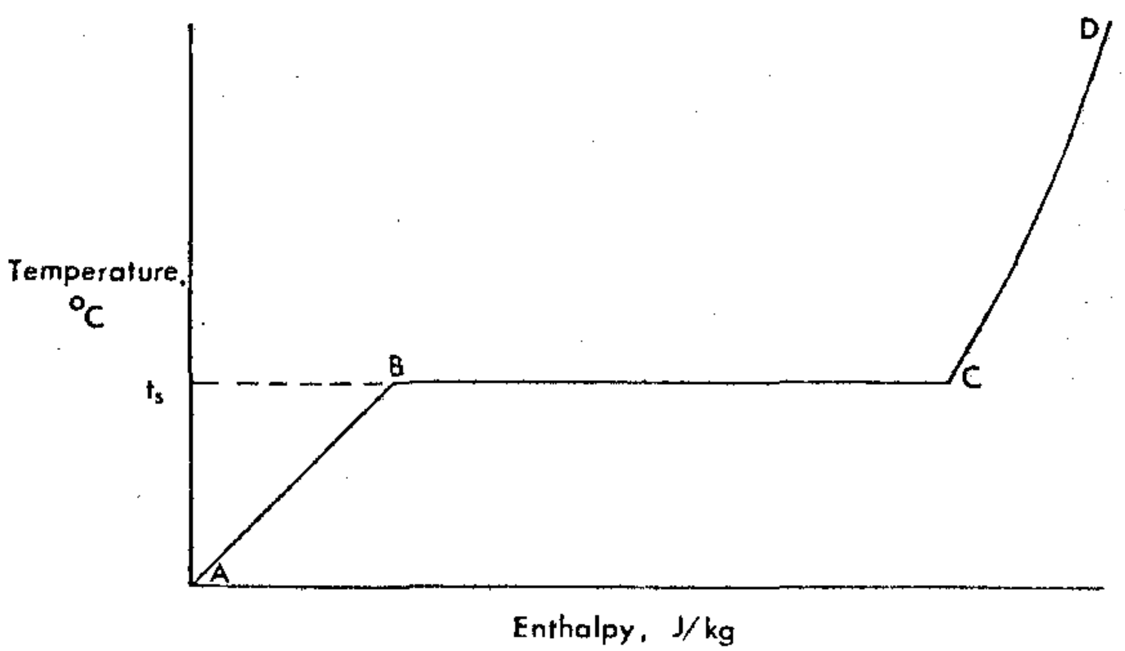

Fig. 6.1

An understanding of this simple graph provides the key to solving the majority of thermodynamic processes we can find in the station.

From the graph, starting at A, you can see that the temperature rises uniformly with increasing enthalpy until the temperature at B is reached. At this point further increase in enthalpy does not produce a corresponding temperature rise. This is because a change of state is taking place and the liquid is being turned into vapour, at constant temperature. Once all the liquid has been turned into vapour, point C, the temperature will continue to rise with the continuing increase in enthalpy, but not at the same rate as previously.

Saturation Temperature

"Saturation temperature" is the temperature at which the liquid is changed into vapour and depends upon the pressure of the system. The higher the pressure, the higher the saturation temperature. The symbol for saturation temperature is t_s. The saturation temperature provides a very useful reference point as we will see.

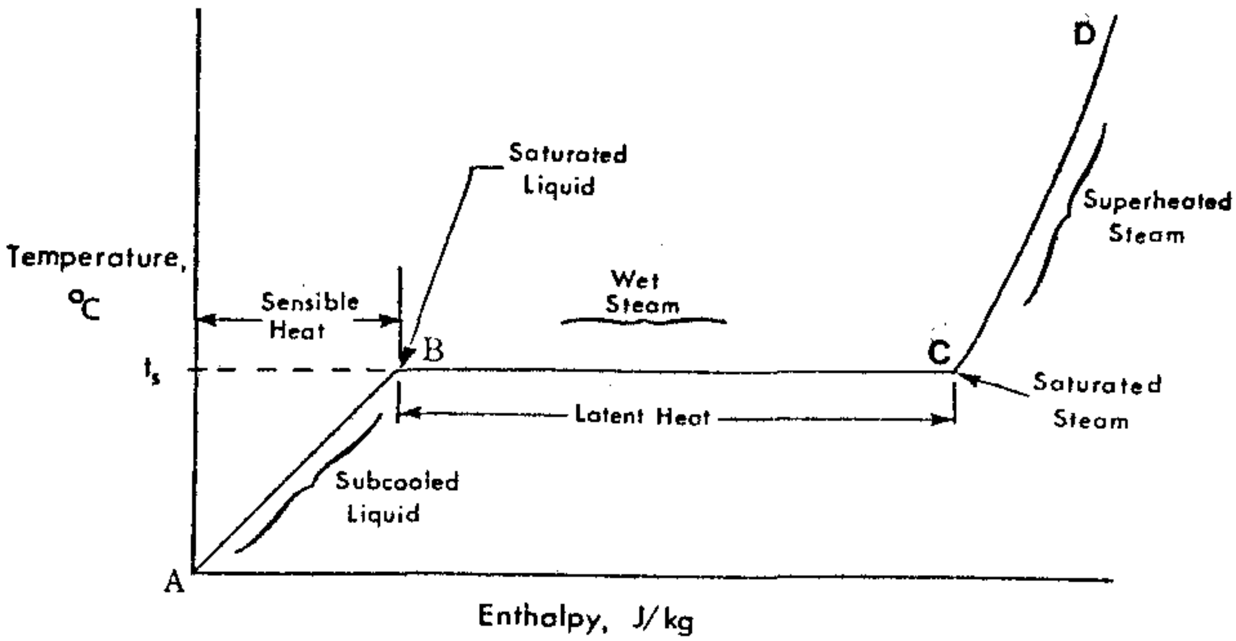

Fig. 6.2

Sensible Heat - Points A to B

The enthalpy of the liquid is often referred to as "sensible heat". 'Sensible' because the addition of heat to the liquid is observed by a temperature rise. The sensible heat range is the enthalpy of liquid at 0°C to liquid at saturation temperature t_s. The addition of superheat C-D also produces a temperature rise but this is not referred to as "sensible heat".

Subcooled Liquid

"Subcooled liquid" is liquid which has not received enough heat for the temperature to reach the saturation temperature and consequently exists at a temperature below t_s.

Saturated Liquid - Point B

"Saturated liquid" is liquid which has received enough heat that it exists at the saturation temperature, t_s. We use the term 'saturated' because the liquid cannot absorb any more heat without the liquid starting to turn into vapour.

Saturated Steam - Point C

"Saturated steam" is steam which has no liquid left and is saturated with the amount of heat which was required to change from a liquid at point 'B' to saturated vapour at point 'C'. Again it is saturated with heat because if any more heat was added the temperature would no longer remain constant but would start to rise again.

The heat which had to be added from point 'B' to point 'C' is called the latent heat of vapourization. 'Latent' or hidden because there is no temperature change to indicate that heat addition is occurring. The water is changing its state from liquid to vapour.

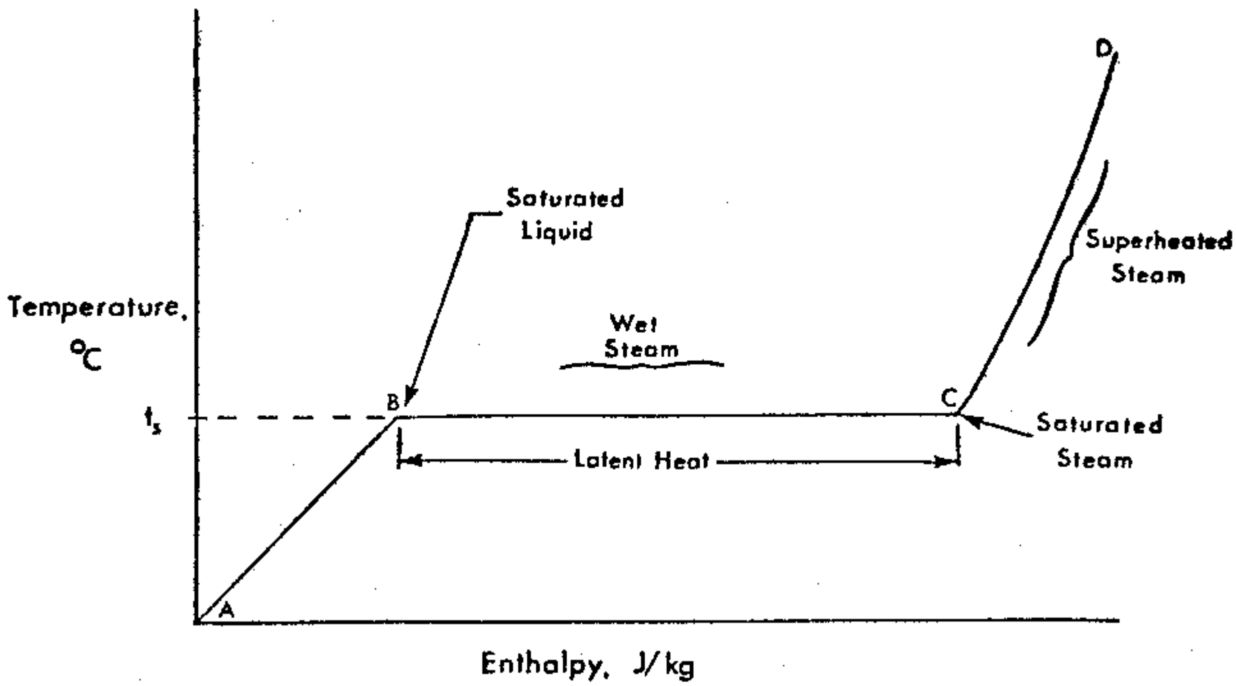

Fig. 6.3

Wet Steam - Between Points B and C

"Wet steam" is steam which exists at the saturation temperature and may be anywhere between points B and C. If there is a lot of liquid in the mixture the condition of the steam will be close to B. If there is little moisture in the steam the condition will be close to C. Another way of describing wet steam is to say that this is steam which has not received all its latent heat. It is a mixture of fine moisture droplets and water vapour existing at the saturation temperature t_s.

Superheated Steam - Between Points C and D

"Superheated steam" is steam which has received all its latent heat and has been further heated so that its temperature is above t_s. The steam behaves like a gas once it is more than approximately 50°C above the saturation temperature.

Heat Transfer Mechanisms

There are three main mechanisms of heat transfer: conduction, convection, and radiation. Heat is transferred from a higher temperature substance to a lower temperature substance by at least one of these mechanisms. Let's look a little more closely at each mechanism.

Conduction

Conduction involves heat transfer with no transfer of mass. Heat is transferred from particle to particle through a substance, while the particles themselves remain in the same relative positions in the substance. An example of heat transfer by conduction is the heat transfer through the steam generator tubes from the primary heat transport side to the light water side.

Convection

Convection involves heat transfer that is accomplished by the movement of a fluid. As the fluid moves, it carries heat with it.

There are two types of convection:

a) Natural Convection: In natural convection, the movement of the fluid is due to density differences that occur in the fluid as heat transfer occurs. For example, as the water in the boiler is heated, it vapourizes to produce steam, which has a much lower density than the surrounding water. The steam thus rises through the water to the top of the boiler, carrying the heat added to it by the primary heat transport system.

b) Forced Convection: This type of convection makes use of pressure differences to force the fluid to move. The pressure differences are generated by equipment such as pumps, fans, and compressors. For example, the condenser cooling water is pumped through the condenser, picking up heat from the steam exhausted from the turbine and carrying the heat out to the lake.

c) Radiation: The particles of a substance, because of excitation due to temperature, emit electromagnetic energy in the infrared range. This radiant energy that is emitted transfers heat from the substance. Heat is only transferred by radiation in significant amounts from high temperature sources. An example of heat transfer by radiation is the heat transferred through the film surrounding a fuel bundle when film boiling occurs and heat transfer due to forced convection is very small because of the massive reduction in the heat transfer coefficient when the D_2O changes from liquid to vapour. Initially, the heat transfer is by conduction through the vapour but the thermal conductivity of D_2O vapour is very low. The fuel sheath temperature thus rises, and as it rises, more and more heat is transferred by radiation.

Answer these questions and compare your answers with those at the end of the course.

* * * * *

B.6.2

Draw the graph of temperature against enthalpy for heat addition at constant pressure for water.

(a) Label the axes.
(b) Indicate sensible heat region.
(c) Indicate latent heat region.
(d) Mark the saturation temperature.
(e) Indicate the subcooled regions.
(f) Mark the point for saturated liquid.
(g) Mark the point for saturated steam.
(h) Indicate the superheated region.
(i) Indicate the wet steam range.

When you have done this turn to the end of the module and check your answers.

When you have labelled the diagram correctly, describe the following when applied to various states of water, using your own words:

(a) Saturation temperature.
(b) Sensible heat.
(c) Latent heat of Vapourization.
(d) Subcooled liquid.
(e) Saturated liquid.
(f) Saturated steam.
(g) Superheated steam.
(h) Wet steam.

B.6.3

Explain the following heat transfer mechanisms in your own words and give an example of each mechanism:

(a) Conduction.
(b) Natural convection.
(c) Forced convection.
(d) Radiation.

Compressed Gas

Gas is compressed for a variety of reasons: to reduce its volume for storage, to raise its energy level so that it may provide useful work, and to raise its pressure above atmospheric so that it prevents air in leakage.

A compressor is the equipment used to raise the pressure of the gas. An electric motor usually supplies the energy for the compression work done in a compressor. The energy used in the compressor raises the pressure of the gas to a higher value. If the system was free from frictional effects, this process would occur at constant temperature.

The compression process occurs at high speed and creates a lot of turbulence within the gas which appears in the form of unwanted heat from the effects of friction within the gas. The effect of the increase in temperature is to cause the gas to expand even though it is at a higher pressure.

The gas volume is reduced so that the size of the receiver is not unreasonable for the mass of gas which is required to be stored. The volume of the gas is reduced by cooling the gas using an "aftercooler" which is fitted after the compressor but before the receiver.

The change of volume with temperature is apparent on fixed volume systems such as the D_2O storage tank and the moderator cover gas system. In both these systems, an increase in temperature will cause the gas pressure to rise and result in bleeding of gas from the system. Equally a cooling of the gas will cause the pressure to fall and result in gas being fed to the system.

B.6.4

Explain why gas increases in temperature when compressed and why an aftercooler is necessary.

B.6.5

Explain the effect of heating a closed volume of gas and illustrate your answer with an application in the station.

Check your answers at the end of the course.

* * * * *

Gas is a compressible fluid and requires large amounts of energy to raise the pressure.

Most of this energy is recoverable. If all the pressure energy is recovered in a very short time, eg, a compressed air tank ruptures, then this energy release produces an *explosion*.

This is the reason that pressure testing should not be performed using fluids that need very high energy input to raise their pressure, ie, gases and vapours. Fluids that do not need high energy input for compression, ie, liquids, should be used so that if the system being pressure tested fails, the release of energy is minimal.

Storage of Gases

Gases may be stored as liquids or compressed gas depending upon the saturation temperature at the pressure involved. If the saturation temperature is well below ambient values, then the gas will probably be stored as compressed gas. If the gas has a saturation temperature equal to ambient or above, then the gas will probably be stored as a liquid.

It is important to know when a gas cylinder is becoming empty so that the cylinder remains uncontaminated. If the cylinder is allowed to become totally empty, reverse flow into the cylinder may occur (suck-back) which may introduce air, moisture. The presence of oxygen and moisture will allow corrosion to occur and may also create explosive conditions if the gas is flammable.

As the gas is used from a cylinder of compressed gas, the pressure falls as the mass of gas in the cylinder decreases. The cylinder should be isolated from service when there is still a positive pressure in the cylinder with respect to the system to which it is connected. A pressure of at least 30 psi or 200 kPa above system pressure should exist in the cylinders when considered "EMPTY".

The pressure in a liquified gas cylinder does not change as gas is used. As a result, the pressure cannot indicate when the cylinder is empty. The only way that the cylinder can be checked for contents is to be weighed.

B.6.6

Explain why compressed gas should not be used for pressure testing.

B.6.7

Explain why gas cylinders should not be allowed to empty completely.

B.6.8

State how you would determine the contents of a compressed air and a liquified gas cylinder.

* * * * *

When you have mastered the exercises and feel you are ready for the Criterion Test, obtain the test from the Course or Shift Manager. Upon completion of the test, request the Self Evaluation Sheet and check your work. Finally, have the Manager review your test so that you may:

(a) progress to the next module, or

(b) continue to study to pass test B.6.

Answers

MODULE B.6

BASICS

B.6.1

This time we want to determine the value of 'm'. If we rearrange the formula for the heat energy so that the mass is expressed in terms of C, ΔT and Q we get:

$$M = Q/C\Delta T \text{ kg.}$$

Substituting the given values,

$$Q = 1300 \times 10^6 \text{ J}$$

$$C = 4.18 \times 10^3 \text{ J/kg°C}$$

$$\Delta T = 11\text{°C.}$$

$$\text{Thus } m = \frac{1300 \times 10^6}{4.18 \times 10^3 \times 11} \text{ kg}$$

$$= 28.3 \times 10^3 \text{ kg of CCW every second.}$$

B.6.2

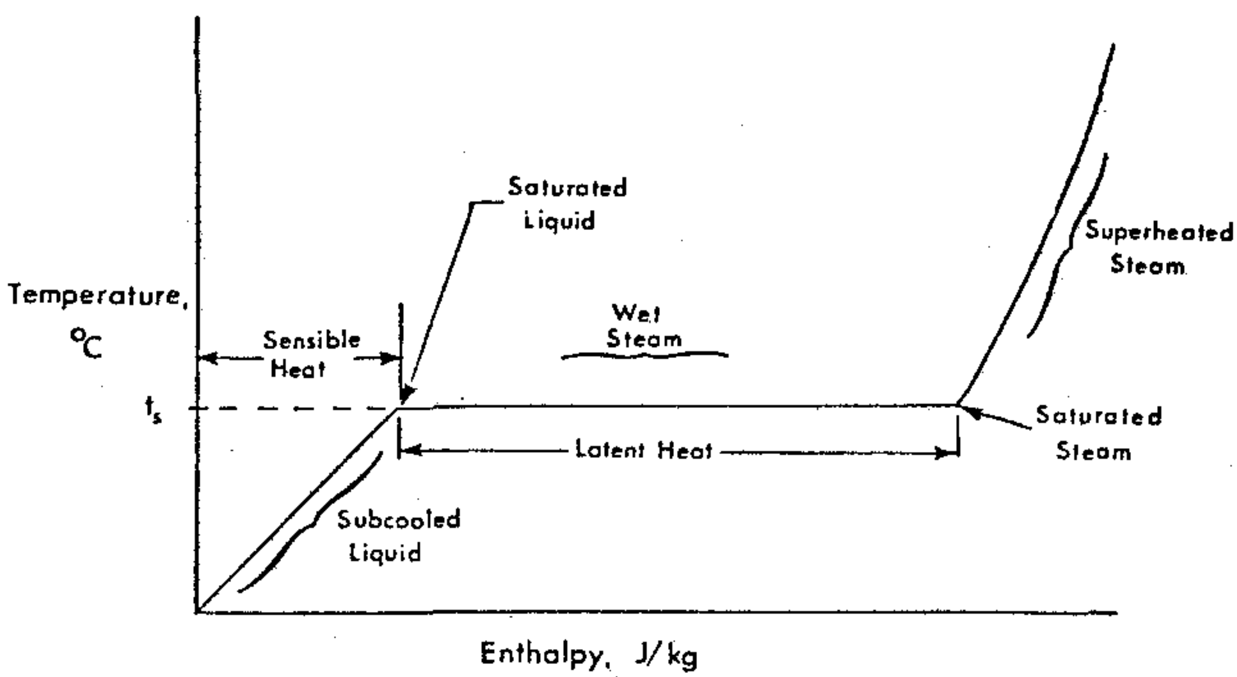

Fig. 6.2

B.6.3

a) Conduction of heat occurs through a material from the higher temperature to the lower temperature without movement of the molecules, eg, heat conducted through the fuel sheath.

b) Natural Convection of heat occurs due to the movement of fluid caused by density difference, eg, the thermo-syphoning of the PHT system when the PHT pumps are shut-down.

c) Forced Convection of heat occurs due to the movement of fluid which is caused by pressure difference due to pumps, fans, etc. eg, the heat is removed from the fuel bundles under normal power operation by forced convection.

d) Radiation of heat energy occurs from relatively hot materials due to electromagnetic radiation, eg, the majority of heat from a fuel bundle is transferred by radiation when the bundle is surrounded by vapour as in film boiling.

B.6.4

Turbulence during compression causes the gas temperature to rise and this increases the volume of the compressed gas. The volume is reduced using an aftercooler, after the compressor and before the receiver, to reduce the size of the receiver.

B.6.5

A closed volume of gas will increase in pressure as the temperature rises. In a closed system which requires a constant pressure, this results in gas being bled from the system. An example occurs when the moderator temperature rises causing the cover gas pressure to rise and results in the operation of the bleed valves.

B.6.6

Gas is a compressible fluid and requires a large amount of energy to raise its pressure. Most of this energy is recoverable and if the system being pressured tested was to fail, the result would be an explosion. Incompressible fluids, ie, liquids require little energy to raise their pressure and should be used for pressure testing.

B.6.7

Gas cylinders that are completely empty can be subjected to reverse flow (suck-back) which can cause contamination due to the entry of oxygen and moisture. This may result in explosive conditions with flammable gases.

B.6.8

A compressed gas cylinder may be checked for contents by pressure.

A liquified gas cylinder may only be checked for contents by weight.

* * * * *

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HEAT & THERMODYNAMICS

MODULE B.5

STEAM TABLES

Heat & Thermodynamics

MODULE B.5

STEAM TABLES

Course Objectives

1. Given values for temperature, pressure, enthalpy and a set of steam tables, you will be able to identify the state of water as one of the following:

   (a) Subcooled Water.
   (b) Saturated Water.
   (c) Wet Steam.
   (d) Saturated Steam.
   (e) Superheated Steam.

2. Given the initial and final state of water and two out of three of the following parameters: pressure, temperature, enthalpy, you will be able to perform simple calculations to determine the third quantity.

3. Briefly describe the process of "steam hammer" and explain why it is a problem and how it may be avoided.

4. Given a constant volume system with provision for adding or removing water, stated initial conditions, and one or more final condition, you will be able to state whether the remaining final conditions increase, decrease, or stay constant. You will be able to explain your statement and determine the amount of any changes that result.

Enabling Objectives

1. Given changes of temperature, pressure and enthalpy, you will be able to determine the corresponding changes in volume.

STEAM TABLES

The steam tables provide us with a very effective means of quantifying operating conditions.

You should have a copy of steam tables as part of the module. The units for the tables are mainly S.I. Turn to page 4 in the first set of steam tables. You will see a whole series of columns under a variety of headings.

TABLE 1 – SATURATION LINE (TEMPERATURE)

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm^3/kg			Temp. °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
100.0	1.013	419.1	2256.9	2676.0	1.3069	6.0485	7.3554	1.0437	1672.0	1673.0	100.0
100.5	1.031	421.2	2255.6	2676.8	1.3125	6.0369	7.3494	1.0441	1644.3	1645.3	100.5
101.0	1.050	423.3	2254.3	2677.6	1.3182	6.0252	7.3434	1.0445	1617.2	1618.2	101.0
101.5	1.069	425.4	2252.9	2678.3	1.3238	6.0136	7.3374	1.0449	1590.6	1591.6	101.5
102.0	1.088	427.5	2251.6	2679.1	1.3294	6.0020	7.3315	1.0453	1564.5	1565.5	102.0
102.5	1.107	429.6	2250.3	2679.9	1.3350	5.9905	7.3255	1.0457	1538.9	1540.0	102.5
103.0	1.127	431.7	2248.9	2680.7	1.3406	5.9790	7.3196	1.0461	1513.8	1514.9	103.0
103.5	1.147	433.8	2247.6	2681.4	1.3462	5.9675	7.3137	1.0465	1489.2	1490.3	103.5
104.0	1.167	435.9	2246.3	2682.2	1.3518	5.9560	7.3078	1.0469	1465.1	1466.2	104.0
104.5	1.187	438.1	2244.9	2683.0	1.3574	5.9446	7.3020	1.0473	1441.4	1442.5	104.5

The steam tables may be using a reference of pressure or temperature depending purely upon convenience. You will recall that in the 'Basics' module, when we were discussing temperature, we read that as temperature increased so the force exerted by the molecules of the fluid on the containment increased and this was in fact the increase of pressure. In a saturated system, ie, a system operating between saturated liquid and saturated steam, pressure and temperature are unique and interdependent,ie, if you knew the pressure of the system you could look up the saturation temperature at which the system was operating. Equally, if you knew the temperature you could look up the saturation pressure at which the system was operating.

Temperature

The temperature of the fluid is shown in the extreme left hand column. This is in fact the saturation temperature and as you can see, is measured in °C.

TABLE 1 – SATURATION LINE (TEMPERATURE)

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm³/kg			Temp. °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
100.0	1.013	419.1	2256.9	2676.0	1.3069	6.0485	7.3554	1.0437	1672.0	1673.0	100.0
100.5	1.031	421.2	2255.6	2676.8	1.3125	6.0369	7.3494	1.0441	1644.3	1645.3	100.5
101.0	1.050	423.3	2254.3	2677.6	1.3182	6.0252	7.3434	1.0445	1617.2	1618.2	101.0
101.5	1.069	425.4	2252.9	2678.3	1.3238	6.0136	7.3374	1.0449	1590.6	1591.6	101.5
102.0	1.088	427.5	2251.6	2679.1	1.3294	6.0020	7.3315	1.0453	1564.5	1565.5	102.0
102.5	1.107	429.6	2250.3	2679.9	1.3350	5.9905	7.3255	1.0457	1538.9	1540.0	102.5
103.0	1.127	431.7	2248.9	2680.7	1.3406	5.9790	7.3196	1.0461	1513.8	1514.9	103.0
103.5	1.147	433.8	2247.6	2681.4	1.3462	5.9675	7.3137	1.0465	1489.2	1490.3	103.5
104.0	1.167	435.9	2246.3	2682.2	1.3518	5.9560	7.3078	1.0469	1465.1	1466.2	104.0
104.5	1.187	438.1	2244.9	2683.0	1.3574	5.9446	7.3020	1.0473	1441.4	1442.5	104.5

Pressure

The pressure upon which the steam tables is based is absolute pressure. A slight confusion arises here because the pressure is measured in 'bar' which is roughly one atmosphere.

TABLE 1 – SATURATION LINE (TEMPERATURE)

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm³/kg			Temp. °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
100.0	1.013	419.1	2256.9	2676.0	1.3069	6.0485	7.3554	1.0437	1672.0	1673.0	100.0
100.5	1.031	421.2	2255.6	2676.8	1.3125	6.0369	7.3494	1.0441	1644.3	1645.3	100.5
101.0	1.050	423.3	2254.3	2677.6	1.3182	6.0252	7.3434	1.0445	1617.2	1618.2	101.0
101.5	1.069	425.4	2252.9	2678.3	1.3238	6.0136	7.3374	1.0449	1590.6	1591.6	101.5
102.0	1.088	427.5	2251.6	2679.1	1.3294	6.0020	7.3315	1.0453	1564.5	1565.5	102.0
102.5	1.107	429.6	2250.3	2679.9	1.3350	5.9905	7.3255	1.0457	1538.9	1540.0	102.5
103.0	1.127	431.7	2248.9	2680.7	1.3406	5.9790	7.3196	1.0461	1513.8	1514.9	103.0
103.5	1.147	433.8	2247.6	2681.4	1.3462	5.9675	7.3137	1.0465	1489.2	1490.3	103.5
104.0	1.167	435.9	2246.3	2682.2	1.3518	5.9560	7.3078	1.0469	1465.1	1466.2	104.0
104.5	1.187	438.1	2244.9	2683.0	1.3574	5.9446	7.3020	1.0473	1441.4	1442.5	104.5

Fortunately there is a reasonable conversion, 1 bar = 100 kPa(a). So, if we know the pressure kPa(a) we can divide by 100 to get the pressure in bar. For example, if the steam pressure to the turbine is 4 MPa then the pressure in bar =

$$4 \times 10^3 \text{ kPa} = \frac{4 \times 100^3}{100} \text{ bar} = 40 \text{ bar.}$$

This pressure is the saturation pressure corresponding to that temperature. for example, if the turbine is being fed with saturated steam at 200°C, we can determine the steam pressure. Keep looking down the temperature column, over the pages, until you reach t_s = 200°C. In the next column the saturation pressure is quoted as 15.549 bar.

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm^3/kg			Temp. °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
200.0	15.549	852.4	1938.6	2790.9	2.3307	4.0971	6.4278	1.1565	126.00	127.16	200.0
201.0	15.877	856.9	1934.6	2791.5	2.3401	4.0802	6.4203	1.1580	123.46	124.62	201.0
202.0	16.210	861.4	1930.7	2792.1	2.3495	4.0633	6.4128	1.1596	120.97	122.13	202.0
203.0	16.549	865.9	1926.7	2792.7	2.3590	4.0464	6.4054	1.1612	118.55	119.71	203.0
204.0	16.893	870.5	1922.8	2793.2	2.3684	4.0296	6.3980	1.1628	116.18	117.34	204.0

Similarly, if a steam generator is producing steam at 10.027 bar we can determine the temperature. Still using the first table, we can travel down the ps column until we get to 10.017 bar. The value of t_s is 180.0°C.

Try these examples, you'll find the answers at the end of the module.

B.5.1

Water is heated to produce saturated steam at 135°C. Determine the pressure of the steam.

B.5.2

Saturated steam at 1.985 bar has heat removed until it becomes wet steam at 1.985 bar. Determine the temperature of the steam at the new condition.

B.5.3

The temperature in a steam generator has to be raised to, 140.0°C. What is the pressure in the steam generator at this temperature?

Sensible Heat

You will recall from module B6 that when sensible heat is applied to the liquid state it causes a change of temperature. The enthalpy of the liquid state is determined by its temperature primarily, ie, for the majority of needs the enthalpy of subcooled water at 140°C and 50 bar is the same as the enthalpy of saturated liquid at 140°C.

The symbol for the heat in the liquid is 'h_f' and the units are kJ/kg.

Examples

Feedwater enters a boiler at 175°C and 6 MPa. Determine the enthalpy of the feedwater. The pressure of 6 MPa is equal to 60 bar. Does the pressure or the temperature determine the enthalpy of the liquid? Right, so look up in Table 1 until you find t_s = 175°C. Now read across to column h_f where h_f = 741.1 kJ/kg.

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm^3/kg			Temp. °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
175.0	8.924	741.1	2030.7	2771.8	2.0906	4.5314	6.6221	1.1209	215.42	216.54	175.0
176.0	9.137	745.5	2027.3	2772.7	2.1004	4.5136	6.6140	1.1222	210.63	211.75	176.0
177.0	9.353	749.9	2023.7	2773.6	2.1101	4.4958	6.6059	1.1235	205.96	207.08	177.0
178.0	9.574	754.3	2020.2	2774.5	2.1199	4.4780	6.5979	1.1248	201.41	202.54	178.0
179.0	9.798	758.7	2016.7	2775.4	2.1296	4.4603	6.5899	1.1262	196.98	198.11	179.0

Try these examples:

B.5.4

Condensate leaves the condensate extraction pump at 36°C. Determine the enthalpy of the condensate.

B.5.5

Feedwater is brought up to the saturation temperature in the preheater. The steam pressure is 4 MPa(a). Determine the enthalpy and temperature of the saturated liquid.

B.5.6

A steam generator operates at 4.11 MPa(a). The feed-water entering the steam generator is subcooled by 65°C, ie, 65°C below t_s. Determine the enthalpy of the feedwater.

B.5.7

Heat is added to the feedwater in the feedheaters and deaerator. If the initial temperature of the feedwater was 35°C and the suction to the boiler feedpump was at 126°C, determine the amount of heat added when the feedwater has reached the boiler feedpump suction. Check your answers at the back of the module.

Latent Heat of Vapourization

This is the amount of heat required to effect a complete change of state from saturated liquid to saturated vapour or from vapour to saturated liquid. Although the value of latent heat appears under the heading of specific enthalpy - it is not! If you recall, enthalpy was a heat value measured from 0°C. The latent heat is the amount of heat added or removed at constant temperature. The symbol is h_{fg} and the units are again kJ/kg. The suffix '$_{fg}$' denotes transition from a fluid to a gas.

Example

Feedwater enters a boiler as saturated liquid at 140°C. Determine the amount of heat that has to be added to produce saturated steam and also the pressure of the steam.

Using Table 1, find t_s = 140°C. If the feedwater is saturated it is already at 140°C and only the latent heat has to be added. Look across at column h_{fg} and h_{fg} = 2144 kJ/kg and the steam pressure is the saturation pressure of 3.614 bar.

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm³/kg			Temp. °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
140.0	3.614	589.1	2144.0	2733.1	1.7390	5.1894	6.9284	1.0801	507.41	508.49	140.0
140.5	3.665	591.3	2142.5	2733.7	1.7442	5.1795	6.9237	1.0806	500.71	501.79	140.5
141.0	3.717	593.4	2140.9	2734.3	1.7493	5.1696	6.9190	1.0811	494.11	495.19	141.0
141.5	3.770	595.5	2139.4	2735.0	1.7545	5.1597	6.9142	1.0816	487.61	488.69	141.5
142.0	3.823	597.7	2137.9	2735.6	1.7597	5.1499	6.9095	1.0821	481.22	482.30	142.0

Try these examples, the answers to which are at the end of the module.

B.5.8

Saturated steam is produced from a steam generator at a pressure of 5 MPa(a). The feedwater entering the steam generator is saturated. Determine the temperature of the feedwater, the temperature of the steam and the amount of heat which has to be added in the steam generator in order to produce the saturated steam.

B.5.9

A condenser produces condensate at 32°C from saturated steam. There is no subcooling of the condensate. Determine the amount of heat which must be removed from the steam in the condenser and the condenser pressure.

Enthalpy of Saturated Steam

This is the total amount of heat that the saturated steam possesses when measured from 0°C. This quantity is shown under the column labelled 'h_g' - total heat in the 'gas'. A closer inspection will show that h_g is the sum of h_f and h_{fg}.

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm³/kg			Temp. °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
210.0	19.077	897.7	1898.5	2796.2	2.4247	3.9293	6.3539	1.1726	103.07	104.24	210.0
211.0	19.462	902.3	1894.3	2796.6	2.4340	3.9126	6.3466	1.1743	101.05	102.23	211.0
212.0	19.852	906.9	1890.2	2797.1	2.4434	3.8960	6.3394	1.1760	99.09	100.26	212.0
213.0	20.249	911.5	1886.0	2797.5	2.4527	3.8794	6.3321	1.1777	97.162	98.340	213.0
214.0	20.651	916.0	1881.8	2797.9	2.4620	3.8629	6.3249	1.1794	95.282	96.462	214.0

It is a great benefit to be able to have some type of schematic so that we can see where we are at this point in time and subsequently determine either where the process was previously or where it will be in the future.

As we have already discussed, our major aid in this area, is the temperature enthalpy diagram.

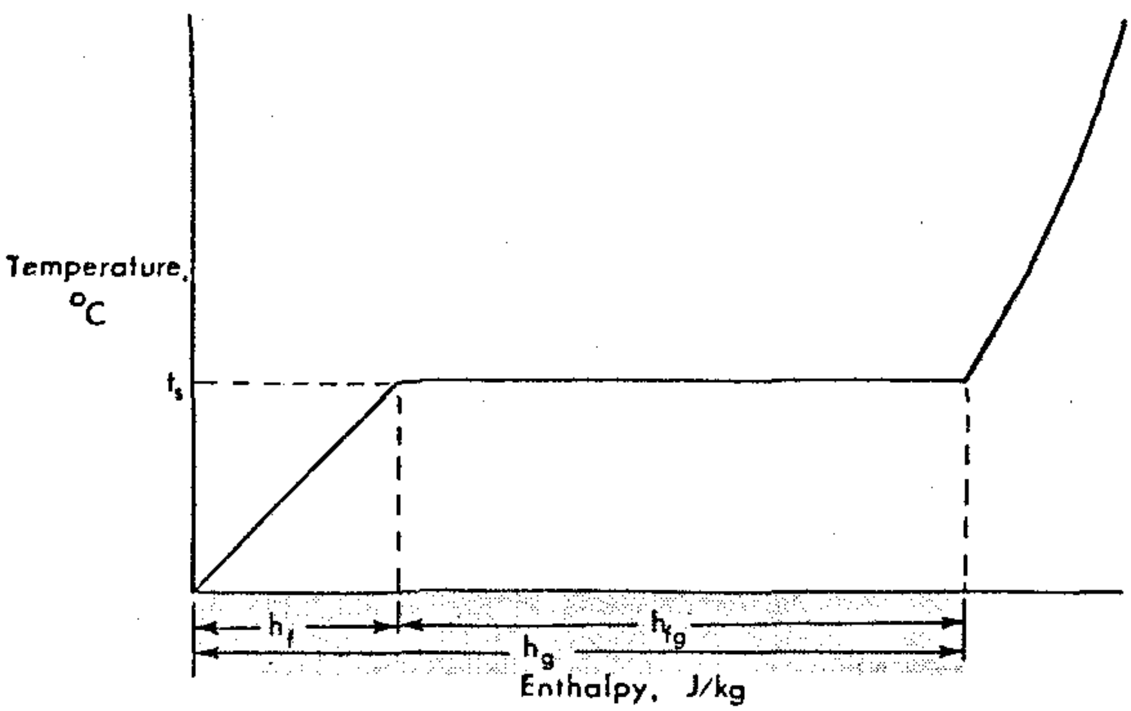

Fig. 5.1

The steam tables are excellent if all we need to do is calculate some values from given data. The only problem with using steam tables is that you must know what is happening in the process before you can use the tables. The temperature/enthalpy diagram provides a visualization of the process which may help us to understand when and how we may use the steam tables.

Before we look at any examples, let's consider some of the aspects of the steam tables.

1. What happens to the saturation temperature as the pressure increases?

2. What happens to the enthalpy of the saturated liquid as the pressure increases?

3. What happens to the latent heat as pressure increases?

4. What happens to the enthalpy of saturated steam as pressure increases? Have a look at the steam tables before you read any further, and see if you can fully answer these four questions.

Temperature

As the pressure increases, so the saturation temperature increases until it reaches a temperature of 374.15°C at a pressure of 221.2 bar. At this pressure some major changes occur as we will see in a minute.

Saturated Liquid

The enthalpy of the saturated liquid rises with pressure up to a maximum value at this pressure of 221.2 bar.

Latent Heat

The value of latent heat falls as the pressure rises. At the pressure of 221.2 bar the value of latent heat is zero. The significance of this fact is that there is now no gradual transition while steam is being generated. As soon as the liquid has reached the saturation temperature, any further addition of heat will cause a total change of liquid to vapour. The pressure of 221.2 bar is called the critical pressure. This is not an area with which we have any continuing concern but explains why h_{fg} goes to zero at this pressure.

Enthalpy of Saturated Steam

As the pressure increases, the enthalpy of the saturated steam increases. However, a closer inspection will reveal that the value of the enthalpy of saturated steam reaches a maximum of 2802.3 kJ/kg at a saturation pressure around 32 bar. The enthalpy then falls to a value of 2107.4 kJ/kg at the critical pressure.

If we plotted the temperature enthalpy lines for all the range of pressures we would produce a curve as shown below, produced by joining all the saturated liquid points and all the saturated steam points.

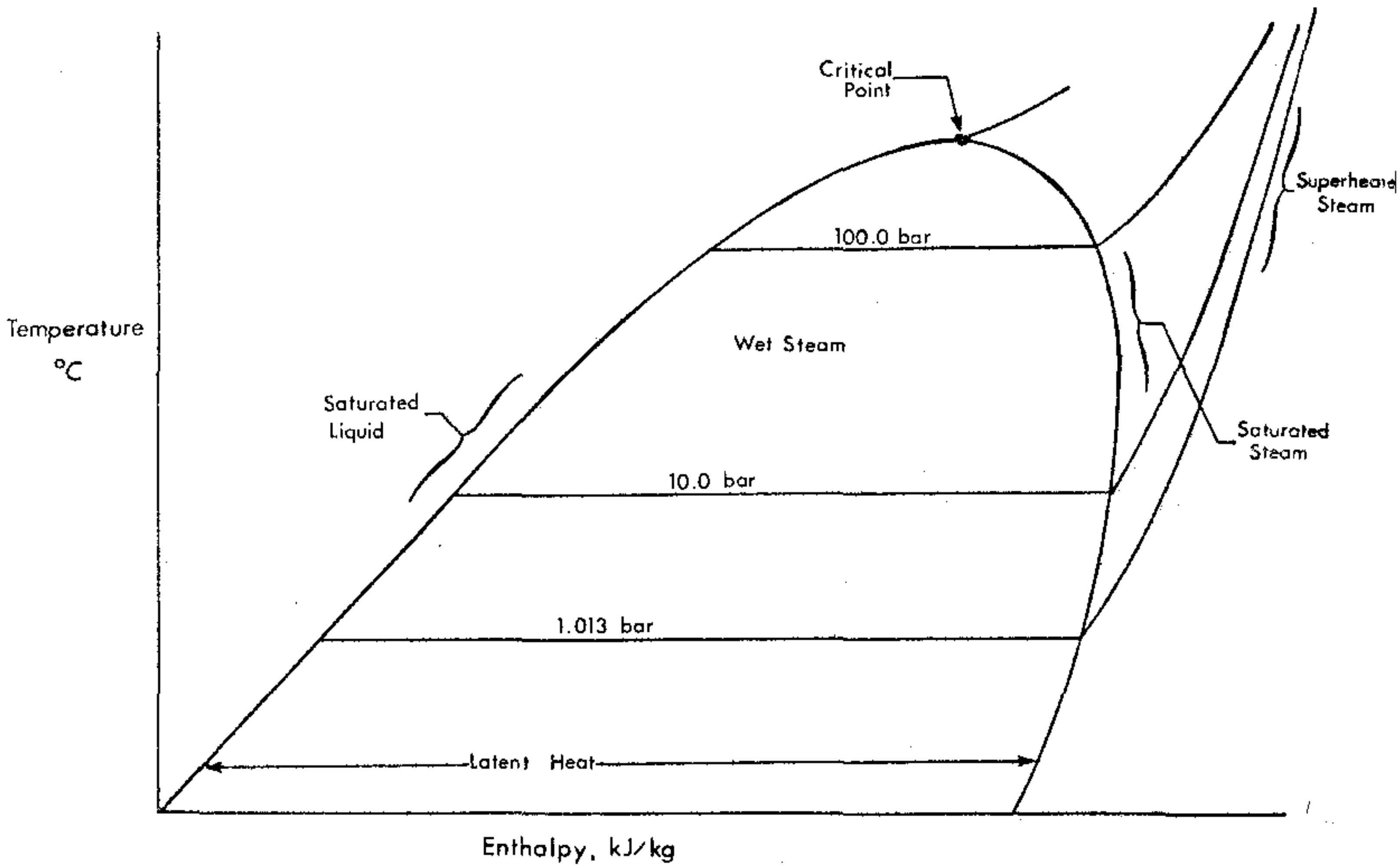

Fig. 5.2

On this diagram we can see the saturation temperature increasing, and the latent heat reducing as the critical pressure is approached.

Let's consider an example to make this more meaningful.

Feedwater enters a steam generator at 175°C. The steam generator produces saturated steam at 4 MPa(a). Determine how much heat must be added to change the feedwater into saturated vapour.

Before we consider using the steam tables, we must examine the process. We know that the steam is saturated at 4 MPa(a), which translates to 40 bar. At 40 bar the saturation temperature is a little over 250°C. The feedwater is subcooled when it enters the steam generator. Drawing the temperature enthalpy diagram we produce the following:

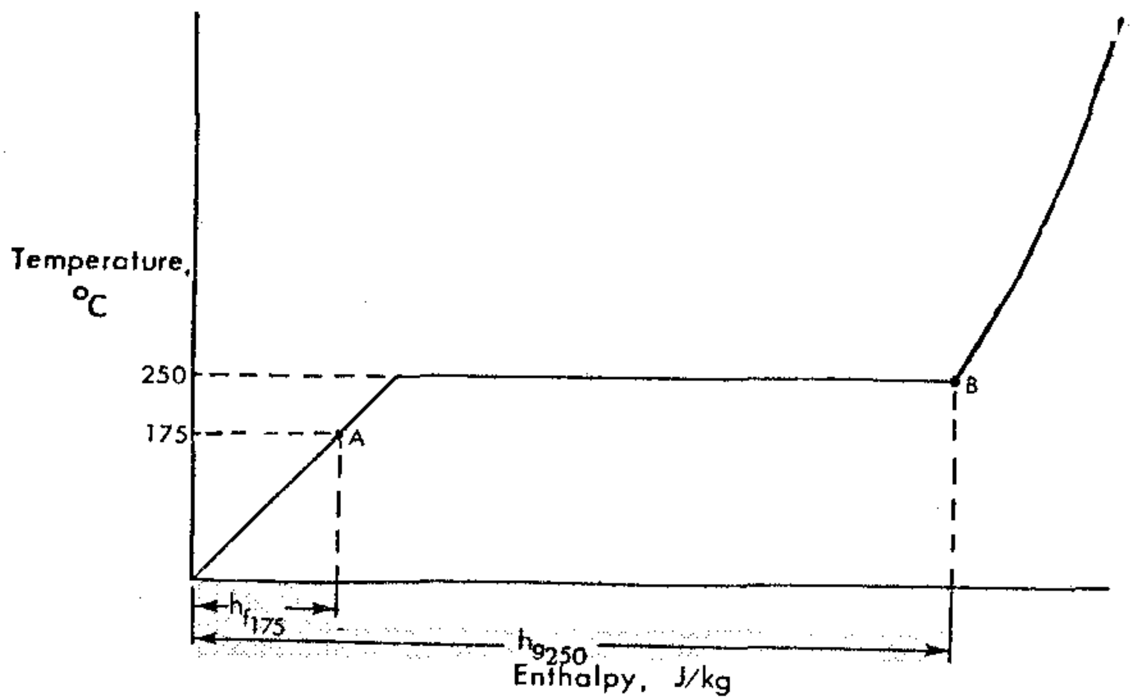

Fig. 5.3

The process starting point is A where the enthalpy of the liquid is h_f @ 175°C (h_{f175}). The completion point is at B where the enthalpy of the saturated steam is h_g at 250°C (h_{g250}).

The amount of heat to be added in the steam generator is the difference between points B and A.

Thus heat to be added = $h_{g250} - h_{f175}$.

Using steam tables,

h_{g250} = 2800.4 kJ/kg

h_{f175} = 741.1 kJ/kg.

Thus Q = 2800.4 - 741.1

= 2059.3 kJ/kg.

Before you try some examples, just examine Table 2 of the steam tables. They are based on exactly the same layout as Table 1, except that they use even increments of pressure as the basis instead of temperature. If the temperature is quoted in whole degrees - use **Table 1,** if the pressure is quoted in whole numbers use **Table 2.**

Try these examples, the answers to which are at the end of the module. I would suggest you draw a partial temperature/enthalpy curve to illustrate the condition.

B.5.10

Saturated water at 30 bar is cooled to a temperature that is 108°C below the saturation temperature. How much heat has been removed?

B.5.11

A steam generator produces saturated steam at 186°C. The feedwater, at the suction to the boiler feedpump, which pumps the feedwater directly into the steam generator, is liquid at 4.4 bar and is subcooled by 20°C. How much heat has to be supplied to produce 1 kg of steam?

B.5.12

An oil cooler has cooling water entering at 17°C and leaving at 41°C. Determine the increase in the enthalpy of the water.

B.5.13

A condenser at 5 kPa(a) receives saturated steam. The condensate is subcooled by 5°C. Determine how much heat is rejected to the condenser per kg of steam.

Enthalpy of Wet Steam

You may recall from the 'Basics' Module B6 that we could describe 'wet steam' as steam which had not received all its latent heat of vapourization. This is a little contradictory and it would be more accurate to describe wet steam as a mixture of water droplets and vapour, both at the saturation temperature.

Only the vapour has received its latent heat of vapourization. How much latent heat will the wet steam receive? That depends upon the proportion of vapour in the mixture. If 70% of the mixture by weight is vapour, then 70% of the latent heat has been added and a further 30% has to be added before the droplets have all been converted into vapour and we have saturated steam. Determining the enthalpy of wet steam requires one more step in the calculation than previously.

In practice, we often use names and terminology which makes understanding unnecessarily complicated. For example, we talk about 'wet steam' but when we perform calculations using 'wet steam' it is more usual to think about how 'dry' it is and not how wet.

Dryness Fraction

The dryness fraction is a ratio, by weight, of the amount of vapour in a mixture to the total weight of liquid plus vapour.

$$q = \frac{\text{weight of vapour} \times 100}{\text{weight of vapour} + \text{weight of liquid}}$$

If the dryness fraction is 80% then 80% of the mixture is saturated vapour and equally 80% of the latent heat must have been added. Equally, 20% of the mixture is saturated liquid.

Let's look again at the temperature enthalpy diagram to see how we determine the enthalpy of the wet steam.

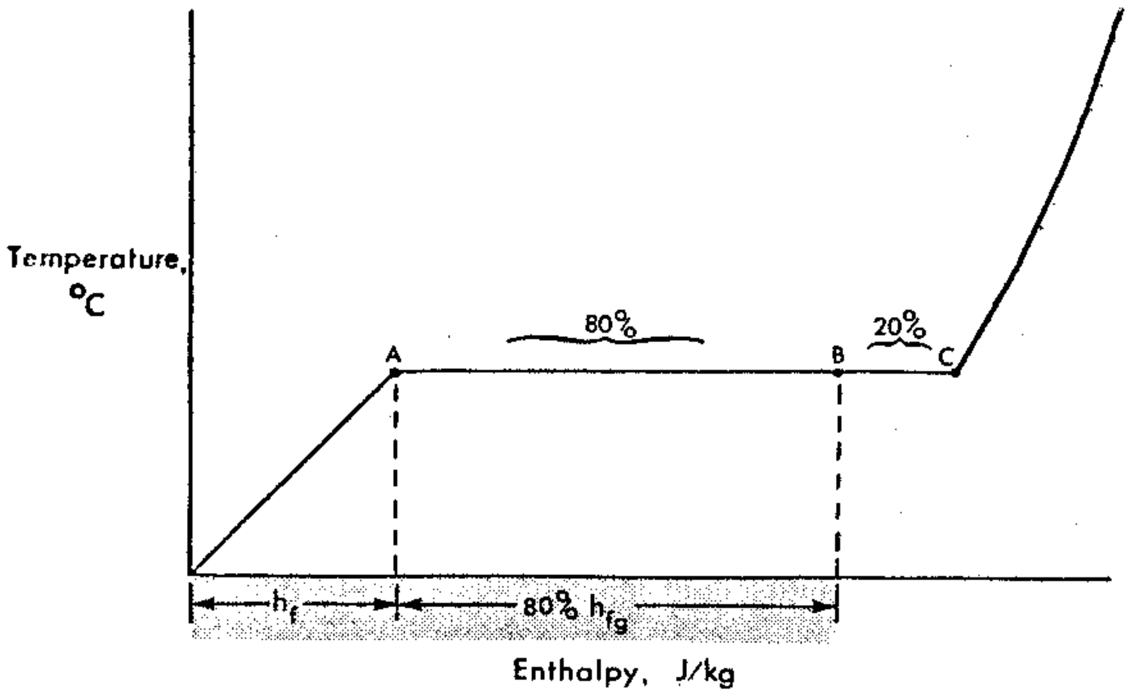

Fig. 5.4

Suppose point B represents wet steam having a dryness of 80%. At point A the enthalpy is h_f of the liquid. At a point 80% along the line AC we will have added 80% of h_{fg}. Consequently, the enthalpy of the 80% dry steam will be $h_f + 0.8\ h_{fg}$.

Consider this example: A steam generator produces steam at 40 bar. The steam is 15% wet. Determine the enthalpy of the steam.

If the steam is 15% wet it must also be 85% dry - thus $q = 0.85$.

Using Table 2 h_f at 40 bar = 1087.4 kJ/kg
& h_{fg} = 1712.9 kJ/kg.

Thus enthalpy of steam = 1087.4 + 0.85 x 1712.9 kJ/kg

= 1087.4 + 1456 kJ/kg

= 2543.4 kJ/kg.

Do these exercises. The answers are at the end of the module.

B.5.14

A low pressure turbine exhausts steam at 12% moisture and at a pressure of 6 kPa(a). Determine the enthalpy of the steam.

B.5.15

4 kg of liquid are removed from a moisture separator. If the steam was 88% dry, what was the mass of wet steam entering the moisture separator? Assume that the steam leaving the moisture separator is saturated.

B.5.16

A steam generator produces wet steam of 92% dryness at 196°C. The feedwater enters the steam generator at 134°C. Determine how much energy is added to the feedwater in the steam generator.

B.5.17

A process heater produces saturated steam at 300°C from 18% wet steam at 18 bar. Determine how much heat has been added to the steam.

B.5.18

A condenser receives 12% wet steam at 35°C. The condensate is subcooled by 5°C. Determine how much heat has been removed in the condenser.

B.5.19

Feedwater enters a steam generator at 160°C and is converted into steam having a saturation temperature of 220°C. The heat supplied by the steam generator is 1900 kJ per kilogram of steam. Determine the dryness fraction of the steam.

Superheated Steam

In module B.6 on 'Basics', we define superheated steam as steam which exists at a temperature above the saturation temperature. Steam Tables 1 & 2 only deal with saturated conditions; so another set of tables is required for superheated steam.

Table 3 presents information for superheated steam. This information is presented using a base of pressure which is in bar as previously and is the first quantity across the top of the page.

TABLE 3 – PROPERTIES OF WATER AND STEAM

p(ab)/bar	2.0			3.0			4.0		
t_s °C	120.2			133.5			143.6		
	h	s	v	h	s	v	h	s	v
Sat. Liquid	504.7	1.530	1.061	561.4	1.672	1.074	604.7	1.776	1.084
Sat. Vapour	2706	7.127	885.4	2725	6.991	605.6	2738	6.894	462.2
t °C									
50	209.4	0.703	1.012	209.5	0.703	1.012	209.6	0.703	1.012
100	419.1	1.307	1.044	419.2	1.307	1.044	419.3	1.307	1.044
150	2769	7.279	959.5	2760	7.077	633.7	2752	6.929	470.7
200	2871	7.507	1080	2866	7.312	716.4	2860	7.171	534.3
250	2971	7.710	1200	2968	7.519	796.4	2965	7.380	595.2
300	3072	7.894	1316	3070	7.703	875.3	3067	7.568	654.0
350	3174	8.064	1433	3172	7.874	953.5	3170	7.640	713.9
400	3277	8.223	1549	3275	8.034	1031	3274	7.899	772.5
450	3381	8.372	1665	3380	8.184	1109	3379	8.050	830.9
500	3487	8.514	1781	3486	8.326	1187	3488	8.192	889.2
550	3595	8.649	1897	3594	8.461	1264	3593	8.327	947.4
600	3704	8.779	2013	3703	8.590	1341	3702	8.456	1005
650	3815	8.901	2129	3814	8.714	1419	3814	8.580	1063

p(ab)/bar	5.0			6.0			7.0		
t_s °C	151.8			158.8			165.0		
	h	s	v	h	s	v	h	s	v
Sat. Liquid	640.1	1.860	1.093	670.4	1.931	1.101	697.1	1.992	1.10
Sat. Vapour	2748	6.819	374.7	2756	6.738	315.5	2762	6.705	272.
t °C									
50	209.7	0.703	1.012	209.8	0.703	1.012	209.9	0.703	1.01
100	419.4	1.307	1.044	419.4	1.307	1.043	419.5	1.306	1.04
150	632.2	1.842	1.091	632.2	1.842	1.091	632.3	1.841	1.00
200	2855	7.059	425.0	2850	6.963	352.0	2844	6.888	299
250	2961	7.272	474.4	2958	7.183	393.9	2954	7.107	336.
300	3065	7.461	522.6	3062	7.374	434.4	3060	7.300	371.
350	3168	7.634	570.1	3166	7.548	474.2	3164	7.475	405.
400	3272	7.795	617.2	3271	7.709	513.6	3269	7.636	439.
450	3377	7.946	664.1	3376	7.860	552.8	3375	7.788	473.
500	3484	8.088	710.3	3483	8.003	591.9	3482	7.931	506
550	3592	8.223	757.4	3591	8.138	630.8	3590	8.063	540.
600	3702	8.353	804.0	3701	8.268	669.6	3700	8.196	573.
650	3813	8.477	850.4	3812	8.397	708.4	3811	8.320	607.

Consider the column under the pressure heading of 4.0 (bar). The next line lists the saturation temperature for that pressure, ie, at 4.0 (bar) the t_s is 143.6°C. The next two lines contain three headings and we are only interested in the enthalpy column headed 'h'. The enthalpy of the saturated liquid and vapour is shown. In our illustration at 4.0 (bar) h_f = 604.7 kJ/kg and hg = 2738 kJ/kg.

All this information is readily available from Tables 1 and 2. Now we have the difference. We have already seen that the saturation temperature at 4.0 (bar) is 143.6°C. Suppose we have steam at 4.0 bar and at a temperature of 300°C. How do we determine the enthalpy? At the extreme left hand of the sheet is a temperature column. Look down the column to the temperature of 300°C, then read across to the entry in the column 'h' at 4.0 (bar) when the enthalpy may be seen to be 3067 kJ/kg.

Example

Saturated steam at 10 bar from a moisture separator is heated to 230°C in a reheater. Determine a) the enthalpy of the steam leaving the reheater, b) the heat added in the reheater.

Again we can use the temperature/enthalpy diagram to illustrate the conditions.

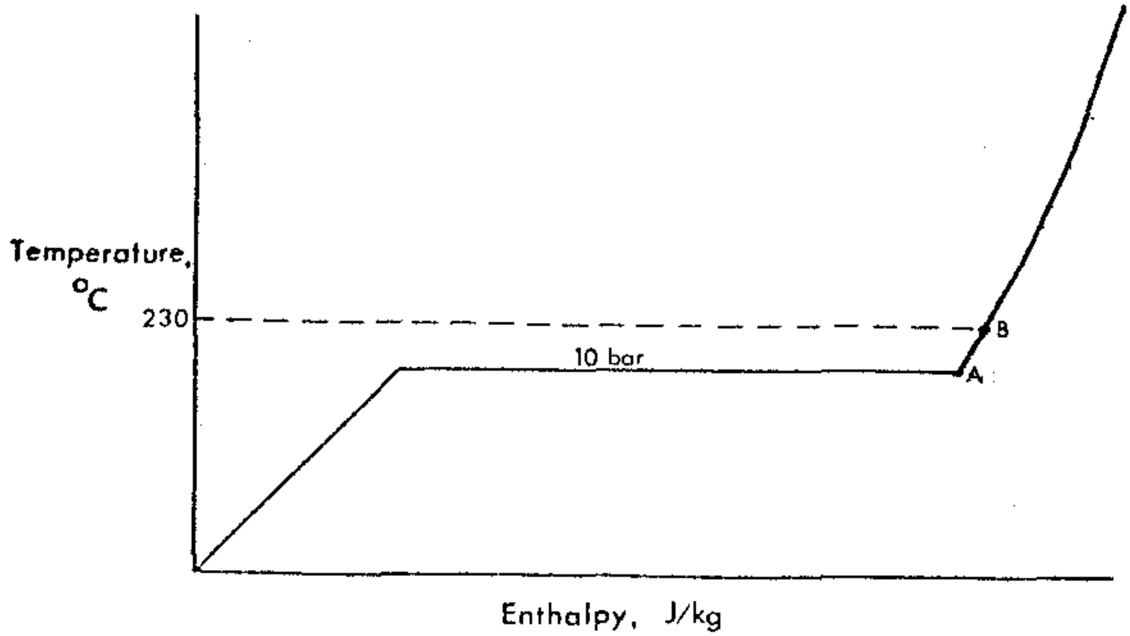

Fig. 5.5

The initial condition is at point A where the steam is saturated at 10 bar. The enthalpy may be determined from Table 2, hg = 2776 kJ/kg.

The final condition is superheated steam at a temperature of 230°C and a pressure of 10 bar. Using Table 3 we have to take two readings because the temperature scale in Table 3 only progresses in steps of 50°C.

At 10 bar and 200°C h = 2827 kJ/kg, and

at 10 bar and 250°C h = 2943 kJ/kg.

The difference for 50°C is 2943 - 2827 = <u>116</u> kJ/kg.

At 230°C the enthalpy will be enthalpy at 200°C + 30/50 of the difference 116.

Thus h = 2827 + 3/5 x 116

a) = <u>2896.6</u> kJ/kg.

The enthalpy difference represents the amount of heat added in the reheater.

Final enthalpy - initial enthalpy = heat added in the reheater.

b) 2896.6 - 2776 = <u>120.6</u> kJ/kg.

Do these examples, the answers are at the end of the module.

B.5.20

Determine the enthalpy of steam at 20 bar and a temperature of 375°C.

B.5.21

380 kJ of heat are added to 1 kg of 15% wet steam at 8 bar. Determine the temperature of the final steam.

* * * * *

Before we proceed, with the course material, do the following exercises in preparation for the criterion test.

B.5.22

Given the following information, identify the states of water as:

subcooled liquid
saturated liquid
wet steam
saturated steam
or superheated steam.

	Enthalpy	Temperature	Pressure
a)	561.4 kJ/kg	133.5°C	3.0 bar
b)	2323 kJ/kg	32.9°C	0.05 bar
c)	2855 kJ/kg	200°C	5.0 bar
d)	2538.2 kJ/kg	20°C	0.02337 bar
e)	125.7 kJ/kg	30°C	0.07375 bar

B.5.23

Feedwater enters a steam generator at 180°C and is converted into steam with 4% moisture at 260°C. How much heat is added in the steam generator per kg of steam?

B.5.24

Steam which is 12% wet enters a condenser at 36°C. The condensate is subcooled by 3°C. Determine how much heat is rejected to the condenser per kg of steam.

Volume of Liquid and Vapour

As discussed in the 'Basics' module, one of the effects of changing temperature on a fluid is the change of volume. This applies to both liquids and vapours. In the specific process of adding the latent heat of vapourization the change in volume is phenomenal. The steam tables will allow the volumes to be calculated without any difficulty.

Looking at Table 1 of the steam tables, the last column group is headed "Specific Volume". Specific volume is volume per unit mass. In the S.I. system there are two acceptable volume measurements:

a) the cubic meter - 'm^3'

b) the liter, which is one thousandth of a cubic meter - 'ℓ'.

The steam tables use the liter which they call the cubic decimeter - dm^3.

Volume of Liquid

The volume of liquid per kilogram is found under the column headed v_f - volume of fluid.

Example

Determine the volume of 30 kg of water at 55°C.

Looking at Table 1, at temperature t_s = 55°C, select the value of v_f = 1.0145 ℓ/kg. Thus 30 kg will occupy 30 x 1.0145ℓ = 30.435ℓ.

Do these examples and check your answers at the end of the module.

B.5.25

A tank holds 3 m^3 of water at 90°C. How many kg of water are in the tank?

B.5.26

Condensate at 36°C is heated to 175°C in the feedheating system. Determine the percentage increase in volume of the feedwater.

Volume of Saturated Steam

There is a large increase in the volume of working fluid as the transition from liquid to vapour occurs. This is particularly true of vapour at low pressures. The volume of saturated steam is shown in the steam tables, still looking at Table 1, under column v_g.

Example

Saturated steam at 80°C is condensed to saturated liquid. Determine the reduction of volume which occurs.

Using Table 1, v_g at 80°C = 3409.1 ℓ/kg, and v_f = 1.0292 ℓ/kg.

So sensibly, the volume has been reduced from 3409 liters to just over 1 liter.

Do these examples and check your answers at the end of the module.

B.5.27

Feedwater enters the steam generator at 175°C. The steam leaving the steam generator is saturated steam at 250°C. Determine the volume increase that occurs within the steam generator.

B.5.28

Saturated steam at 40°C is condensed to subcooled liquid at 35°C. Determine the volume reduction.

Volume of Wet Steam

The volume of wet steam is treated in exactly the same way as we treated the enthalpy of wet steam. The volume of the wet steam is equal to the volume of the liquid plus the dryness fraction multiplied by the change in specific volume when going from liquid to vapour, ie, $v = v_f + qv_{fg}$.

Example

Determine the volume of steam at 12% moisture and 165°C.

From Table 1, v_f = 1.1082 ℓ/kg and v_{fg} = 271.29 ℓ/kg.

$$v = v_f + qv_{fg}$$
$$= 1.1082 + 0.88 \times 271.29$$
$$= \underline{239.8}\ \ell/\text{kg}.$$

Do these problems and check your answers at the end of the module.

B.5.29

Saturated steam at 250°C enters the hp turbine and steam with 12% moisture leaves the low pressure turbine at a pressure of 5 kPa(a). Compare the initial steam volume per kg with the final volume.

B.5.30

The low pressure steam in question B.5.29 is condensed to condensate which is subcooled by 3°C. Determine the volume reduction which occurs in the condenser.

Steam Hammer

This process should not be confused with "water hammer" which is the result of rapidly accelerating or decelerating the flowrate of fluids and is usually more of a problem in liquids.

Steam hammer is associated with hot pressurized water systems. Steam hammer is the result of continuous rapid vapour production and continuous recondensation within the system.

The problem occurs in lines which have large amounts of pressurized hot liquid that is reasonably close to the saturation temperature. Imagine you have a line full of hot water at 160°C at a pressure of 1 MPa(a). The saturation temperature corresponding to 1 MPa(a) is 180°C which means that the liquid in the line is subcooled and there can be no vapour present.

Suppose there is no flow and we have to commission the circuit by opening the downstream valve. What will happen to the pressure in the line upstream when the valve is opened? It will fall! If the pressure falls to the saturation pressure corresponding to 160°C, ie, 618 KPa(a) vapour will be produced in the line.

The effect of producing vapour creates a momentary pressure increase which results in some of the vapour recondensing. As the vapour condenses, liquid moves in rapidly to occupy the low pressure volume previously occupied by the vapour and produces a shock or hammering of the line.

The liquid shuttles to and fro in the line with violent reaction which can result in severe damage to pipework and valves.

In this overall process the pressure is unstable and fluctuating rapidly, causing pockets of vapour to be produced at the same time causing other pockets of vapour to condense.

The solution to this problem is to prevent the pressure falling down to the saturation value. The problem is most likely to be encountered when warming up a line where heavy condensation may have resulted in a large volume of liquid. Open the valves <u>very slowly</u> and if steam hammer is experienced, you know that the pressure in the line is too low and the flowrate should be reduced to raise the line pressure until the line is free of liquid.

* * * * *

<u>B.5.31</u>

Briefly describe the process of "steam hammer" and explain how it could be avoided.

Pressure, Volume, Temperature, Mass Relationships

In a constant volume water filled system provided with means of adding and/or removing water, the variance of temperature, pressure, mass and fraction of liquid and vapour is determined as follows:

Example

You are given a constant volume, 4 m^3 system that has provision for addition and/or removal of water with the following initial conditions:

Temperature	150°C
Pressure	476.0 kPa(a)
Volume of Liquid	3.5 m^3
Volume of Vapour	0.5 m^3
Mass of Water	3210 kg

If the temperature of the system is lowered to 100°C at constant pressure, state whether the volume of liquid, volume of vapour, and mass of water will increase, decrease, or remain constant. Explain your statement and determine the amount of any changes that occur.

* * * * *

As the temperature of the system goes from 150°C to 100°C, water must be added to the system to maintain constant pressure.

The pressure of the system will fall as the temperature goes from 150°C to 100°C (unless water is added to maintain the pressure at 476.0 kPa(a)). This is because the system is a mixture of liquid and vapour, ie, a saturated system. As water is added, the system will no longer be saturated; the vapour will condense. The system will be completely liquid at the final conditions (ie, the liquid volume will increase from 3.5 m^3 to 4.0 m^3 and the vapour volume will decrease from 0.5 m^3 to 0.0 m^3). Water must also be added to maintain the pressure because of the contraction of the liquid as its temperature drops.

To determine the increase in the mass of the water, we will use the specific volume at the final conditions. For practical purposes, liquid water is incompressible. Its specific volume at 100°C and 4.76 bar is thus the same as $v_{f100°C}$, ie, 1.044 ℓ/kg, or 1.044 x 10^{-3} m^3/kg.

4m^3 of liquid water at 100°C and 4.76 bar represents:

$4\ m^3 \div 1.044 \times 10^{-3}\ m^3/kg = 3831\ kg.$

Therefore the mass of water will increase 3831 - 3210 = 621 kg.

* * * * *

Do these problems, then check your answer with those at the end of the module.

B.5.32

Consider a constant volume 5 m^3 water filled system with these initial conditions (and with provision for adding and/ or removing water):

Temperature	198.3°C
Pressure	1.5 MPa(a)
Volume of Liquid	5.0 m^3
Volume of Vapour	0.0 m^3
Mass of Water	4334 kg

The system is cooled to 150°C constant pressure. Will the volume of liquid, volume of vapour, and mass of water increase, decrease, or remain constant? Explain your answers, and determine the amount of any changes that occur.

B.5.33

The system in B.5.32 is cooled to 150°C at constant mass. Will the pressure, volume of liquid, and volume of vapour increase, decrease, or remain constant? Explain your answers.

B.5.34

The system in B.5.32 is heated at constant pressure until the temperature reaches 250°C. Will the volume of liquid, volume of vapour, and mass of water increase, decrease, or remain constant? Explain your answer, and determine the amount of any changes that occur.

* * * * *

This module is perhaps the most demanding in this program. The benefit of having worked your way through this material will become apparent in later modules.

When you are ready to take the criterion test, ask the Course/Shift Manager for the test.

After you have written the test, ask for the self evaluation sheet and compare your answers with those on the evaluation sheet.

Finally discuss your criterion test with the Course/ Shift Manager and if you are both satisfied with the results, have the Manager sign your progress summary sheet. If you identify areas that need reinforcing, return to the course material and retake the test when you feel that you are competent.

When you have successfully completed module B.5 you may proceed to the next module on the course map, B.4.2 or B.3.2.

Answers

MODULE B.5

STEAM TABLES

B.5.1

In Table 1 of the steam tables, find 135°C in the t_s column. The pressure corresponding to 135°C is found in the next column on the right, ie, 3.131 bar.

B.5.2

Find 1.985 bar in the p_s column of Table 1. The saturation temperature is 120°C. Does the temperature of the steam fall as the heat is removed from the saturated steam? No it does not! The steam quality changes as the latent heat is removed making the steam wetter but the temperature remains the saturation temperature of 120°C.

B.5.3

Find 140°C in the t_s column and the corresponding pressure is 3.614 bar.

B.5.4

Find 36°C in the column t_s. Look at the value of enthalpy under the column h_f. The enthalpy of the condensate is 150.7 kJ/kg.

B.5.5

The pressure of 4 MPa(a) is equal to a pressure of 40 bar. Finding the nearest pressure to p_s = 40 bar p_s = 39.776 bar (in Table 1). The saturation temperature at 39.776 bar is 250°C and the enthalpy of the liquid h_f is 1085.8 kJ/kg.

B.5.6

The pressure of 4.11 MPa(a) is equal to 41.1 bar. Looking down the p_s column for 41.1 we can see p_s = 41.137 to the nearest reading. The saturation temperature at this pressure is 252°C. If the liquid is subcooled by 65°C it must be 65°C below the saturation temperature. Thus, the temperature of the liquid entering the steam generator is 252 - 65 = 187°C.

The enthalpy of the liquid at 187°C may be found by looking at the value of h_f when t_{sat} is 187°C and you can see the value of h_s is 794.2 kJ/kg.

B.5.7

The initial enthalpy at 35°C is h_f when t_s = 35°C h_f 146.6 kJ/kg.

The final enthalpy at 126°C is h_f when ts = 126°C h_f = 529.2 kJ/kg.

So the amount of heat added is the difference, ie, 529.2 - 146.6 = 382.6 kJ/kg.

B.5.8

A pressure of 5 MPa(a) is equal to 50 bar. The nearest pressure in Table 1 is 50.071 bar. The saturation temperature at this pressure is 264°C. The feedwater is saturated so its temperature is 264°C. The steam from the steam generator is saturated, so its temperature is 264°C as well. The heat which has to be added in the steam generator to produce the saturated steam is the latent heat of vapourization h_{fg} and h_{fg} at 264°C is 1639.2 kJ/kg.

B.5.9

There is no subcooling of the condensate, therefore, the temperature of the condensate is the saturation temperature. The steam is saturated and so the amount of heat that has to be removed to change saturated steam into saturated liquid is again the latent heat of vapourization. h_{fg} at t_s = 32°C is 2425.9 kJ/kg.

The saturation temperature determines the pressure and p_s at t_s = 32°C is 0.04753 bar which is 4.753 kPa(a).

B.5.10

By sketching the temperature/enthalpy curve for 30 bar we can examine the problem more closely.

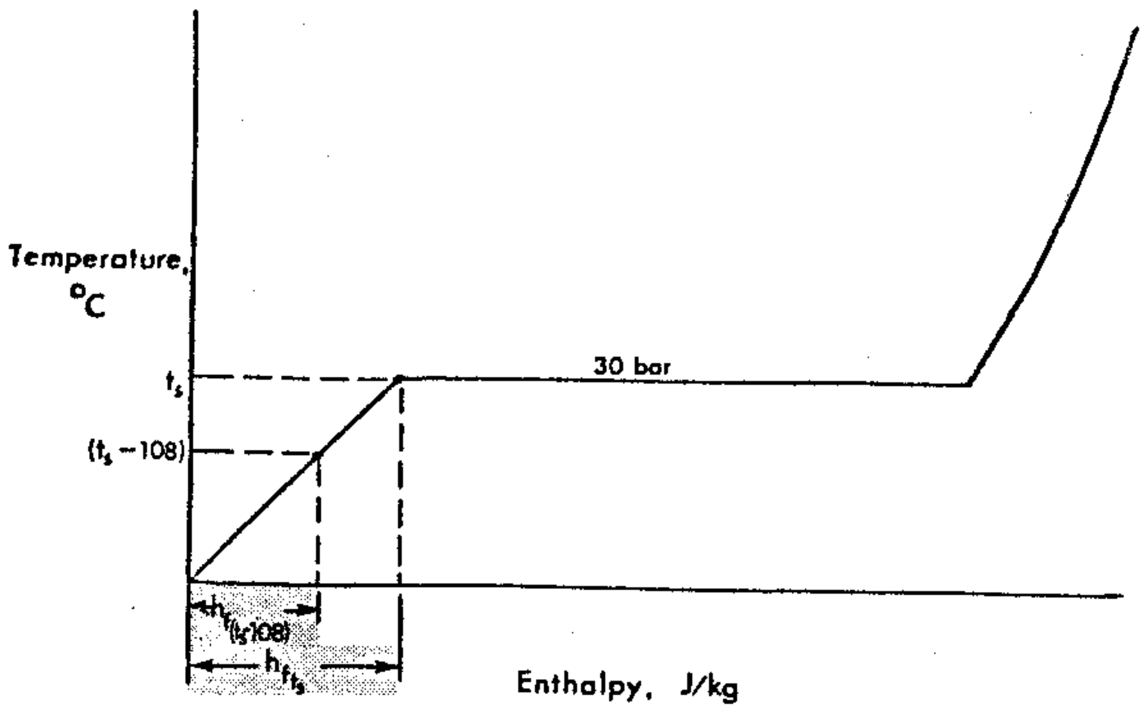

Fig. 5.6

At 30 bar the saturation temperature is 233.8°C from Table 2. The liquid is subcooled by 108°C so its final temperature is 233.8 - 108 = 125.8°C. The enthalpy of the saturated liquid is h_f at 233.8°C and the enthalpy of the liquid at 125.8°C is h_f at 125.8°C. Consequently, the difference in the enthalpies represents the amount of heat which has been removed.

$h_{f233.8}$ = 1008.4 kJ/kg

$h_{f125.8}$ = 529.2 kJ/kg.

So the heat removed = 1008.4 - 529.2

= <u>479.2</u> kJ/kg.

B.5.11

Again plot the two conditions on the temperature enthalpy diagram. The final condition is saturated steam at 186°C and the initial condition is subcooled liquid at 4.4 bar, the amount of subcooling is 20°C. If we look up t_s for 4.4 bar in Table 2, we find the value is t_s = 147°C. Thus the temperature of the liquid is 147 - 20 = 127°C.

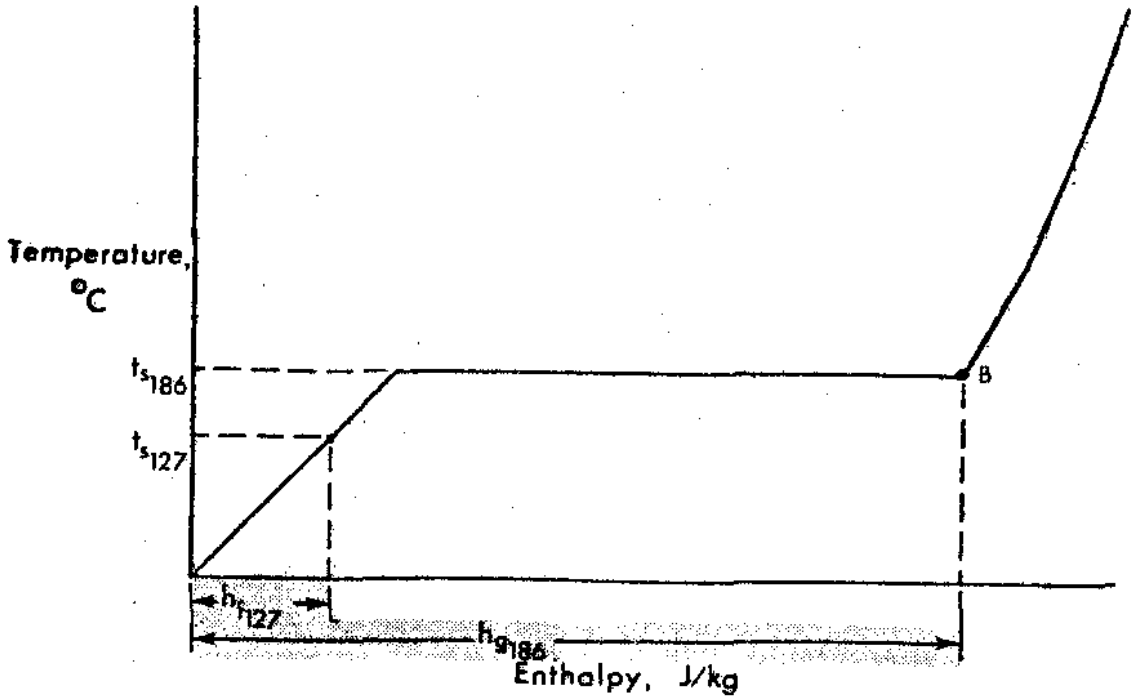

Fig. 5.7

The enthalpy of the saturated steam is hg at 186°C. Using Table 1, h_{g186} = 2781.2 kJ/kg.

The enthalpy of liquid at 127°C is h_f at 127°C, again using Table 1 h_{f127} = 533.5 kJ/kg.

So the amount of heat to be supplied is the difference between the final and initial conditions, ie, $h_{g186} - h_{f127}$

2781.2 - 533.5 = 2247.7 kJ/kg.

B.5.12

The increase in enthalpy of the cooling water is the difference between the enthalpy of the water at 41°C and the initial condition of 17°C.

Enthalpy at 41°C = h_{f41} = 171.6 kJ/kg.

Enthalpy at 17°C = h_{f17} = 71.3 kJ/kg.

(Both values from Table 1)

Thus the increase = 171.6 - 71.3 = 100.3 kJ/kg.

B.5.13

The condenser pressure is 5 kPa(a) which is 0.05 bar. From Table 2 the saturation temperature for this pressure is 32.9°C. The condensate is subcooled by 5°C which means that the condensate temperature is 32.9 - 5 = 27.9°C.

Again a sketch on the temperature enthalpy diagram is worthwhile.

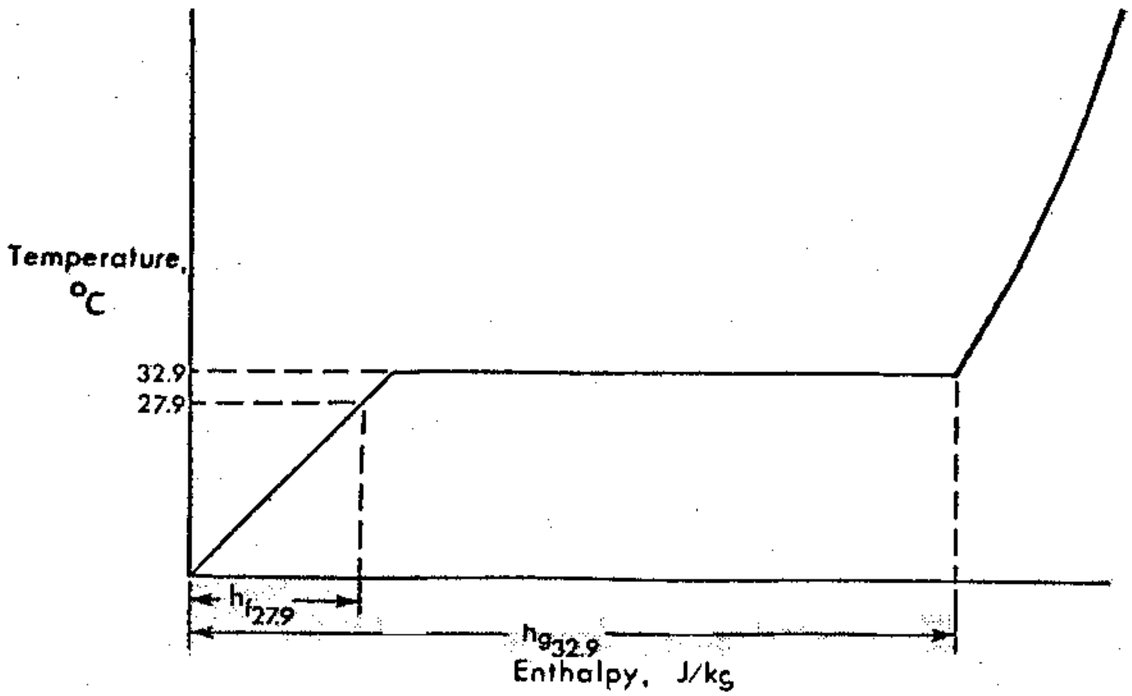

Fig. 5.8

Although this is a removal of heat, the quantity involved is still the difference between the initial and final conditions.

The enthalpy of the initial condition is hg at 0.05 bar, which from Table 2 is 2561.6 kJ/kg.

The enthalpy of the final condition is h_f at 27.9°C, which from Table 1 is 117 kJ/kg.

Again the change in enthalpy is the amount of heat rejected to the condenser per kg of steam, ie, 2561.6 - 117 = 2444.6 kJ/kg.

B.5.14

If the steam has 12% moisture, it is 88% dry and has therefore received 88% of its latent heat of vapourization.

Consequently the enthalpy of the steam is $h_f + 0.88\ h_{fg}$.

h_f at 6 kPa(a), Table 2 = 151.5 kJ/kg.

h_{fg} at 6 kPa(a), Table 2 = 2416.0 kJ/kg.

The enthalpy of the wet steam = 151.5 + 0.88 x 2416.0 kJ/kg

= 151.5 + 2126.1 kJ/kg

= 2277.6 kJ/kg.

B.5.15

The 4 kg that was removed represents the liquid or droplets in the steam. If the steam was 88% dry it must also have been 12% wet. Consequently the 4 kg represents 12% so the total weight of wet steam is $\frac{4}{12}$ x 100 = 33.3 kg.

B.5.16

The energy added to the feedwater in the steam generator is the difference between the final enthalpy of the wet steam at 196°C and the feedwater at 134°C.

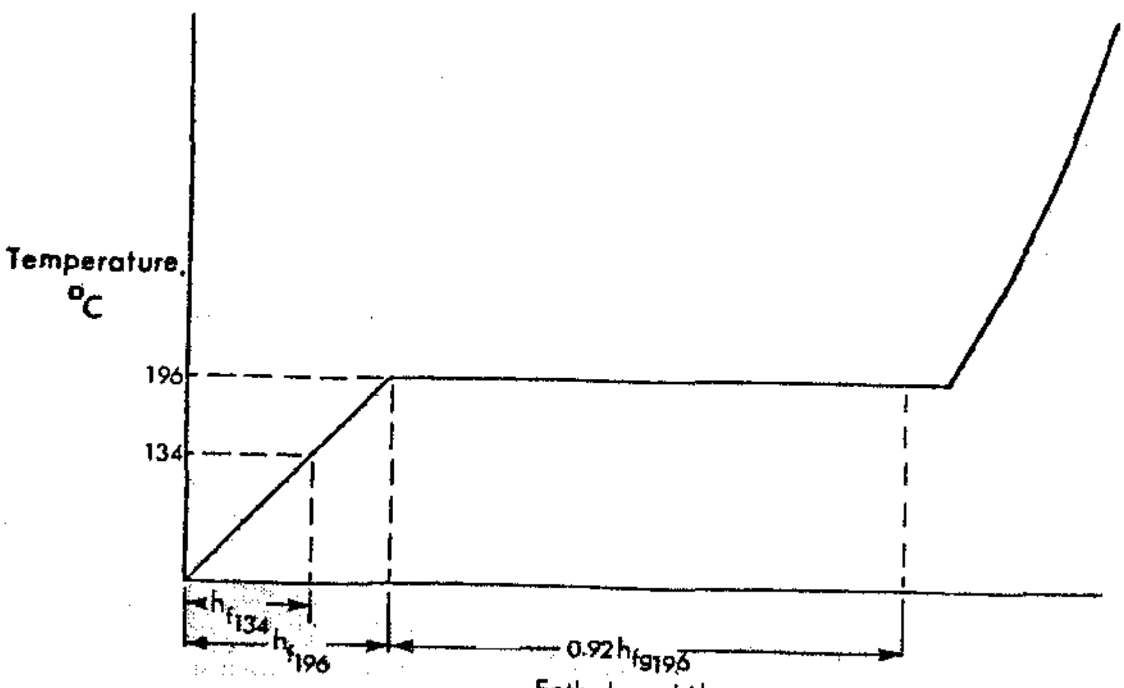

Fig. 5.9

Using Table 1, enthalpy of saturated liquid at 196°C is 834.4 kJ/kg and the value of h_{fg} is 1954.1 kJ/kg.

The enthalpy of the wet steam is

$h_f + qh_{fg}$ = 834.4 + 0.92 x 1954.1 kJ/kg

= 834.4 + 1797.8 kJ/kg

= 2632.2 kJ/kg.

From Table 1, enthalpy of liquid at 134°C = 563.4 kJ/kg.

Energy added in the steam generator is the difference between the two enthalpies ie, 2632.2 - 563.4 = 2068.8 kJ/kg.

B.5.17

Again the difference in the enthalpies is the solution to the problem. The final condition is saturated steam at 300°C - from Table 1 - h_g = 2751 kJ/kg.

The initial condition of 18% wet steam at 18 bar may be quantified using Table 2. The enthalpy of the saturated liquid is 884.6 kJ/kg and the value of h_{fg} is 1910.3 kJ/kg.

Enthalpy of wet steam is $h_f + qh_{fg}$

= 884.6 + 0.82 x 1910.3 kJ/kg

= 884.6 + 1566.4 kJ/kg

= 2451.0 kJ/kg.

Quantity of heat added is the difference between these two enthalpies, ie,

2751 - 2451 kJ/kg

= 300 kJ/kg.

B.5.18

This problem is exactly the same as the steam generator problem except that the heat is being removed and not added. The initial condition is 12% wet steam at 35°C. The condensate is subcooled by 5°C. The saturation temperature is 35°C so the condensate temperature is 35 - 5 = 30°C.

A sketch of the temperature/enthalpy curve may be useful.

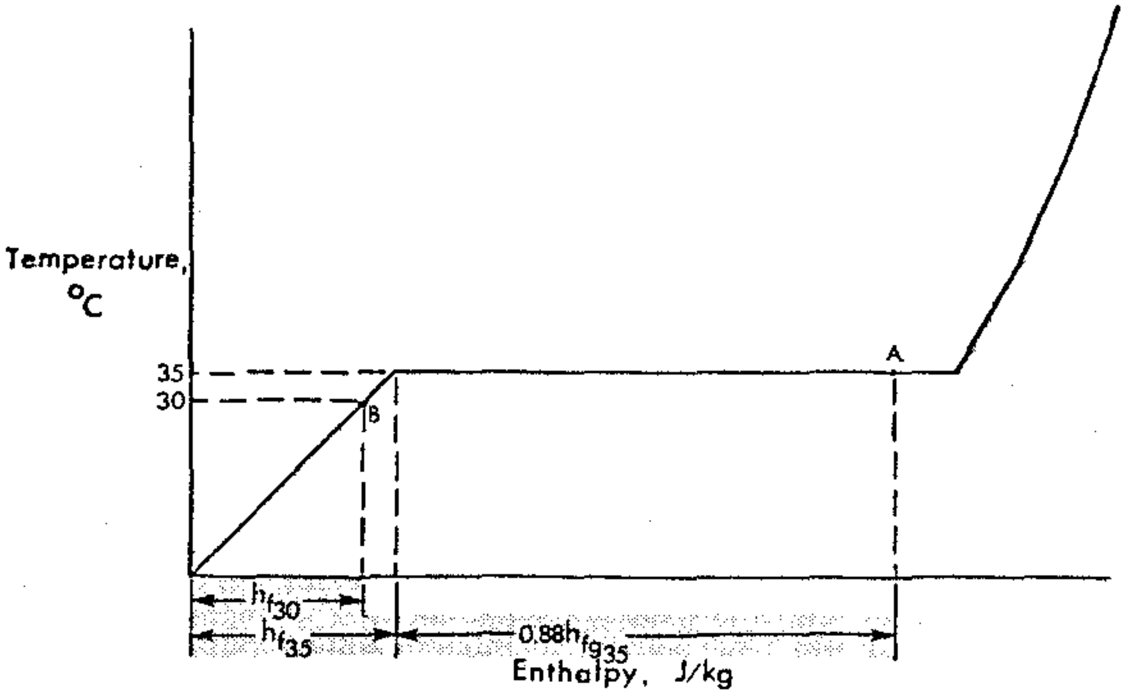

Fig. 5.10

The initial condition is the wet steam. Using Table 1, h_f at 35°C = 146.6 kJ/kg and h_{fg} = 2418.8 kJ/kg.

Enthalpy of wet steam = $h_f + qh_{fg}$

= 146.6 + 0.88 x 2418.8 kJ/kg

= 146.6 + 2128.5 kJ/kg

= <u>2275.1</u> kJ/kg.

The final condition is of condensate at 30°C.

h_{f30} = <u>125.7</u> kJ/kg.

Heat removed is the difference between these two enthalpies, ie,

2275.1 - 125.7 kJ/kg

= <u>2149.4</u> kJ/kg.

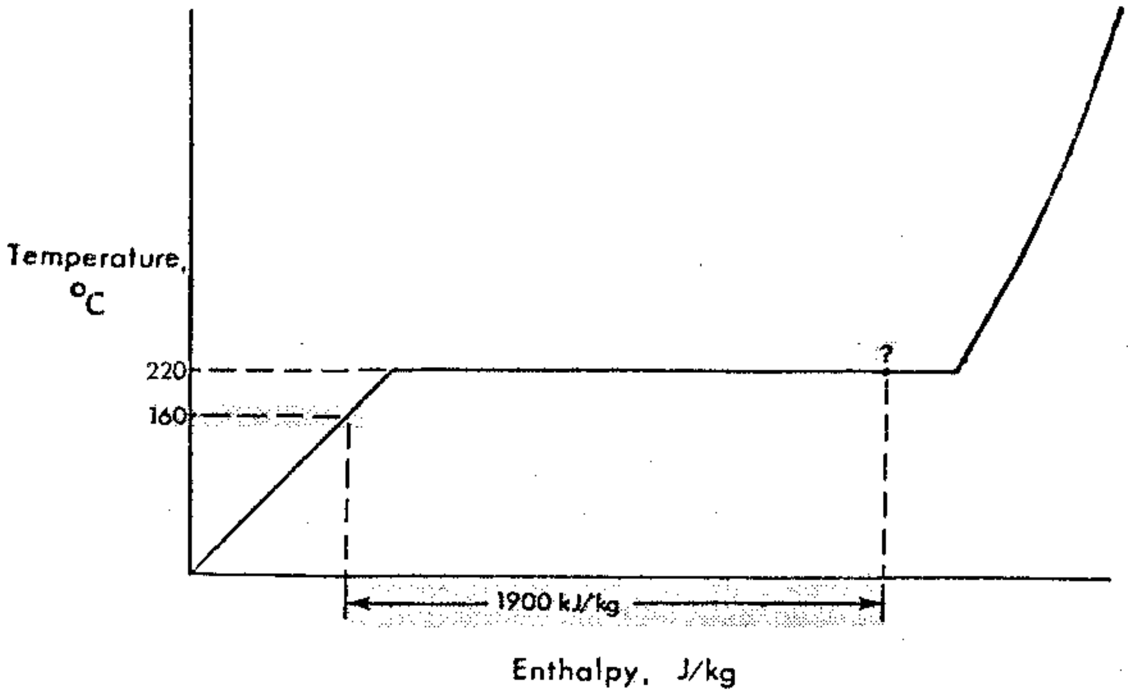

Fig. 5.11

B.5.19

In this problem we know the initial condition, liquid at 160°C and we know that the final condition is after the addition of 1900 kJ of heat.

h_{f160} = 675.5 kJ/kg.

Final enthalpy is 675.5 + 1900 = 2575.5 kJ/kg.

This is the enthalpy of the steam at 220°C. Using Table 1, a quick inspection will tell whether the steam is saturated. h_{f220} = 943.7 kJ/kg and h_{g220} = 2799.99 kJ/kg so the steam from the steam generator is wet steam and we must use the expression for the enthalpy of wet steam $h = h_f + qh_{fg}$.

h_{f220} = 943.7 and h_{fg220} = 1856.2 kJ/kg.

The final enthalpy h is known, ie, 2575.5 kJ/kg the only unknown is 'q'.

Using $h = h_f + qh_{fg}$.

Substituting:

$$2575.5 = 943.7 + q \times 1856.2$$

$$1631.8 = q \times 1856.2$$

$$q = (1631.8/1856.2) \times 100$$

$$= \underline{87.9}\%.$$

B.5.20

Using Table 3, under the pressure column of 20 bar, the value of enthalpy at 350°C is 3139 kJ/kg, and at 400°C is 3249 kJ/kg. The enthalpy at 375°C is the mean of these two values = (3139 +3249) 0.5

= 3194 kJ/kg.

B.5.21

Use the temperature/enthalpy diagram to plot the two conditions.

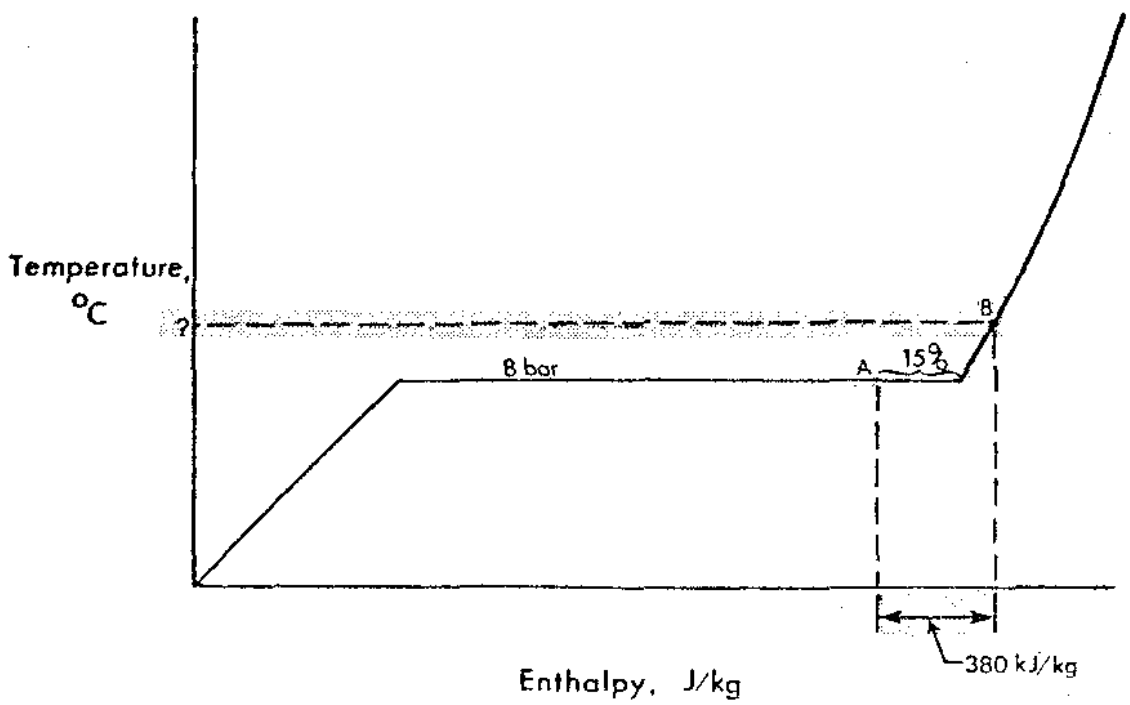

Fig. 5.12

First of all we must determine the enthalpy of the wet steam $h = h_f + qh_{fg}$. At 8 bar and 15% moisture, using Table 2

$$h = 720.9 + 0.85 \times 2046.5$$

$$= 720.9 + 1739.5 \text{ kJ/kg}$$

$$= \underline{2460.4} \text{ kJ/kg.}$$

We are told that the enthalpy is increased by 380 kJ of heat, so we can determine the new enthalpy, ie, 2460.4 + 380 = 2840.4 kJ/kg.

Using Table 3, under pressure column 8 bar, we see that the new enthalpy is for steam just fractionally hotter than 200°C, near enough for convenience.

B.5.22

a) Using Table 2, at 3.0 bar the t_s is 133.5°C so the condition is at t_s. h_f at t_s = 561.4 kJ/kg so the condition is saturated liquid.

b) Using Table 2, at 0.05 bar, t_s is 32.9°C so again the condition is at t_s. h_f, at t_s, = 137.8 kJ/kg so the condition is greater than that of saturated liquid. h_g, at t_s = 2561.6 kJ/kg. Now this is more enthalpy than the stated 2323 kJ/kg so the fluid is not saturated steam. It is somewhere between saturated liquid and saturated vapour, ie, wet steam.

c) Using Table 2, at 5.0 bar t_s = 151.8°C and we are told the steam is at 200°C, so obviously the steam is superheated.

d) Using Table 1, at 20°C the p_s is 0.02337 bar, so the condition of the fluid is at the saturation temperature. h_f at 20°C is 83.86 kJ/kg and the quoted enthalpy was 2538.2 kJ/kg so the condition is well above the saturated liquid condition. In fact as may be seen from the tables, the value of h_g at 20°C is 2538.2 kJ/kg so the condition is saturated steam.

e) Using Table 1, at 30°C the p_s is 0.04241 bar which is less than the quoted pressure. The saturation temperature for the quoted pressure is 40°C so the condition is subcooled liquid.

B.5.23

Using the temperature enthalpy diagram,

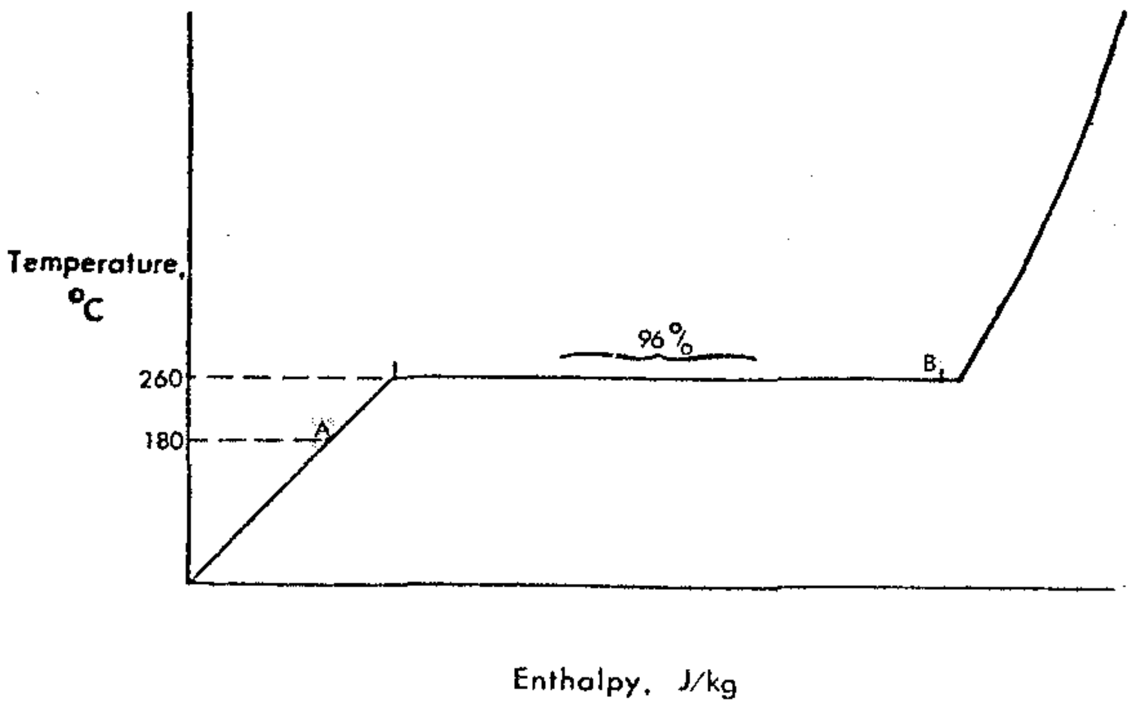

Fig. 5.13

the initial condition is liquid at 180°C. From Table 1, h_f at 180°C = 763.1 kJ/kg. The final condition is steam with 4% moisture at 260°C. The enthalpy of the wet steam is $h = h_f + qh_{fg}$.

h_f at 260°C = 1134.9 kJ/kg.

h_{fg} at 260°C = 1661.5 kJ/kg.

Thus h = 1134.9 + 0.96 x 1661.5 kJ/kg

= 1134.9 + 1595.04 kJ/kg

= 2729.9 kJ/kg.

The amount of heat added in the steam generator is the difference between the two enthalpies, ie, 2729.9 - 763.1

= 1966.8 kJ/kg.

B.5.24

Again use the temperature/enthalpy diagram.

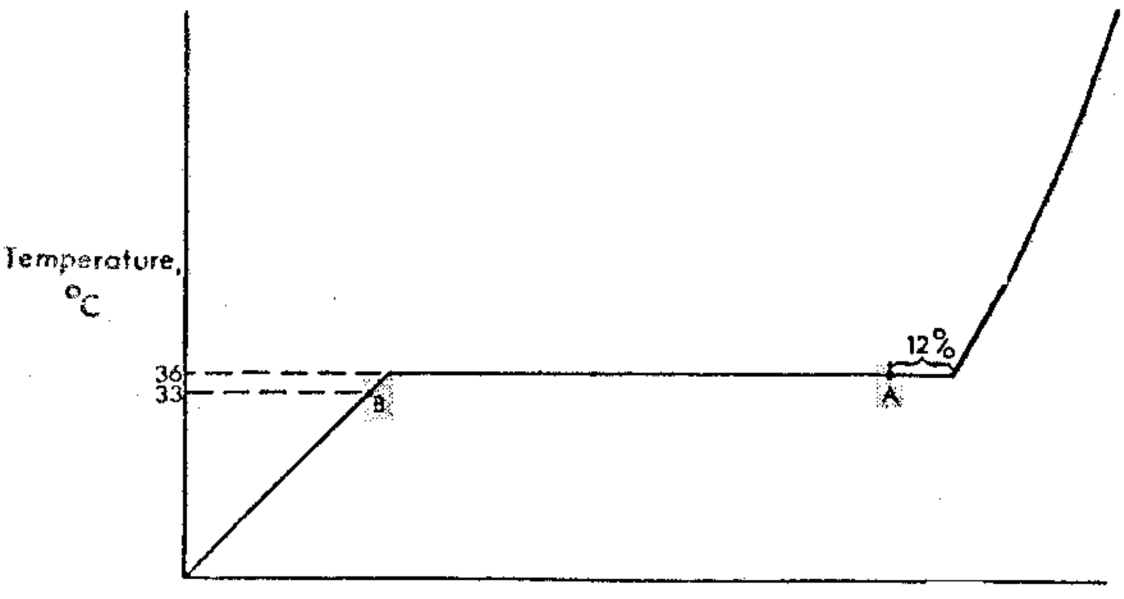

Fig. 5.14

The initial condition is 12% wet steam at 36°C. The final condition is condensate at 36 - 3 = 33°C.

$h_A = h_{f36} + 0.88 \times h_{fg36}$ (12% wet = 88% dry)

$= 150.7 + 0.88 \times 2416.4$

$= 150.7 + 2126.4$ kJ/kg

$= \underline{2277.1}$ kJ/kg.

The enthalpy of the condensate is $h_{f33} = \underline{138.2}$ kJ/kg.

Thus the heat rejected in the condenser is the difference, ie, 2277 - 138.2 = $\underline{2138.9}$ kJ/kg.

B.5.25

The tank of water has a volume of 3 m^3 = 3000 ℓ. Looking at Table 1, v_f at 90°C = 1.0361 ℓ/kg.

From the definitions of specific volume, specific volume = volume/mass.

We can rearrange this equation for mass thus,

mass = volume/specific volume

= 3000/1.0361 kg

= 2895.47 kg.

B.5.26

Using Table 1, v_f at 36°C = 1.0063 ℓ/kg and v_f at 175°C = 1.1209 ℓ/kg.

The increase in v_f is 1.1209 - 1.0063 = 0.1146 ℓ/kg.

As a percentage increase this is $\frac{0.1146}{1.0063}$ x 100 = 11.4%.

B.5.27

Using Table 1, v_f at 175°C = 1.1209 ℓ/kg and v_g at 250°C = 50.037 ℓ/kg.

The volume increase is essentially 49 liters or an increase in volume of 45 times. It is apparent that when a change of state from liquid to vapour, or vice versa occurs, the predominant volume change is concerned with the vapour and to all practical purposes the liquid volume can be considered as unity.

B.5.28

From Table 1, V_g at 40°C is 19546.1 ℓ/kg and v_f at 35°C = 1.0059 ℓ/kg.

Thus the volume reduction is 19546.1 - 1.0059, sensibly 19545 ℓ/kg.

B.5.29

The initial condition is saturated steam at 250°C. Using Table 1, v_g at 250°C = 50.037 ℓ/kg. The final condition is steam with 12% moisture, which is the same as steam which is 88% dry, at a pressure of 5 kPa(a).

Using Table 2, v_f at 0.05 bar = 1.0052 ℓ/kg

and, v_{fg} at 0.05 bar = 28193.3 ℓ/kg.

With v_{fg} as large in comparison to v_f it is by far the predominant factor.

$$\text{Thus } v = v_f + qv_{fg}$$

$$= 1.0052 + 0.88 \times 28193.3$$

$$= 1 + 24810$$

$$= \underline{24811} \ \ell/\text{kg}.$$

So the volume has increased from 50 to 24811 ℓ/kg which is an increase of 496 times. That's why we need three massive low pressure turbine casings to accommodate this tremendous increase in steam volume.

B.5.30

The volume of the low pressure steam is, as we already *calculated in question* B.5.29, *24811 ℓ/kg.*

It is of no consequence, in this application, whether the condensate is subcooled, at 100°C or 200°C. Essentially its volume will be around 1 ℓ/kg. The volume reduction will be from 24811 ℓ/kg to 1 ℓ/kg, ie, a reduction of ~ 25000 times. It is this tremendous reduction in volume that creates the vacuum in the condenser.

B.5.31

The process of "steam hammer" is caused by fluctuating pressure in a line continuously creating pockets of vapour and condensation. This effect occurs when liquid reaches saturation conditions and results in violent oscillations of liquid within the pipe which cause hammering on the pipework that results in severe damage.

The problem may be avoided by operating valves very slowly when warming a line and increasing the line pressure if steam hammer should commence, by reducing the flowrate in the line.

B.5.32

The final conditions for the water are 150°C and 1.5 MPa(a), (= 15 bar). Using Table 2, this will be subcooled liquid. Thus the entire volume of the system is liquid, and the liquid volume remains constant at 5.0 m^3.

Since the liquid volume remains at 5 m^3, the vapour volume is 0 m^3 and this volume also remains constant.

From Table 3, V_f at 150°C and 15 bar is 1.090 ℓ/kg, or 1.090 x 10^{-3} m^3/kg. The mass of 5.0 m^3 of liquid water at 150°C and 15 bar is 5.0 m^3 ÷ 1.090 x 10^{-3} m^3/kg = 4587 kg. Thus the mass of water increases by 4587 - 4334 = 253 kg.

B.5.33

As the liquid water is cooled it contracts. Thus for a constant mass and decreasing temperature, the liquid volume will decrease.

The decrease in liquid volume creates a space in the system. Some vapour is produced to fill this space - that is, the vapour volume increases. Effectively, some of the heat lost by the liquid in going from 198.3°C to 150°C is used to vapourize some of the liquid.

As the water cools, its pressure decreases. The pressure of the system at 150°C and saturated (because there is a mixture of liquid and vapour) has decreased to 4.76 bar (ie, 476 kPa(a)).

B.5.34

Since the water in the tank initially is saturated liquid, addition of heat will produce steam. In order to hold the pressure constant, the steam must be released from the system as it is generated. The temperature of the system remains constant until all the liquid has boiled (all the while vapour is leaving the system). When there is only saturated vapour in the system, heat addition causes the temperature to rise to 250°C. At the final conditions (250°C and 15 bar) the system contains superheated steam, ie, the volume of liquid has decreased from 5.0 m^3 to 0.0 m^3 and the volume of vapour has increased from 0.0 m^3 to 5.0 m^3.

The mass of the water has decreased, since steam is released as boiling occurs and as superheated vapour is produced. From Table 3, superheated steam at 250°C and 15 bar has specific volume 152.0 ℓ/kg = 152.0 x 10^{-3} m^3/kg. 5 m^3 of superheated steam at 250°C and 15 bar have mass 5 m^3 ÷ 152.0 x 10^{-3} m^3/kg = 32.9 kg. The mass has decreased 4334 - 32.9 = 4301 kg.

J. Irwin-Childs

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HEAT & THERMODYNAMICS

MODULE B.4.2

ENTROPY, THROTTLING AND MOLIER DIAGRAM

Heat & Thermodynamics

MODULE B.4.2

ENTROPY, THROTTLING & MOLLIER DIAGRAM

Course Objectives

1. Given a calculator and a set of S.I. steam tables, you will be able to perform the following calculations:

   a) Determination of final dryness fraction of steam expanded isentropically.

   b) Initial dryness fraction of steam prior to throttling.

2. Using a sketch of a Mollier diagram that you have drawn, you will be able to explain:

   a) Why nozzle governing is used on peak loading turbines, and

   b) Why throttle governing is used on base loading turbines.

Enabling Objectives

1. Illustrate a series of processes associated with the steam turbine on a Mollier diagram, which the student has sketched.

2. You will be able to explain how moisture separation and reheating increase the enthalpy of the process system.

Entropy

The conception of "Entropy" presents a difficulty because it does not represent anything tangible or anything that has an immediate physical significance.

Entropy means 'spread' and any increase of entropy, increases the spread of energy, and as a result, lowers the availability of that energy for doing useful work.

If we had two different quantities of liquid, both having the same amount of heat but at different temperatures, the liquid at the higher temperature would have less entropy than the liquid at the lower temperature. Although the energy levels are the same, there is less energy available from liquid at the lower temperature.

In any real process, the entropy increases. In a completely ideal process, entropy stays constant. The process when entropy stays at the same value is called an ISENTROPIC process and provides a useful base to compare the performance of practical systems with the ideal performance.

We will not concern ourselves with entropy beyond a simple state. You may recall in Module B.5 'Steam Tables', that the only columns we did not look at were those headed "Specific Entropy".

When looking at the simple use of entropy, we can use it in exactly the same way as we did enthalpy, ie,

entropy of saturated steam is S_g

entropy of saturated liquid is S_f

entropy of wet steam is $S_f + qS_{fg}$.

Example

Saturated steam enters a low pressure turbine at 200°C and is exhausted at a pressure of 6 kPa(a). Determine the dryness fraction of the steam leaving the low pressure turbine if the expansion is ideal, ie, isentropic.

Before we look at any values, the whole question revolves around the fact that the value of entropy before the steam expands is exactly the same as after the expansion.

The steam prior to expansion is saturated at a temperature of 200°C. The entropy will be S_g at 200°C, which from Table 1, is 6.4278 kJ/kg°C. (The units for entropy are the same as those for specific heat capacity).

After expansion the steam will be 'wet' and we don't know the value of 'q', the dryness fraction. The steam is at 6 kPa(a). Using Table 2,

S_f = 0.5209 kJ/kg°C.

S_{fg} = 7.8104 kJ/kg°C.

If the entropy is to be constant during the process, the initial entropy is equal to the final entropy.

ie, $S_{g200} = S_{f(0 \cdot 06bar)} + qS_{fg(0 \cdot 06\ bar)}$

thus $6.4278 = 0.5209 + q \times 7.8104$

$5.9069 = q \times 7.8104$

$\therefore q = \frac{5.9069}{7.8104} = \underline{75.6\%}.$

Do these examples and compare your answers at the end of the module.

B.4.2.1

Saturated steam at 160°C is allowed to expand isentropically until it is rejected to a condenser at pressure of 1 bar. Determine the dryness fraction of the steam at the exhaust to the condenser.

B.4.2.2

Steam which is 4% wet at 15 bar is expanded, isentropically to 60°C. Determine the dryness fraction of the final steam condition.

B.4.2.3

Saturated steam is expanded isentropically to 36°C where the dryness fraction is 87%. Determine the temperature of the initial steam.

Throttling

This is a process where a compressible fluid expands from one pressure to a lower pressure. This is the process which occurs through the governor steam valves on the turbine when the governor steam valves are not full open. The smaller the percentage opening the greater the throttling effect becomes.

When throttling takes place, the enthalpy of the fluid remains constant, ie, the enthalpy before the partially closed governor steam valve is equal to the enthalpy after the valve. This is true because the process occurs at high speed and there is no time for heat to pass through the containment walls. Secondly, there is no reduction of enthalpy due to work because there is no work done.

A significant change occurs with steam that is wet when throttled to a lower pressure.

A look at the temperature enthalpy diagram will help illustrate the condition.

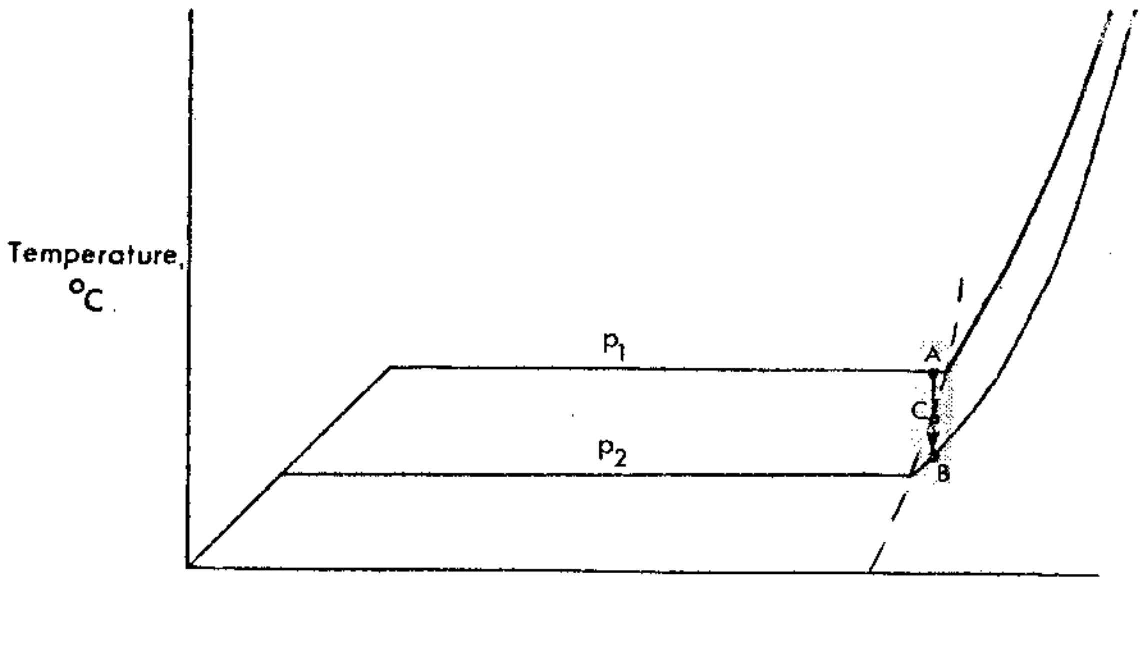


Fig. 4.2.1

Suppose at point A we have steam which has a small moisture content and exists at pressure P_1. If we throttle the steam to a lower pressure P_2, the enthalpy will remain constant and condition of the steam will be at point B.

The saturation line for the steam is not vertical and we can see that as the pressure falls, during the throttling process, the steam becomes dryer until it becomes saturated at point 'C' and then becomes superheated steam at point B. Don't forget the enthalpy has not changed.

Why is this event of any significance? During performance tests and commissioning of steam turbines using wet steam, it is essential to check the steam quality against design value to ensure that the turbine does not suffer severe erosion damage because of excessive levels of moisture.

You know that you have wet steam and you know the temperature and pressure. Is it any problem determining the dryness fraction of this steam? Sure there is! Knowing only the temperature and pressure you could have anything from saturated liquid through to saturated vapour. The missing factor is the value of enthalpy and with the given information, pinpointing this quantity is impossible.

However - if we could throttle the wet steam to a lower pressure and produce superheated steam, then knowing the pressure and temperature at this point would allow us to look up the enthalpy in Table 3 of the steam tables. Once we have found the enthalpy, which remains constant, we can determine the dryness fraction of the wet steam.

Here's an example - wet steam is throttled from a pressure of 40 bar to a pressure of 0.1 bar when the temperature is 100°C. Determine the dryness fraction of the initial wet steam.

Using Table 3, at 100°C and a pressure of 0.1 bar, the enthalpy of the superheated steam is 2688 kJ/kg.

We know that the enthalpy was constant and by using $h = h_f + qh_{fg}$ we can find 'q'.

Using Table 2, at 40 bar h_f = 1087.4 kJ/kg, and

h_{fg} = 1712.9 kJ/kg.

The enthalpy of the steam is 2688 kJ/kg.

$$\text{Thus } 2688 = 1087.4 + q \times 1712.9$$

$$1600.6 = q \times 1712.9 \text{ kJ/kg}$$

$$q = \frac{1600.6}{1712.9}$$

$$= \underline{93.4\%}.$$

Do these problems and check your answers at the end of the module.

B.4.2.4

Wet steam at 154°C is throttled to atmosphere at 1 bar and the temperature is measured to be 125°C. Determine the dryness fraction of the wet steam.

B.4.2.5

Initially wet steam at 15 bar is throttled to produce steam at 75°C and a pressure of 5 kPa(a). Determine the dryness fraction of the wet steam.

Mollier Diagram

This chart may be thought of as a graph of steam table values, with some other information added. Although there are many calculations that may be effectively performed using the diagram, we shall not be concentrating on this use of the diagram.

The temperature enthalpy diagram is limited in what it can show is happening in a process and this is the major benefit of looking at a Mollier diagram. We are going to use the diagram to describe the process and use the steam tables to make any calculations that are necessary.

Let's examine the information which is presented on the diagram.

Axes

The diagram is a plot of enthalpy against entropy and for most purposes we can ignore the entropy values.

Saturation Line

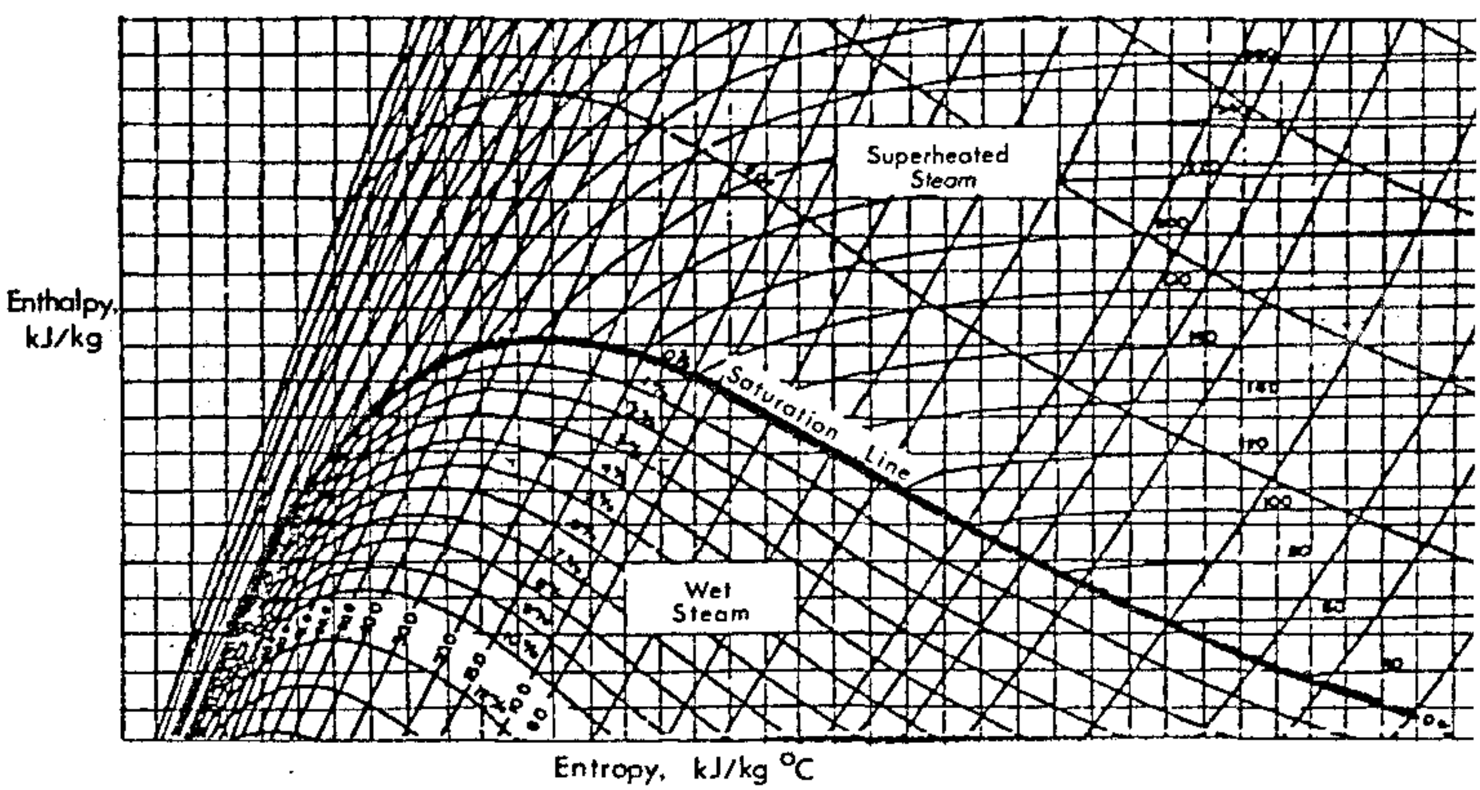


Fig. 4.2.2

The saturation line lies between wet steam and superheated steam regions as shown. Anything below the line is wet steam and anything above the line is superheated steam.

Constant Moisture Lines

These lines run somewhat parallel to the saturation line in the wet steam region. The moisture content increases as the constant moisture lines become further away from the saturation line.

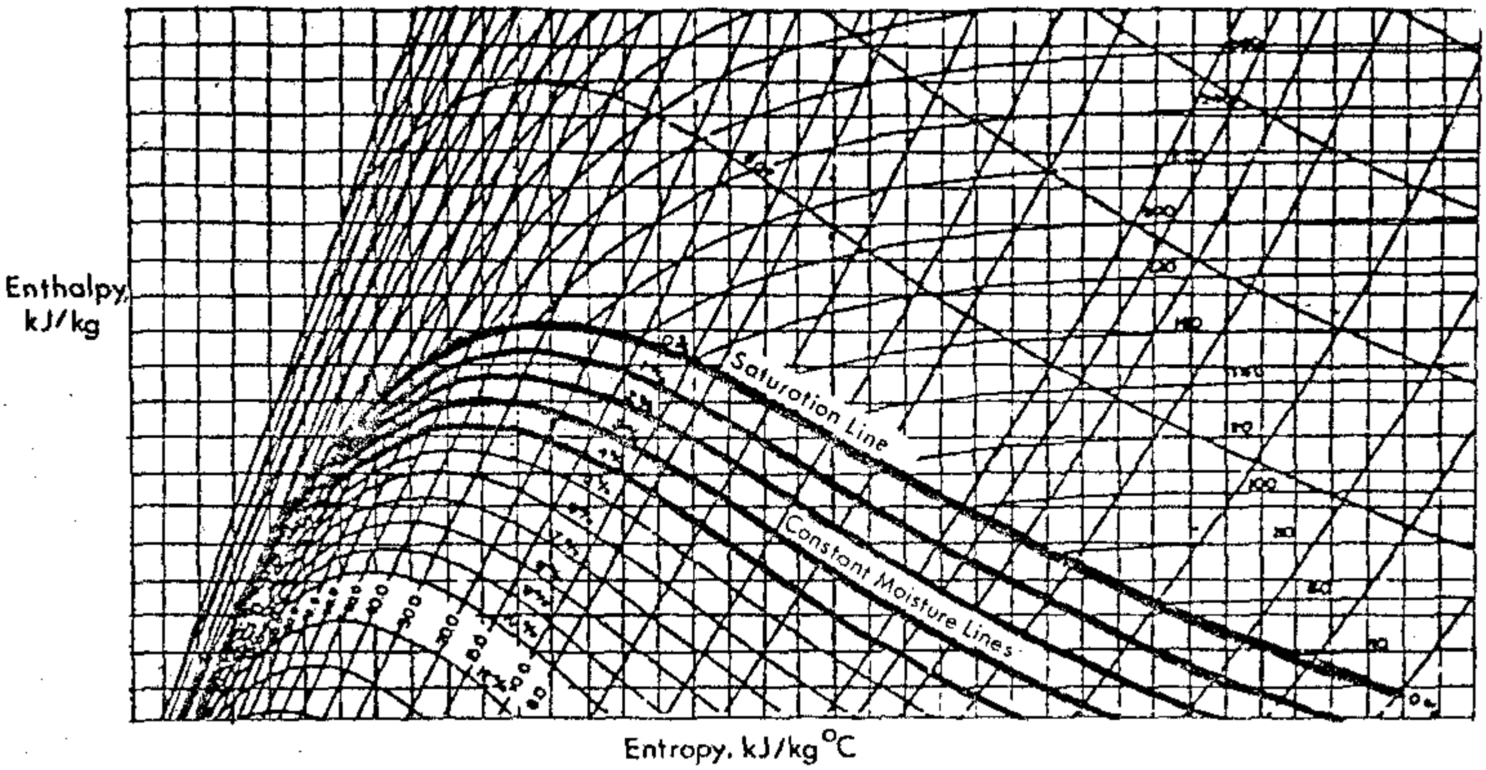


Fig. 4.2.3

Constant Superheat Lines

These lines follow a similar shape to the saturation line but are in the superheat region. The first line represents a condition which is 50°C above the saturation temperature at that pressure.

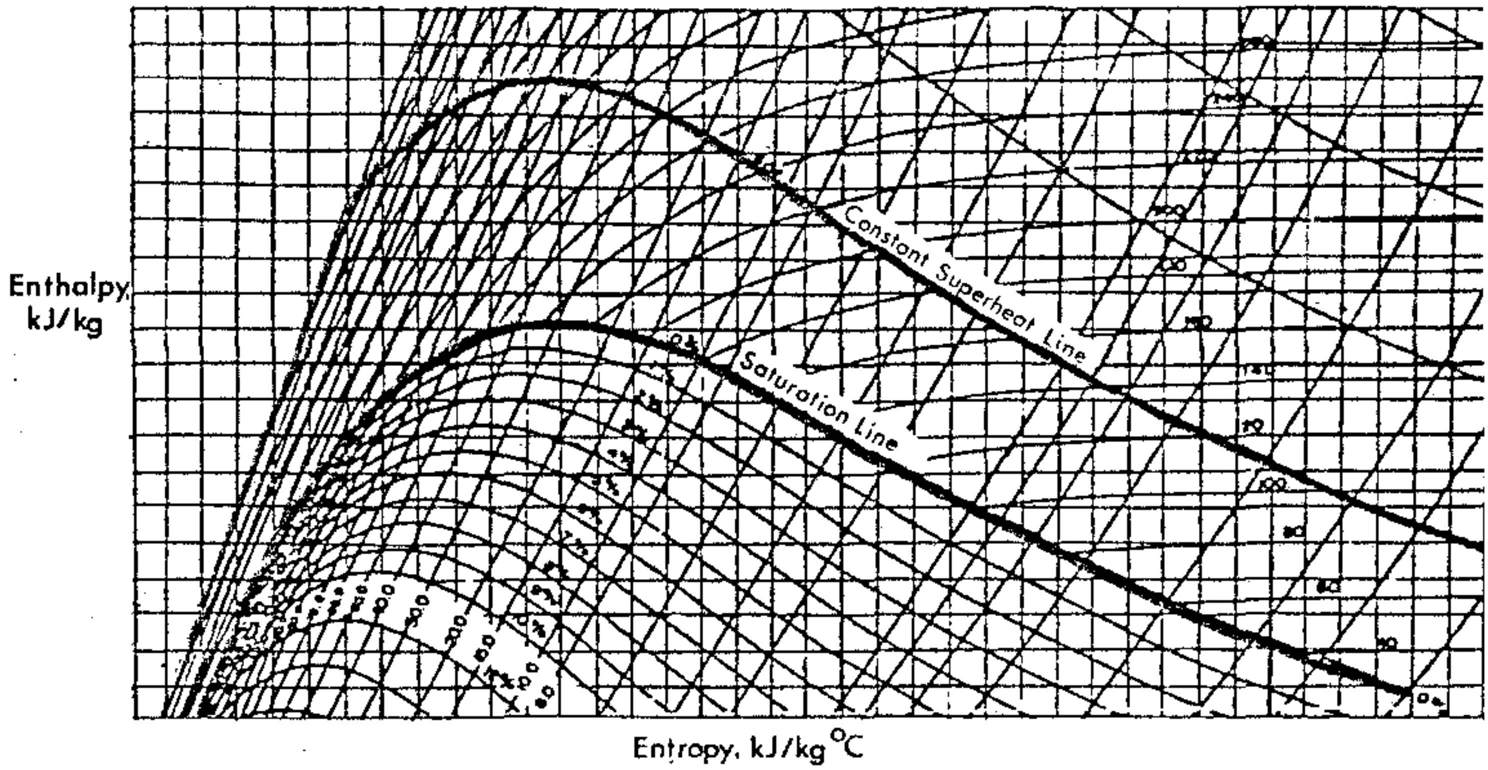


Fig. 4.2.4

Lines of Constant Pressure

These lines run from the bottom left of the diagram towards the top right hand corner.

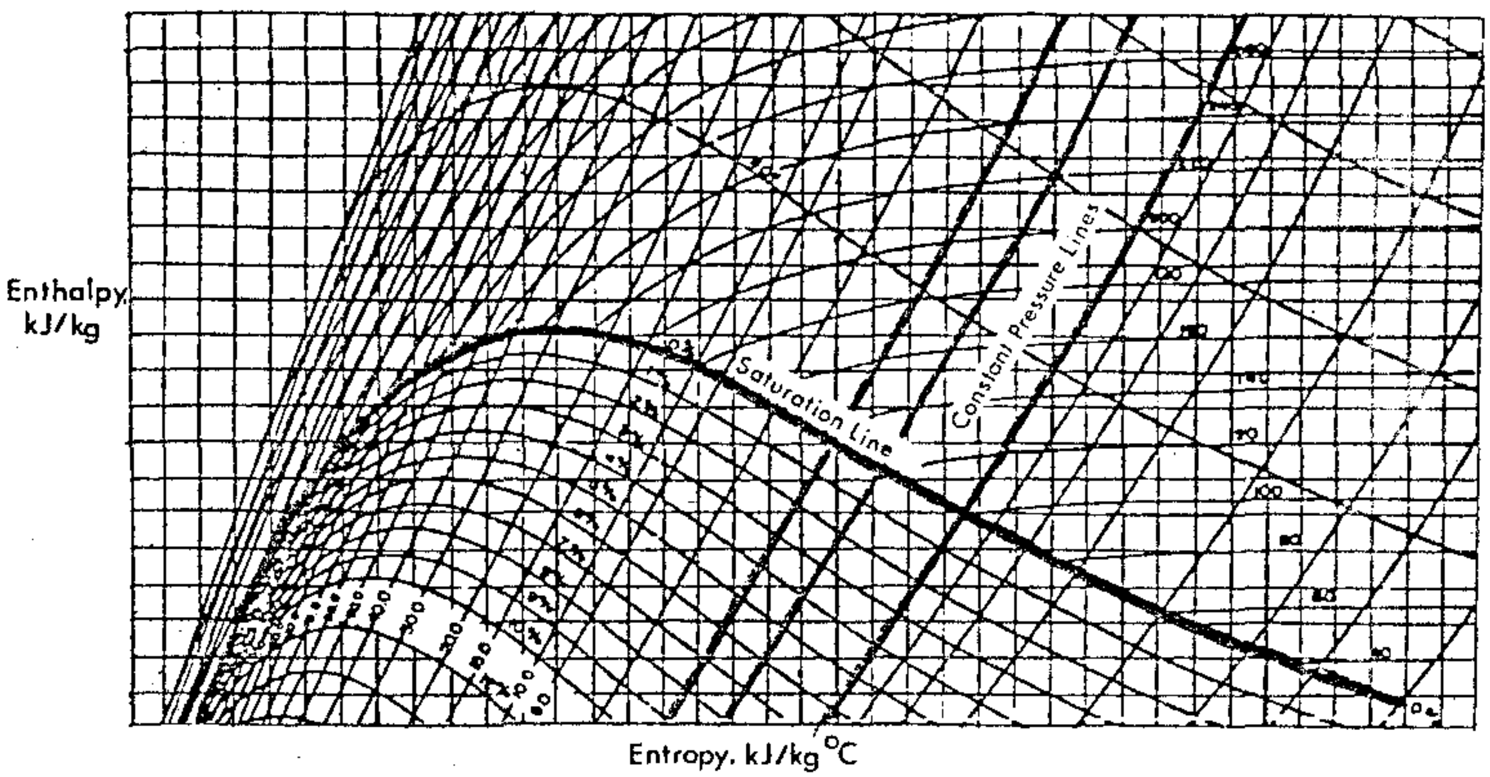


Fig. 4.2.5

Lines of Constant Temperature

In the wet steam region the lines of constant temperature and constant pressure are parallel. This is because all the time the water is at saturation conditions, ie, saturated liquid through to saturated vapour, the temperature remains constant. Above the saturation line the constant temperature line moves over to the right as shown below.

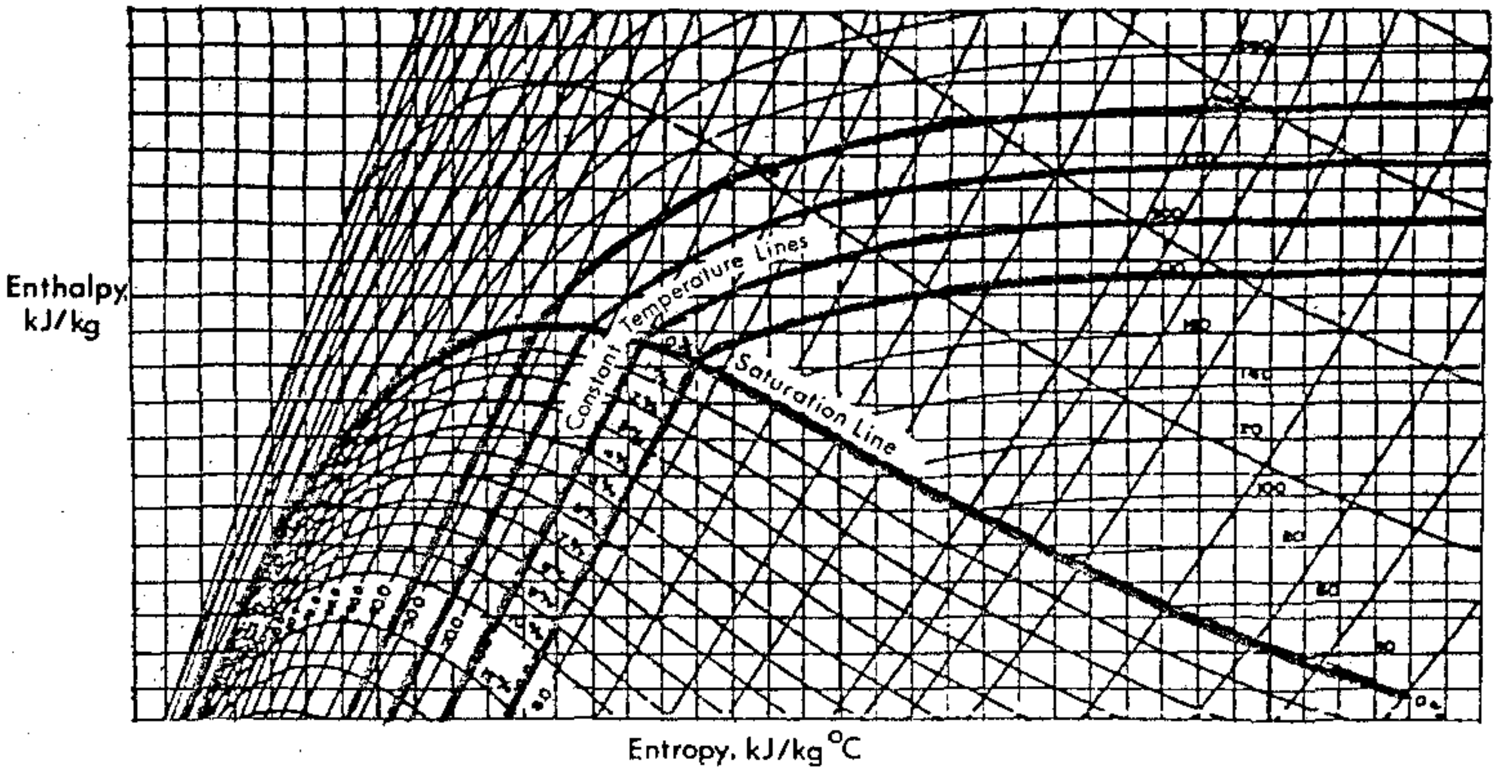


Fig. 4.2.6

Before we look at how we can use this array of lines, do the following exercise and compare with the diagram at the back of the module.

B.4.2.6

Using the Mollier diagram, given at the beginning of the module, as a guide, sketch the following:

a) Draw and label the axes required for the Mollier diagram.
b) Draw the saturation line.
c) Draw a single constant moisture line.
d) Draw a single constant superheat line.
e) Draw a single constant pressure line.
f) Draw a single constant temperature line.

We must examine a few processes to see how they are displayed on the Mollier diagram.

Suppose we consider a typical steam turbine in a nuclear station and plot the various points. You remember when we looked at "entropy" we said that in the real world the entropy always increases. If you watch the progress on the Mollier diagram you will see this is true.

Expansion of Steam in the hp Turbine

If we look at the initial steam condition entering the high pressure turbine where the steam is saturated and at 250°C we have the starting point for the process.

The steam is saturated so the point must lie on the saturation line. If you examine the lines of constant temperature you will find that the intervals are every 20°C. Consequently 250°C will lie between the lines representing 240°C and 260°C.

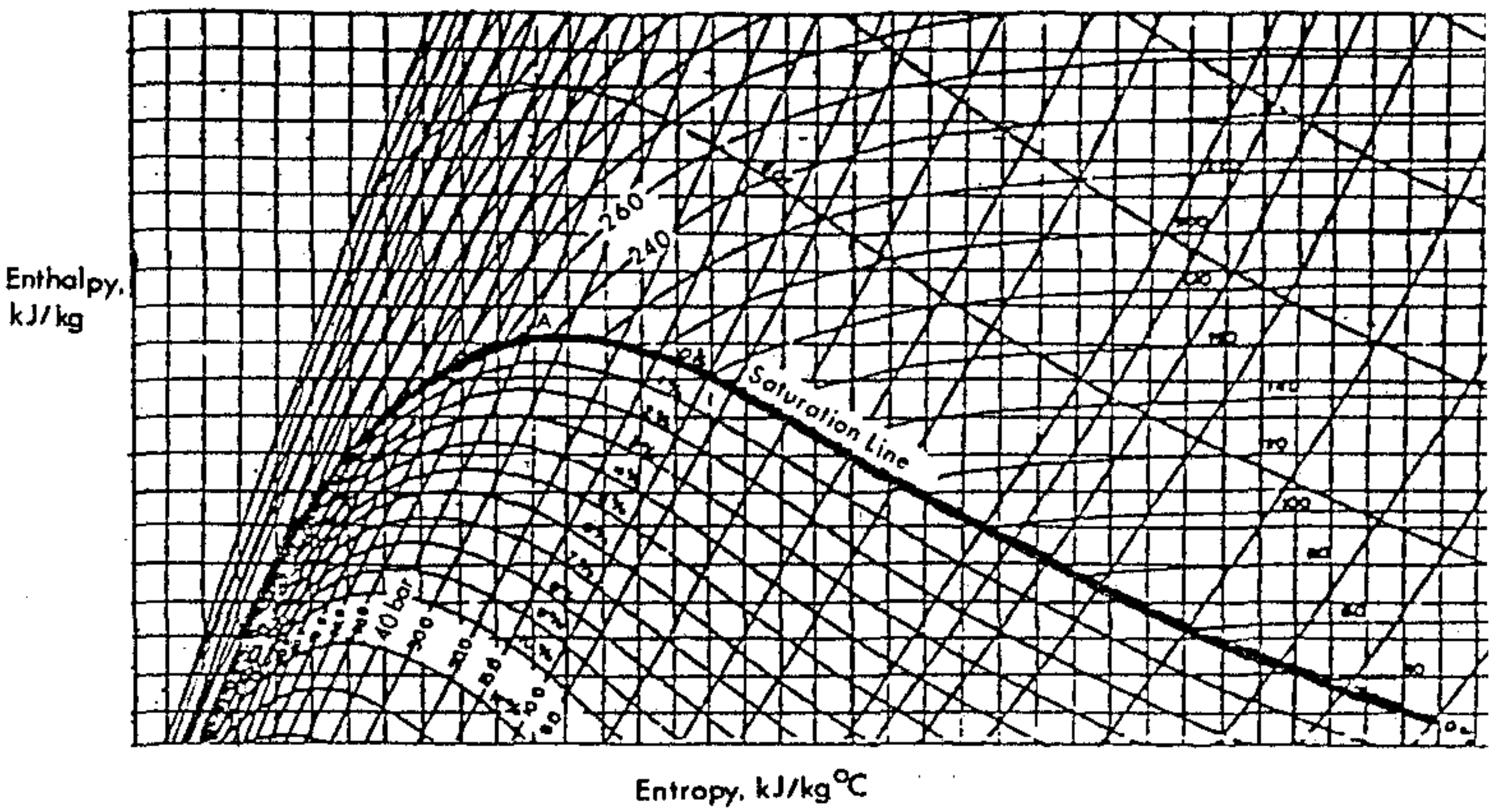


Fig. 4.2.7

The initial operating point is where the 250°C temperature line intersects the saturation line. If you look at the pressure line that passes through 'A' you will see that the saturation pressure is 40 bar. On the enthalpy axis, the enthalpy of the steam is represented by H_A.

The steam is expanded to a lower pressure in the high pressure turbine, down to a pressure of 10 bar. The moisture of the steam leaving the high pressure turbine is 10%. This makes the plotting of the second point very easy. If we follow the constant pressure line for 10 bar up until it intersects with the 10% constant moisture line, this is the operating condition at the turbine exhaust.

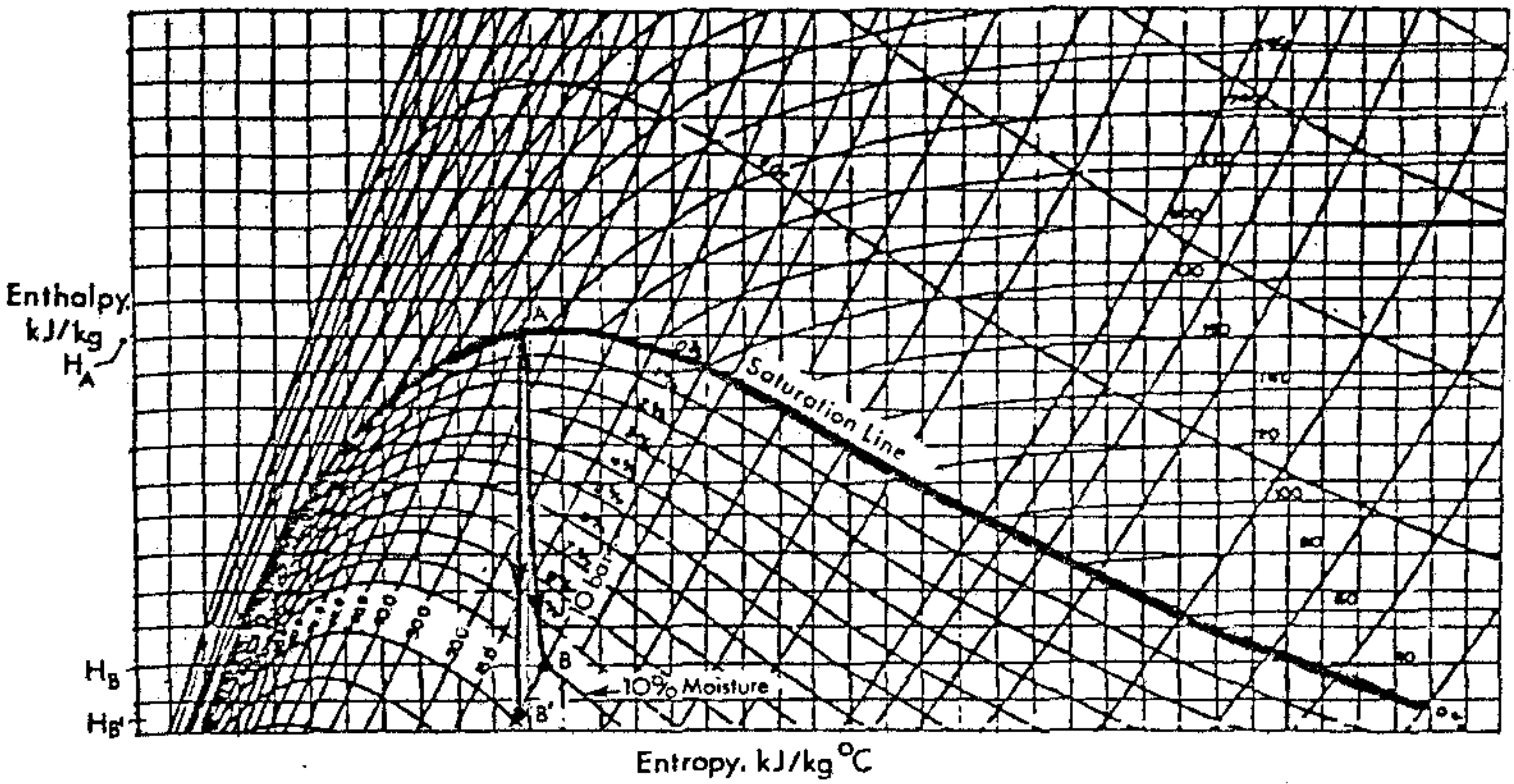


Fig. 4.2.8

The temperature at 'B' is the saturation temperature for a pressure of 10 bar which from the diagram is 180°C. You will notice that point B is further to the right of the diagram than point B' because entropy has increased due to surface and fluid friction. In the ideal case the entropy would remain constant and instead of expanding to point B the steam would have expanded to point B'.

The maximum amount of work available from the turbine would be the enthalpy difference between points A and B', ie, $H_A - H_B'$. In practice the work available was less than the ideal and only equal to the enthalpy difference $H_A - H_B$.

From the information that we used, you can see that we could calculate the enthalpy drop either by using tables, as we have already seen, or by using the scales on the Mollier diagram.

Moisture Separation

This part of the process can be a stumbling block if we are not careful. There are several things happening at once, some real and some apparent.

Ignoring the pressure drop through the moisture separator, we can show moisture separation as taking place at constant pressure. Before we get into detailed discussion, take a look at the separation process on the Mollier diagram.

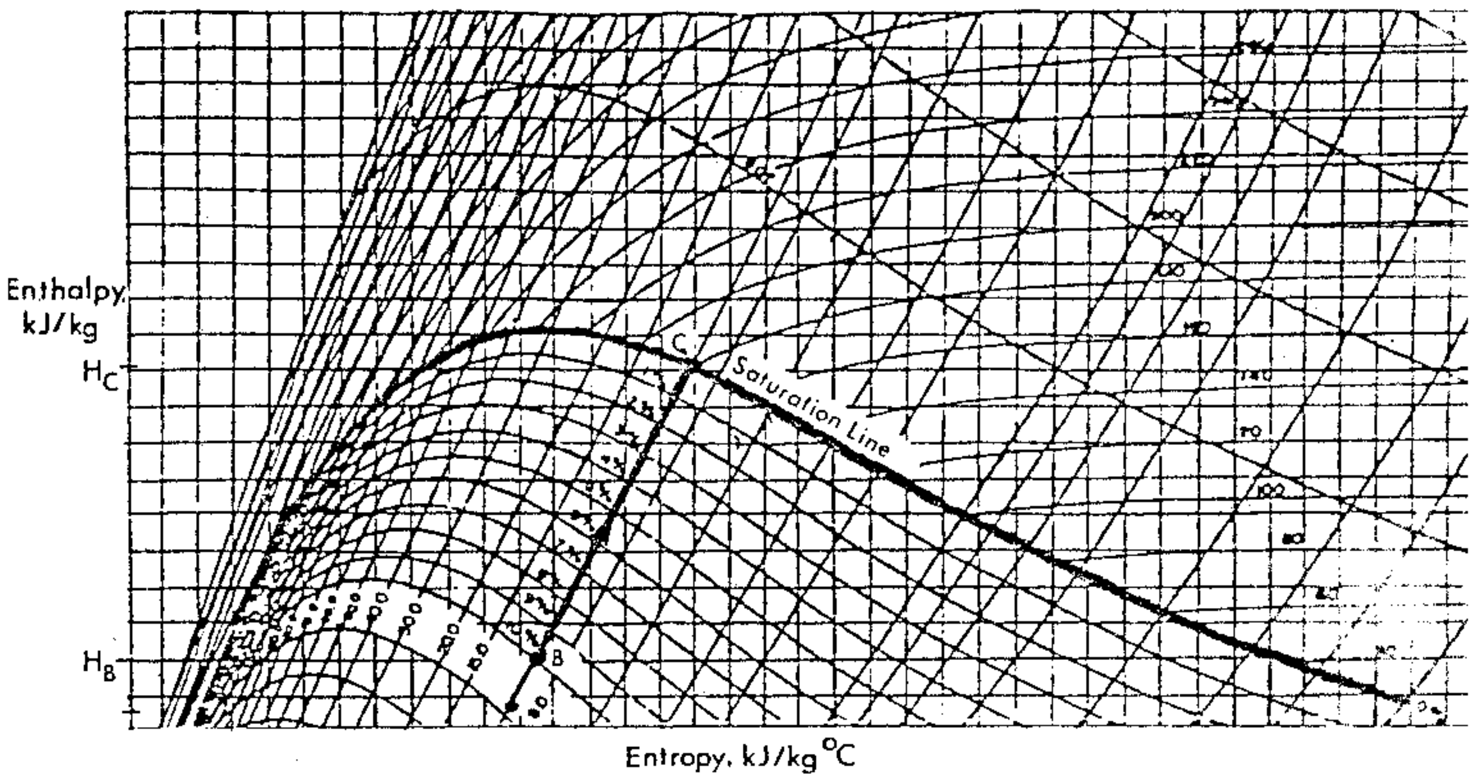


Fig. 4.2.9

The pressure remains constant and the process proceeds from condition B where the steam is 10% wet to condition C where the steam is saturated.

Looking across at the enthalpy scale you will see that the enthalpy has risen from H_B to H_C. So we must obviously have added some heat - Not true!! In fact we removed some heat.

B.4.2.7

If this is so, how is it that the enthalpy of the process steam appears to have increased? Check your answer at the end of the module.

Reheat

Again for purposes of illustration assume that there is no pressure drop through the reheater. Heating is taking place at constant pressure, so the process will continue to follow the constant pressure line.

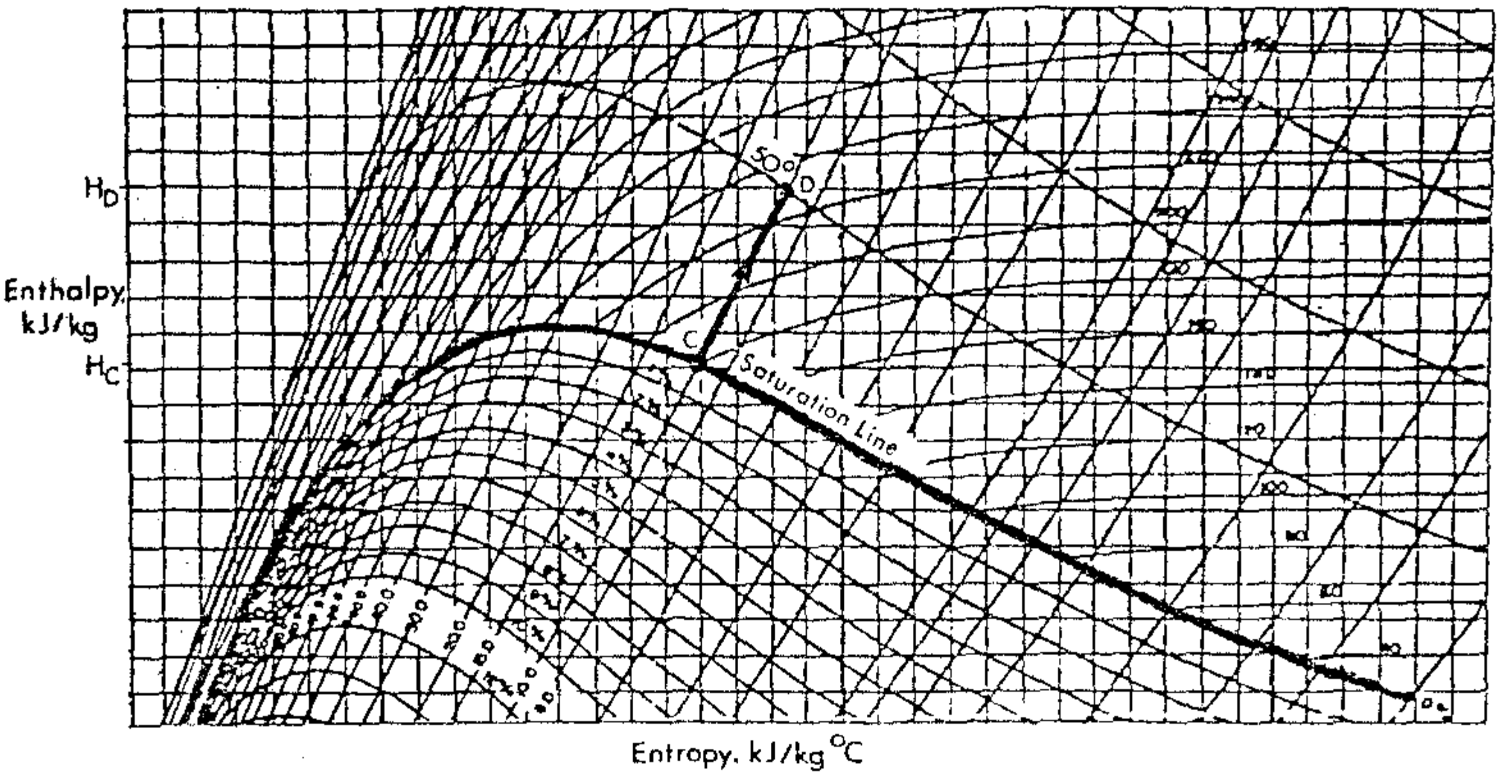


Fig. 4.2.10

Before we leave point 'C' we did not mention that the temperature did not change throughout the moisture separation process and is of course the saturation temperature corresponding to pressure of 10 bar and t_s = 180°C.

The addition of heat from the reheater is going to raise the temperature above the saturation temperature and produce superheated steam. For ease of illustration assume that the reheater adds 50°C of superheat. The operating point 'D' occurs where the constant pressure line intersects the constant superheat line of 50°C. The temperature of the steam is now 180 + 50 = 230°C. The change in enthalpy of the steam is $H_D - H_C$ which is equal to the heat lost by the reheater.

B.4.2.8

How does reheating increase the enthalpy of the process steam?

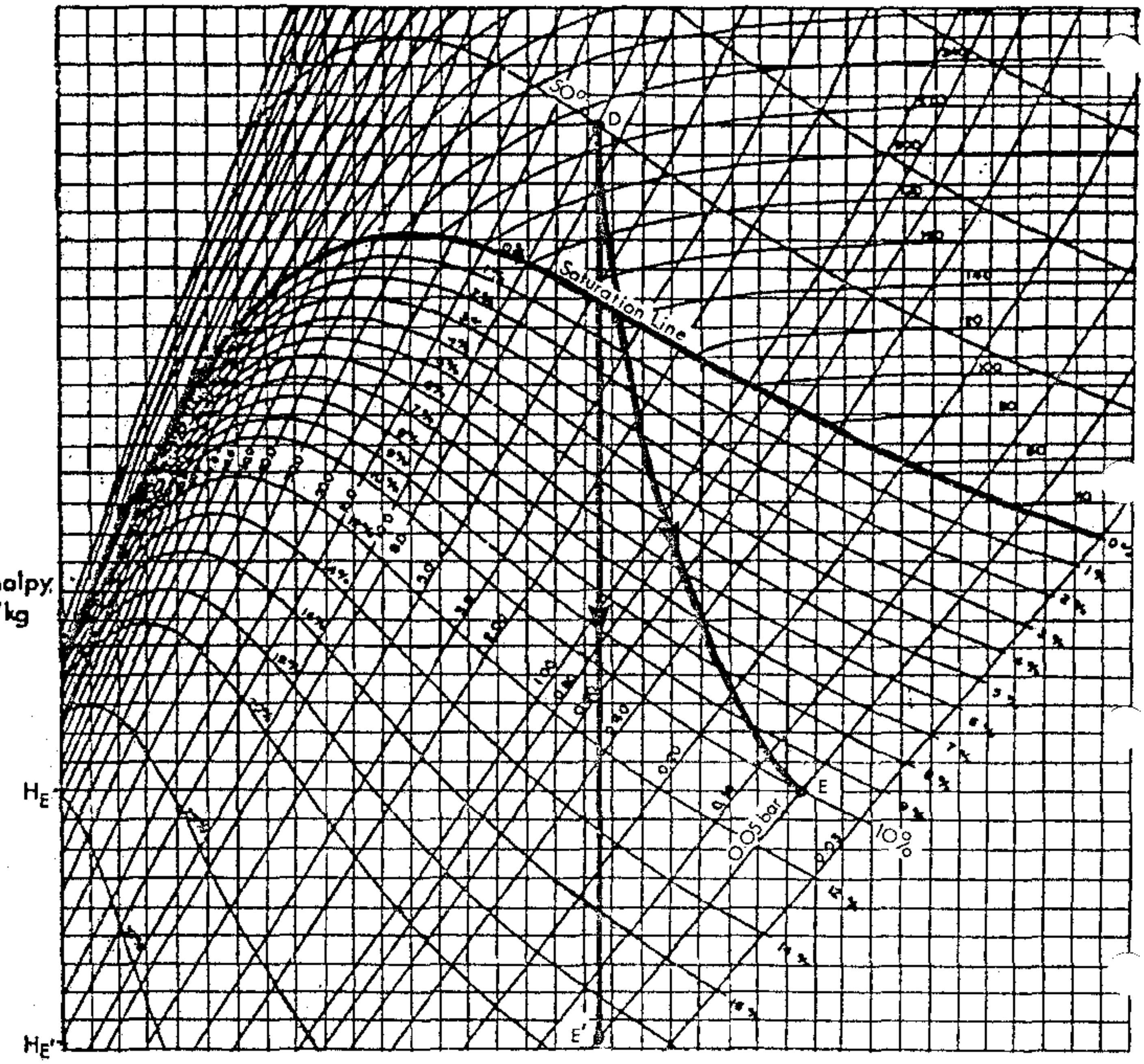
* * * * *

Expansion in the Low Pressure Turbine

The expansion of the steam in the low pressure turbine is the same in principle to the expansion in the high pressure turbine, the only difference being that the steam is initially superheated.

The steam will expand to condenser pressure, say 5 kPa(a) and the condition will be 10% moisture. If we plot this point on the diagram, this represents the end of the steam process before condensation occurs.

Enthalpy, kJ/kg



Entropy, kJ/kg °C

Fig. 4.2.11

If the expansion in the low pressure turbine had been ideal, ie, had there been no friction, then entropy would have been constant and the available work from the low pressure turbine would have been equal to $H_D - H_E'$.

Using the Mollier diagram to illustrate the complete process, we can see the trends in changes of enthalpy, moisture, etc. and when used in conjunction with the steam tables it provides a good graphical aid to help solve the problem.

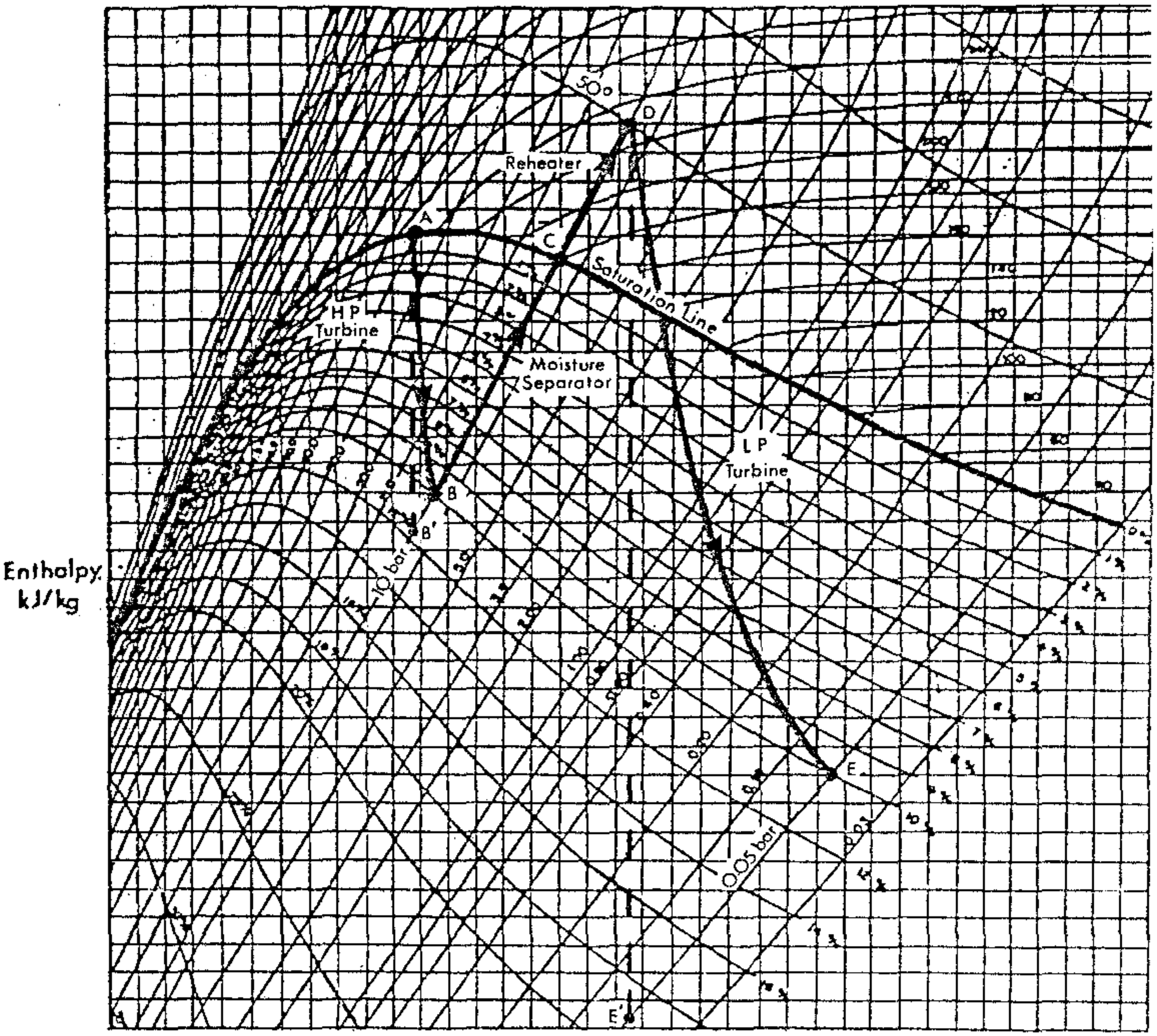


Fig. 4.2.12

Do these problems and check your answers at the end of the module.

B.4.2.9

Sketch your own Mollier diagram to illustrate the following series of processes: A high pressure turbine uses saturated steam at 240°C and exhaust the 10% wet steam to a moisture separator at 160°C. The separator produces 2% wet steam and is followed by a reheater which produces 40°C of superheat. The superheated steam expands in a low pressure turbine to 10% moisture at 35°C.

B.4.2.10

Explain how your sketch would change if you had to show the condensation process in the condenser associated with question B.4.2.9.

B.4.2.11

The mass flowrate of steam into the high pressure turbine, in question B.4.2.9 is 900 kg/s. Determine the mass flow into the reheater.

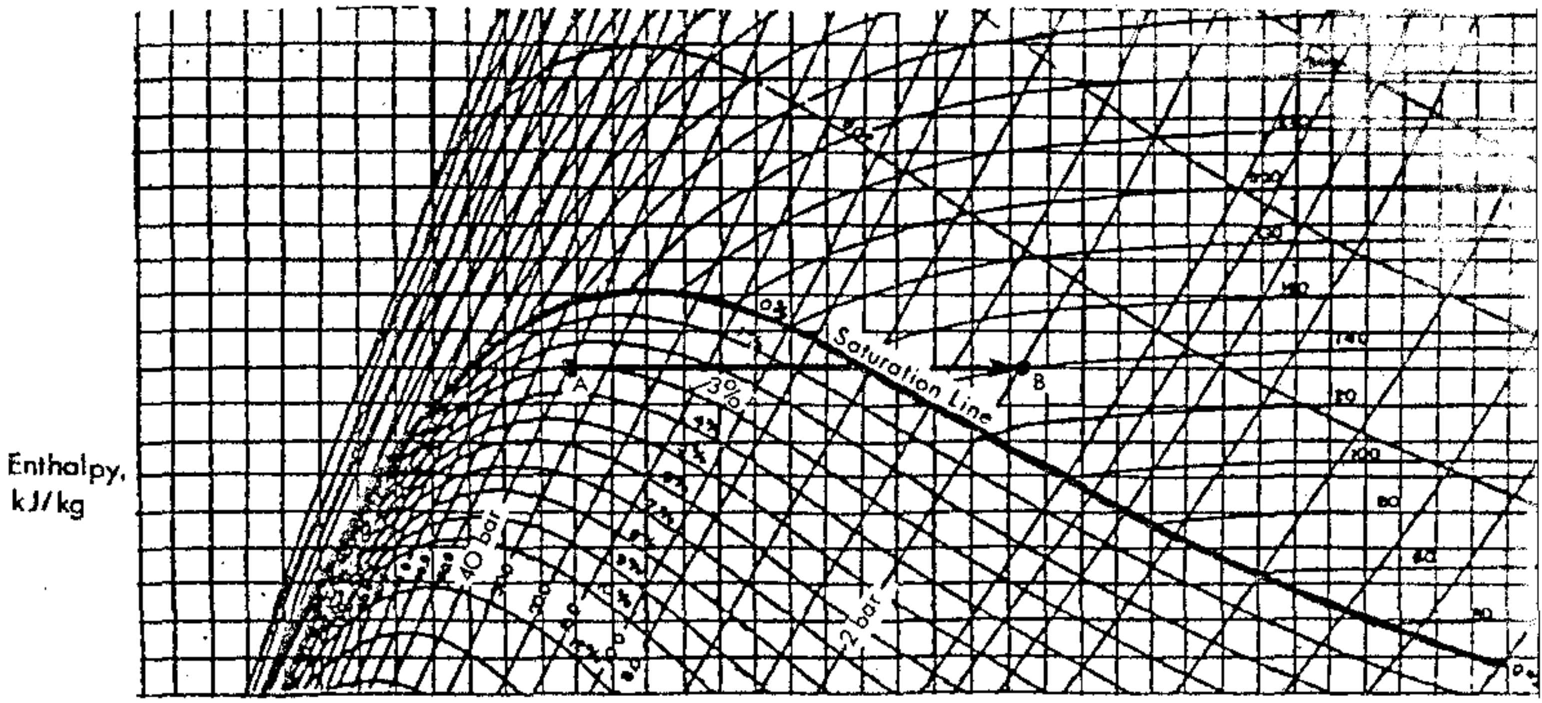
Throttling

We have already looked at this process using enthalpy values from the steam tables. The process may be clearly shown on the Mollier diagram.

Remember that throttling is a constant enthalpy process, so on the Mollier diagram this is represented by a horizontal line.

An example will illustrate the process. Steam at 40 bar with 3% moisture is throttled to 2 bar. Determine the final temperature of the steam and the degree of superheat.

Before we look at the diagram, we know that by throttling wet steam to a low enough pressure we can produce not only saturated steam, but superheated steam.



Entropy, kJ/kg°C
Fig. 4.2.13

As the steam is throttled from point A, to the lower pressure at point B, the quality changes from wet steam to superheated steam at a temperature of 140°C which, from the diagram, is roughly 20°C above the saturation temperature and therefore there are 20°C of superheat.

This looks like a convenient way of producing superheated steam and perhaps we should use this technique to produce superheated steam entering the high pressure turbine. It can be done thermodynamically without any difficulty.

Suppose we take the saturated steam at 250°C, which is the normal condition of steam entering the high pressure turbine, and produce superheated steam by throttling it to 1 bar prior to entry to the turbine. All the time the heat content remains constant.

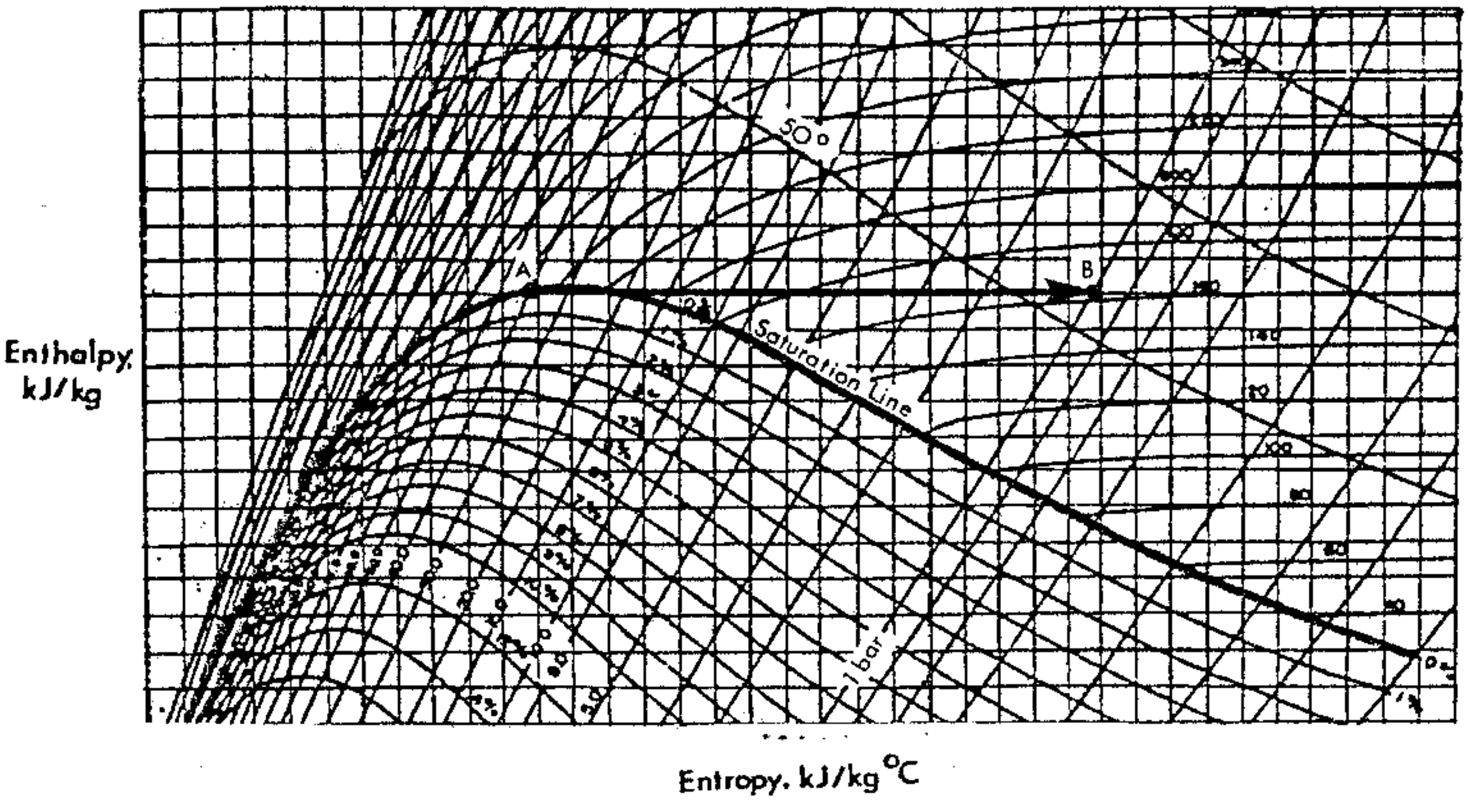


Fig. 4.2.14

This process produces steam which is well superheated with a temperature around 65°C above the saturation temperature so no problems of excessive moisture.

B.4.2.12

Why don't we take advantage of this process? There is no loss of enthalpy and we have steam which is well superheated - how can we go wrong! Analyse this situation and in a few lines write down why you think we do not use this as a solution to the moisture problems in our turbines. Check your answer at the end of the module.

Throttling increases the entropy of the process and we cannot get as much work out of the steam. This factor becomes of major consideration when we consider the control of governor steam valves. Suppose we have a turbine with four governor steam valves. If they all open at the same time, then all four valves will be throttling the steam until the valves are all fully opened when no throttling occurs. This method of control is called "throttle governing" and it produces a loss of efficiency if operating at any load other than full load. If the governor steam valves open one after the other, in principle, there is no more than one valve throttling the steam. This method of control is called "nozzle governing".

B.4.2.13

Using a Mollier diagram, explain why nozzle governing is used for control purposes in peak loading units and why throttle governing is used for control purposes in base loading units. Check your answer at the end of the module.

* * * * *

We have looked briefly at entropy and performed simple calculations. We have looked at the throttling process, both with steam tables and with the Mollier diagram. We have examined the use of the Mollier diagram as an aid to describing the turbine process which is difficult to achieve using the temperature/enthalpy diagram.

If you are confident that you can meet the objectives and are ready to take the criterion test, ask the Course/ Shift Manager for the test.

After you have written the test, ask for the self evaluation sheet and compare your answers with those on the evaluation sheet.

Finally, discuss your criterion test with the Course/ Shift Manager and if you are both satisfied with the results, have the Manager sign the progress summary sheet. If you identify areas that need reinforcing, return to the course material and retake the test when you feel that you are competent.

When you have successfully completed this module you may proceed to Module B.4.1.

Answers

MODULE B.4.2

ENTROPY, THROTTLING & MOLLIER DIAGRAM

B.4.2.1

The whole process takes place at constant entropy, ie, the initial entropy is equal to the final entropy.

The initial condition is saturated steam at 160°C. From Table 1, S_g at 160°C = 6.7475 kJ/kg°C.

The final condition is wet steam at 1 bar, the dryness fraction is unknown.

At 1 bar S_f = 1.3027 kJ/kg°C
and S_{fg} = 6.0571 kJ/kg°C.

$$S_{1\ bar} = S_f = qS_{fg}$$

$$= 1.3027 + q \times 6.0571 \text{ kJ/kg°C.}$$

Equating the initial and final conditions,

$$S_{g160} = S_{1\ bar}.$$

Substituting $6.7475 = 1.3027 + q \times 6.0571$ kJ/kg°C

$$5.4448 = q \times 6.0571$$

$$\text{hence } q = \frac{5.4448}{6.0571} = \underline{89.9\%}.$$

B.4.2.2

Again we know that the entropy remains constant throughout the process and that the initial and final entropies are equal.

The initial condition is 4% wet steam at 15 bar and using Table 2 we can determine the entropy using

$$S = S_f + qS_{fg}.$$

S_f at 15 bar = 2.3145 kJ/kg°C.

S_{fg} at 15 bar = 4.1261 kJ/kg°C.

$S = 2.3145 + 0.96 \times 4.1261$ kJ/kg°C

$= 2.3145 + 3.9611$

$= \underline{6.2756}$ kJ/kg°C.

The final condition will be wetter steam than 4% at 60°C.

S_f at 60°C = 0.8310 kJ/kg°C.

S_{fg} at 60°C = 7.0798 kJ/kg°C.

Equating initial and final conditions we get:

$6.2756 = 0.8310 + q \times 7.0798$ kJ/kg°C

$5.4446 = q \times 7.0798$

$\therefore q = 76.9\%$.

B.4.2.3

Again we know that the entropy is constant throughout and we can determine the value of entropy at the final condition using $S = S_f + qS_{fg}$.

Using Table 1, at 36°C S_f = 0.5184 kJ/kg°C

and S_{fg} = 7.8164 kJ/kg°C.

Thus $S = 0.5184 + 0.87 \times 7.8164$

$= 0.5184 + 6.8003$ kJ/kg°C

$= \underline{7.3187}$ kJ/kg°C.

We know that the entropy is constant so this value of 7.3187 kJ/kg°C is also the initial value.

If we look at S_g, because we are told that the initial steam condition is saturated, in Table 1, we will be able to find the value of t_s which most nearly has a corresponding value of S_g = 7.3187 kJ/kg°C.

The nearest value is S_g = 7.3196 kJ/kg°C at t_s = $\underline{103}$°C.

B.4.2.4

The final condition of the superheated steam allows us to pinpoint the enthalpy. Using Table 3, 125°C is halfway between the quoted values, so at a pressure of 1 bar and a temperature of 125°C, h is

$$\frac{2776 + 2676}{2} = \underline{2726} \text{ kJ/kg.}$$

This enthalpy remains constant.

Using Table 1 we can find the values of h_f and h_{fg} at 154°C which are 649.4 kJ/kg and 2100.6 kJ/kg respectively.

Using $h = h_f + qh_{fg}$ we get

$$2726 = 649.4 + q\ 2100.6 \text{ kJ/kg}$$

$$2076.6 = q \times 2100.6$$

$$q = \frac{2076.6}{2100.6}$$

$$= \underline{98.9\%}.$$

B.4.2.5

Again the final condition is the key to the solution. Using Table 3, 75°C is in between the stated values. At a pressure of 5 kPa(a) and a temperature of 75°C,

$$h = \frac{2594 + 2688}{2} = \underline{2641} \text{ kJ/kg.}$$

This enthalpy remains constant and allows 'q' to be determined using $h = h_f + qh_{fg}$. Using Table 2, h_f and h_{fg} at a pressure of 15 bar are 844.7 kJ/kg and 1945.2 kJ/kg respectively.

Using $h = h_f + qh_{fg}$ we get

$$2641 = 844.7 \times q \times 1945.2 \text{ kJ/kg}$$

$$1796.3 = q \times 1945.2$$

$$q = \frac{1796.3}{1945.2}$$

$$= \underline{92.3\%}.$$

B.4.2.6

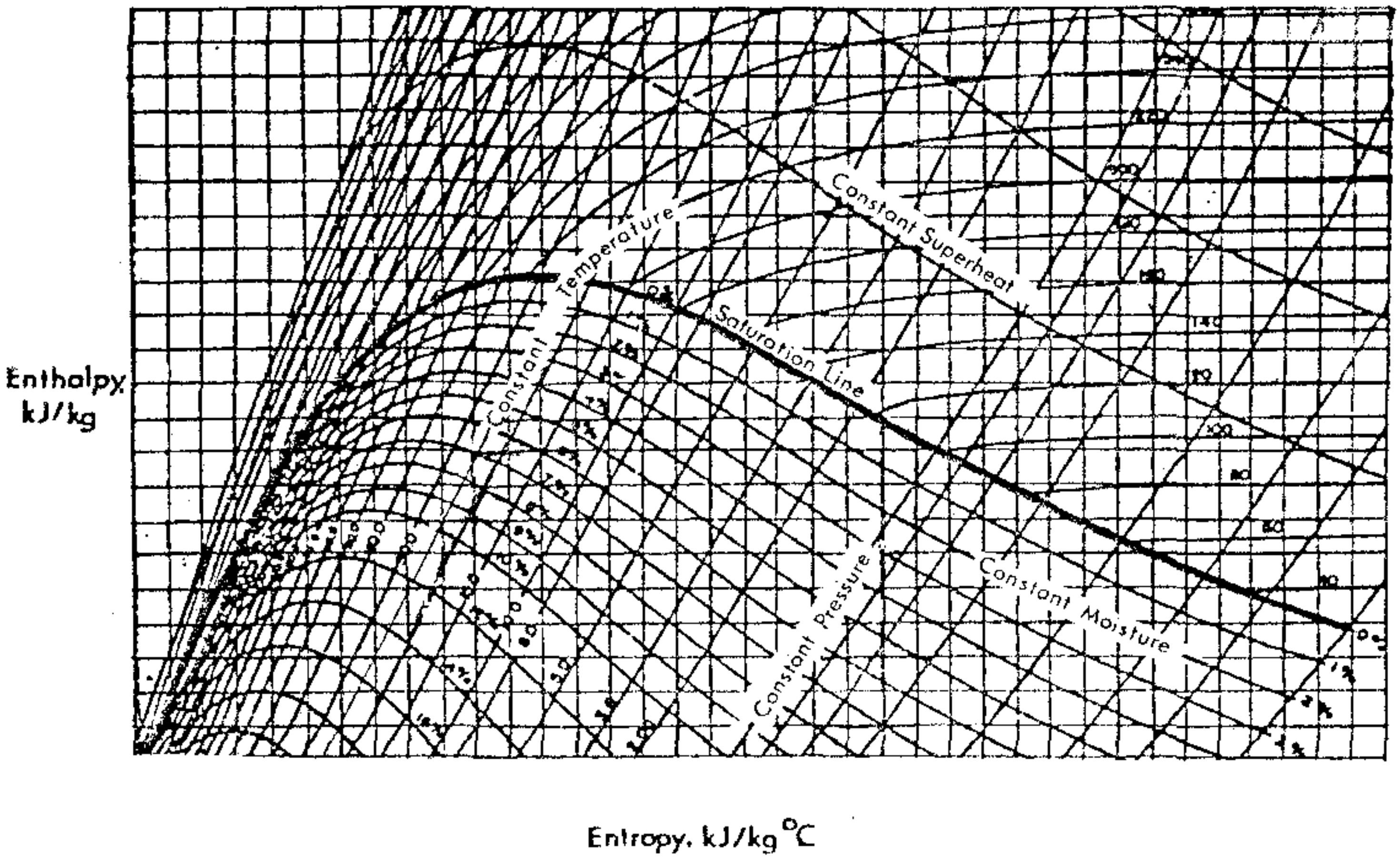


Fig. 4.2.15

B.4.2.7

The answer is fairly simple. The quantity of "steam" at B is not the quantity of steam at C. Suppose we have 10 kg of steam at point B that is 10% wet. This is really the same as saying we have 9 kg of saturated steam and 1 kg of saturated water. Let's put some figures in to make this point. Let h_g = 2700 kJ/kg and h_f = 700 kJ/kg.

Then the average enthalpy of this mixture is

$$\frac{(9\ kg \times 2700\ kJ/kg) + (1\ kg \times 700\ kJ/kg)}{10\ kg}$$

$$= \frac{24300 + 700}{10}$$

$$= \underline{2500}\ kJ/kg.$$

When we pass the wet steam through the moisture separator we removed the 1 kg of saturated liquid, ie, the low grade water and now the enthalpy of the working fluid which is saturated steam, is 2700 kJ/kg, an increase of 200 kJ/kg. BUT the overall quantity of steam has now been reduced by 10%. This is the pitfall when negotiating this part of the process. You must make sure that you change the flowrate after the moisture separation to account for the mass of liquid removed. If the steam leaving the moisture separator is saturated and the steam was x% wet, then the reduction in steam flow as a result of moisture separation is also x%.

B.4.2.8

Reheating increases the enthalpy of the process steam by means of a transfer of heat from main steam that is taken from the balance header. This main steam loses heat (in the reheater) to the process steam, increasing the temperature and thus the enthalpy of the process steam. Typically steam at balance header is 250°C and heats the process steam flowing through the reheater, from 175°C to 235°C.

B.4.2.9

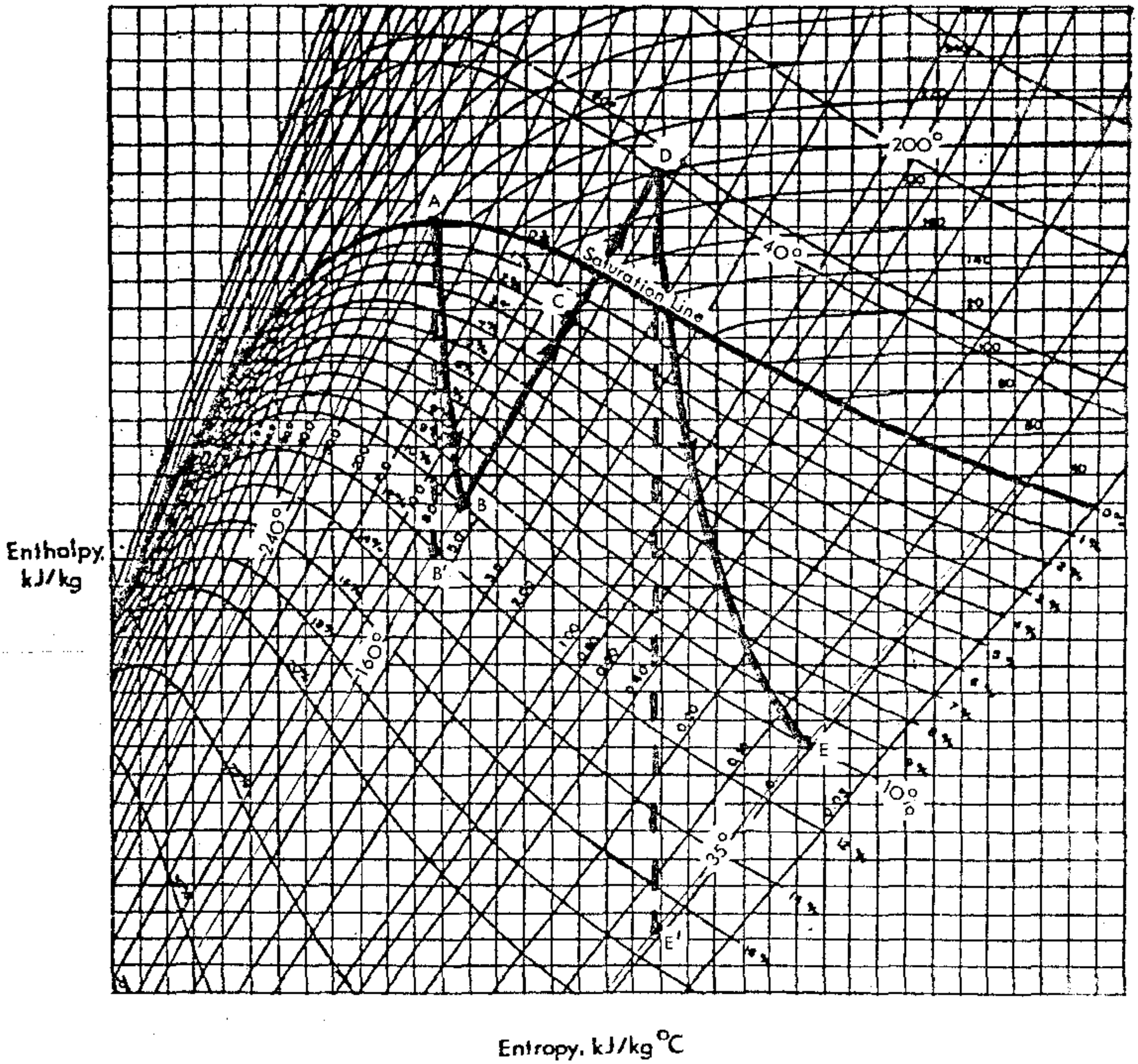


Fig. 4.2.16

Process A - B

Initial condition is saturated steam at 240°C. Expansion in the high pressure turbine, allowing for frictional effects, takes the process to the right of point B' at a moisture level of 10%.

Process B - C

The moisture separator, assuming no pressure drop, removes moisture from 10% to 2%. The temperature remains constant at the saturation temperature of 160°C.

Process C - D

Again assuming no pressure loss in the reheater, the enthalpy of the steam is increased at constant pressure, initially up to the saturated steam condition, after which further addition of heat raises the temperature from 160°C to 200°C.

Process D - E

The superheated steam expands in the low pressure turbine and allowing for friction takes the process to the right of point E' where the final temperature is 35°C and the moisture level is 10%.

B.4.2.10

If the condensation process was illustrated on the Mollier diagram this would take place at constant pressure and temperature while the latent heat was being removed. The process would move down the constant pressure/temperature line to some point off the diagram when the moisture would be 100%, ie, at the saturated liquid line.

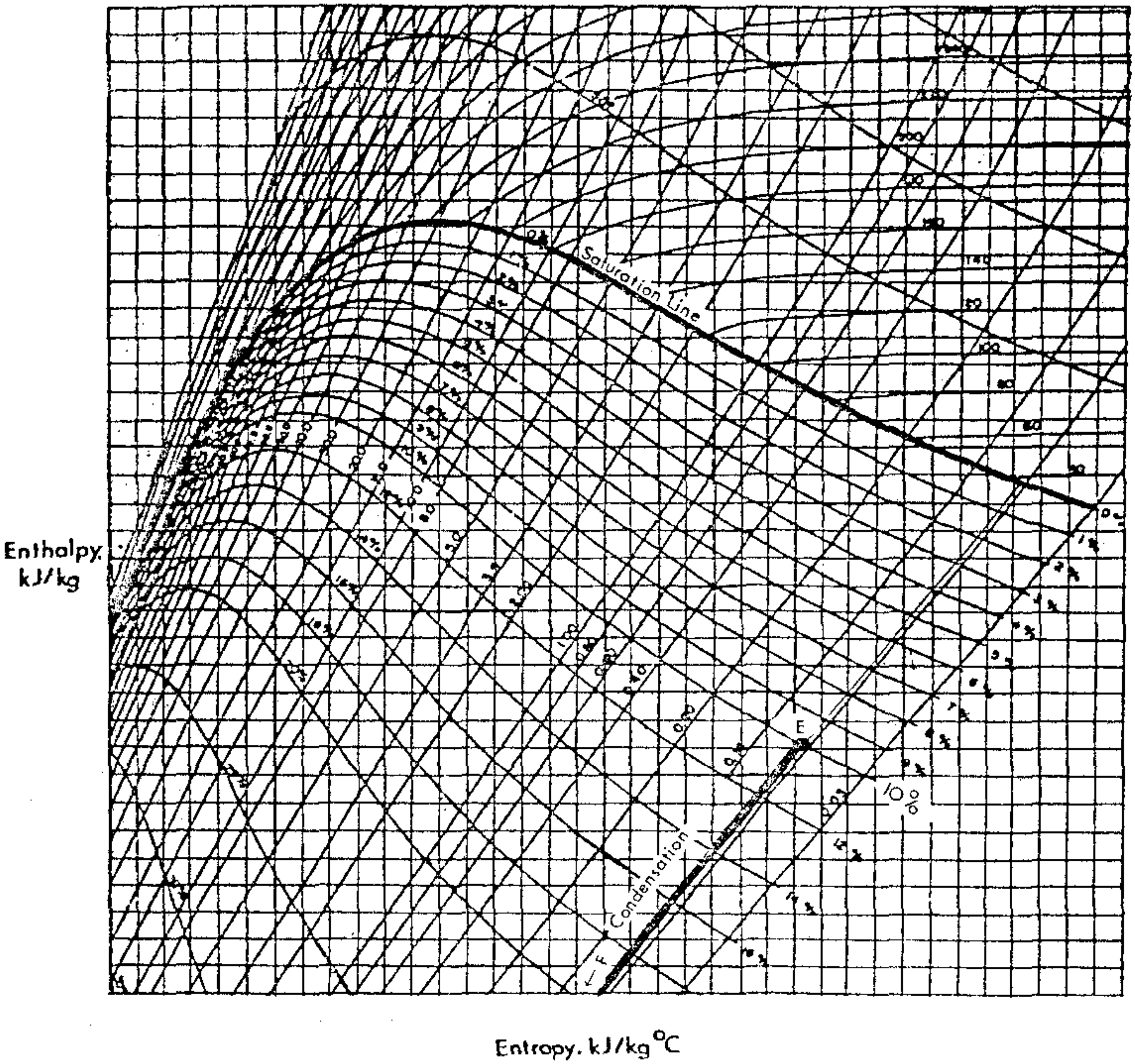


Fig. 4.2.17

B.4.2.11

The change in mass flow occurs in the moisture separator where the dryness fraction is increased from 90% to 98% by removing the moisture droplets. Consequently 8% of the working fluid has been removed and the flow into the reheater

= 0.92 x 900

= 828 kg/s.

B.4.2.12

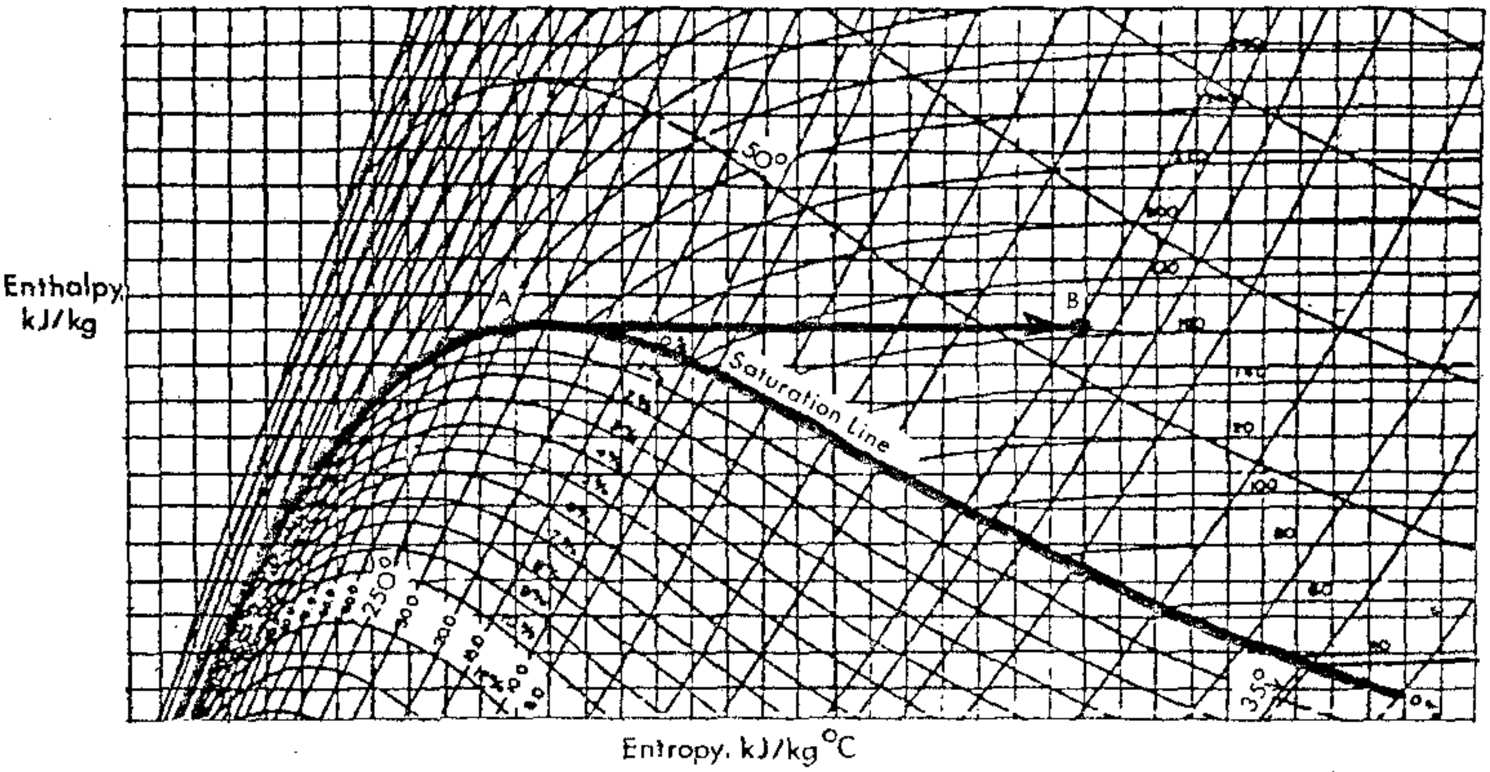


Fig. 4.2.18

The enthalpy at points A and B is the same. The amount of work that is available depends upon the change of enthalpy. In practice we expand the steam in the turbine to a temperature which is dictated by the cooling water supply. Assume that the turbine exhaust is at 35°C. The enthalpy drop from the initial condition to the constant temperature line will indicate the work available.

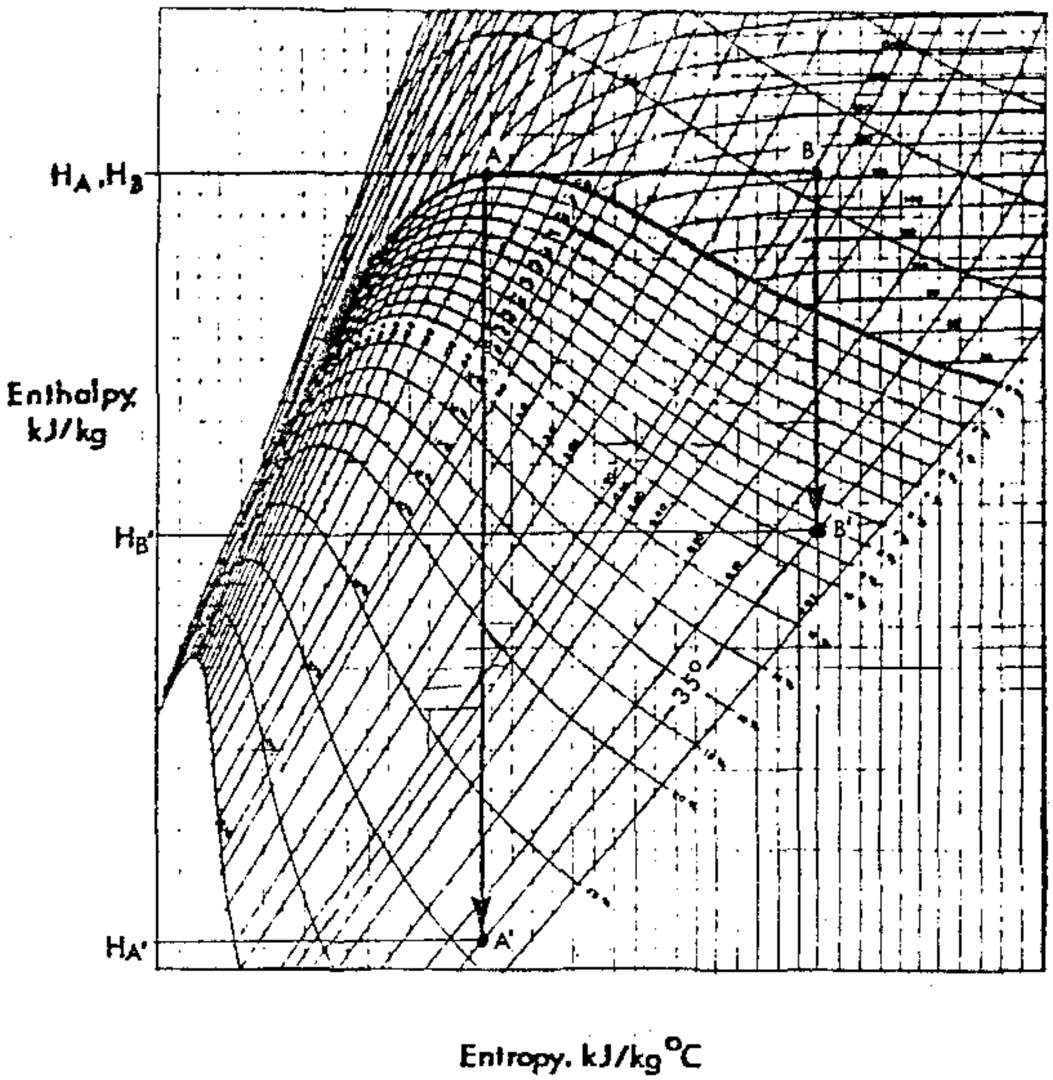


Fig. 4.2.19

If we consider the process from point A, the enthalpy drop is $H_A - H_A'$. Similarly, if we consider the enthalpy drop at point B, the value is $H_B - H_B'$. You can see that although the enthalpy is the same, the work available is decreased as a result of the throttling process increasing the unavailable part of the enthalpy. If the enthalpy $H_B - H_B'$ was only 50% of $H_A - H_A'$, then the steam flowrate would have to be doubled to achieve the same power output using the throttling technique. In practice the low pressure turbines are large enough without increasing the size to accommodate a larger steam flow, which incidentally would result in a less efficient cycle.

B.4.2.13

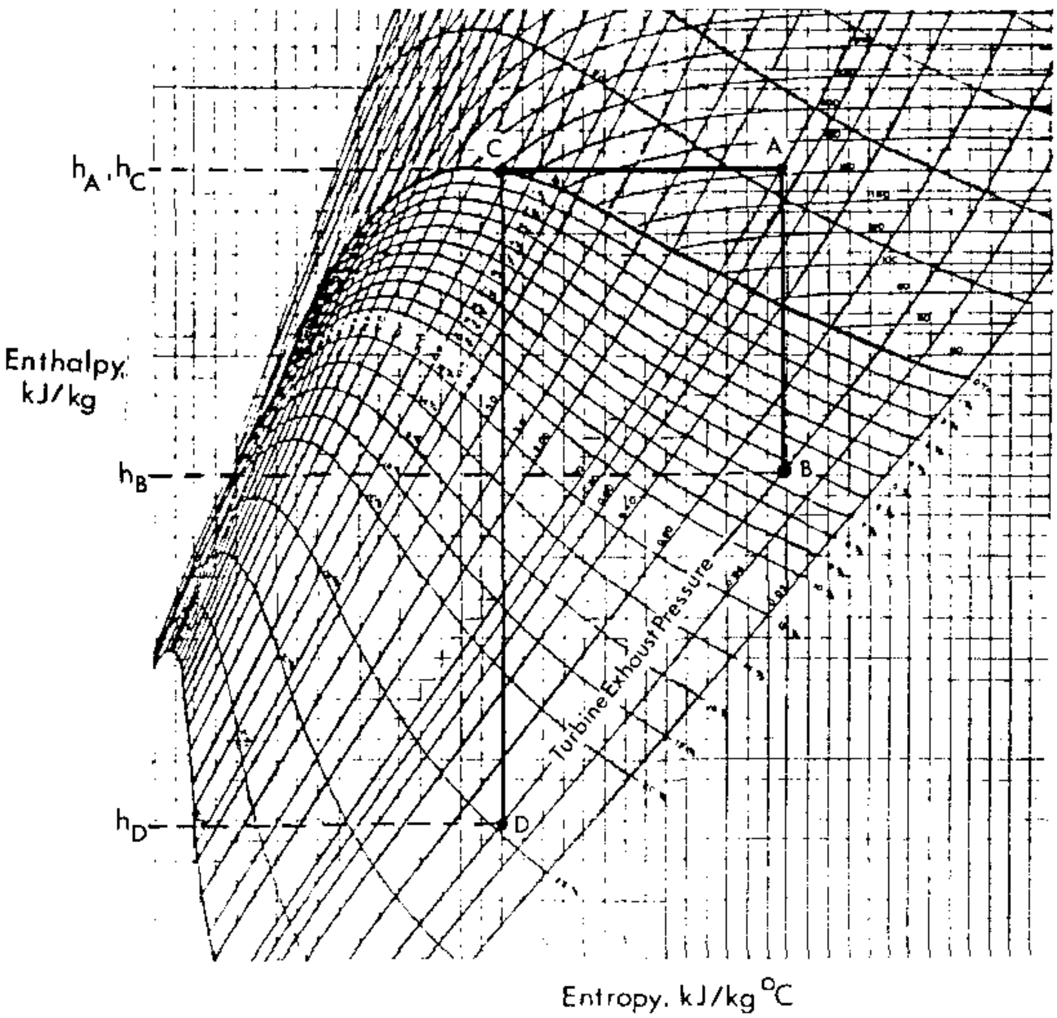


Fig. 4.2.20

Peak loading units should have the capability of operating at varying power levels. Suppose we have a unit operating at 25% power and the unit has four governor steam valves. If the unit is throttle governing, all four governor steam valves will be 25% open and consequently each will be throttling steam. This process is shown from points C to A. The enthalpy available for work is $h_A - h_B$. If the unit is nozzle governing, three governor steam valves will be shut and one will be completely open. There will be no throttling. The enthalpy available for work is $h_C - h_D$. Thus for the same steam flow, there is much more work available using nozzle governing steam control (this is true for all power levels up to 100%). Thus a peak loading unit that is capable of operating at different loads will be nozzle governed.

Base loading units run ideally at 100% power for long periods. At 100% power levels neither throttle governed nor nozzle governed units will throttle steam. Thus each will behave the same - the choice of which type of control is determined by economics. Throttle governing control is less costly, so it is used for base loading units.

J. Irwin-Childs

HEAT & THERMODYNAMICS

MODULE B.4.1

TURBINE WITH REHEAT

Heat & Thermodynamics

MODULE B.4.1

TURBINE WITH REHEAT

Course Objectives

1. Given a set of conditions, a calculator and steam tables, you will be able to calculate values of steam flow, pressure temperature and moisture content at major points through the turbine cycle.

2. You will be able to explain how the pressure and temperature vary through a turbine as the load increases from 0% to 100%, assuming constant vacuum.

Enabling Objectives

1. Given a set of conditions applicable to a steam turbine, with reheat, you will be able to sketch a Mollier diagram and illustrate the overall turbine process.

Module B.4.1 - Turbine with Reheat

This section is an extension of the principles that we examined in Module B.4.2. We will continue to use the Mollier diagram to illustrate the process and then use the steam tables to calculate the required values.

Before we plot the overall process steps on a Mollier diagram, it is of benefit to consider what changes are taking place in the turbine process at any point.

High Pressure Turbine

Steam Flow

If there is no extraction steam, the flow in and out of the turbine remains unchanged.

Enthalpy

The steam flows through the turbine at high speed and consequently there is an insignificant change in enthalpy of the steam due to heat loss through the casing. However, the turbine is a device whereby we can exchange heat energy for mechanical work. It follows that the enthalpy of the steam leaving the high pressure turbine will have a lower value than at the inlet. This lower enthalpy may be measured in terms of a lower temperature and pressure. Additionally, the quality of the steam will have deteriorated as some of the saturated steam condenses in the expansion process, producing wet steam.

Main Moisture Separator

This device removes the majority of the moisture that appears in the steam at the exhaust of the high pressure turbine. The temperature of the steam is not altered as the moisture is mechanically removed. In practice there is a slight pressure drop across the main moisture separator which will reduce the temperature by one or two degrees.

The steam flow out of the moisture separator is not the same as that entering the moisture separator. The reduction in mass flow is equal to the change in moisture content within the main moisture separator, eg, a moisture separator reduces the moisture level in steam at 1.8 MPa(a) from 12% to 4%. Determine the change in mass flow.

The quality is improved by removing the moisture. 12% of the fluid was initially moisture and this was reduced to a final figure of 4%. Thus, 12% - 4% = 8% of the mass flow must have been removed to achieve this new quality.

The enthalpy of the steam increases, not because heat energy was added but because the degrading moisture was removed and the average enthalpy increased while the overall steam flow decreased.

Reheater

The reheater raises the enthalpy of the steam leaving the main moisture separator prior to its admission to the low pressure turbine.

The pressure of steam leaving the reheater does not increase although the enthalpy and temperature have increased due to the addition of heat energy.

There is no change in the steam flow in and out of the reheater, there is no significant moisture to remove nor is there any steam extracted from the reheater.

Low Pressure Turbine

There is always steam extracted for feedheating from the low pressure turbine so the exhaust flowrate into the condenser will be less than the flowrate into the turbine.

As in the high pressure turbine, the loss of enthalpy through the casing is insignificant and the major enthalpy drop is due to the conversion of heat energy into mechanical work. This may be seen by a lowering of pressure and temperature.

As the heat energy is converted into mechanical work, the quality of the steam deteriorates as the moisture level increases.

Before we proceed to examine any further, try the following exercises and check your responses at the back of the course.

B.4.1.1

The steam flow entering a moisture separator is 700 kg/s. The steam has an initial moisture content of 9.4% and has a final dryness fraction of 99.6%. Calculate the flowrate of steam from the moisture separator.

B.4.1.2

Show whether the following parameters increase, decrease or remain the same for the following sections of turbine unit with feedheating:

a) High Pressure Turbine
b) Moisture Separator
c) Reheater
d) Low Pressure Turbine

Item	Enthalpy	Temperature	Pressure	Flowrate	Steam Quality

NOTE: Ignore any pressure drop through the moisture separator and reheater.

* * * * *

Let's examine a question which reflects the main points of our discussion.

> 900 kg/s of steam exits the HP stage of a turbine at 1.5 MPa(a) with a moisture content of 10%. This steam passes through a moisture separator which removes its total moisture content and then passes through a reheater. There is no significant pressure drop in the moisture separator and reheater.
>
> The secondary side of the reheater operates at 4.5 MPa(a) and is fed with 65 kg/s of saturated steam from the boiler. The condensed steam which results, leaves the reheater at saturation temperature.

a) i) Draw a schematic diagram of the process described above showing the following parameters at each step of the process:

- flow
- pressure
- moisture content.

ii) Determine the steam temperature at the exit of the reheater, showing clearly how you proceed.

b) The steam enters the LP stages of the turbine where it expands isentropically (ie, with constant entropy), the exhaust pressure being 10 kPa(a). Calculate the moisture content of the steam at the LP exhaust, showing clearly how you proceed.

The information presented may initially seen overwhelming but with a systematic approach, we should be able to satisfy all the requirements of the question.

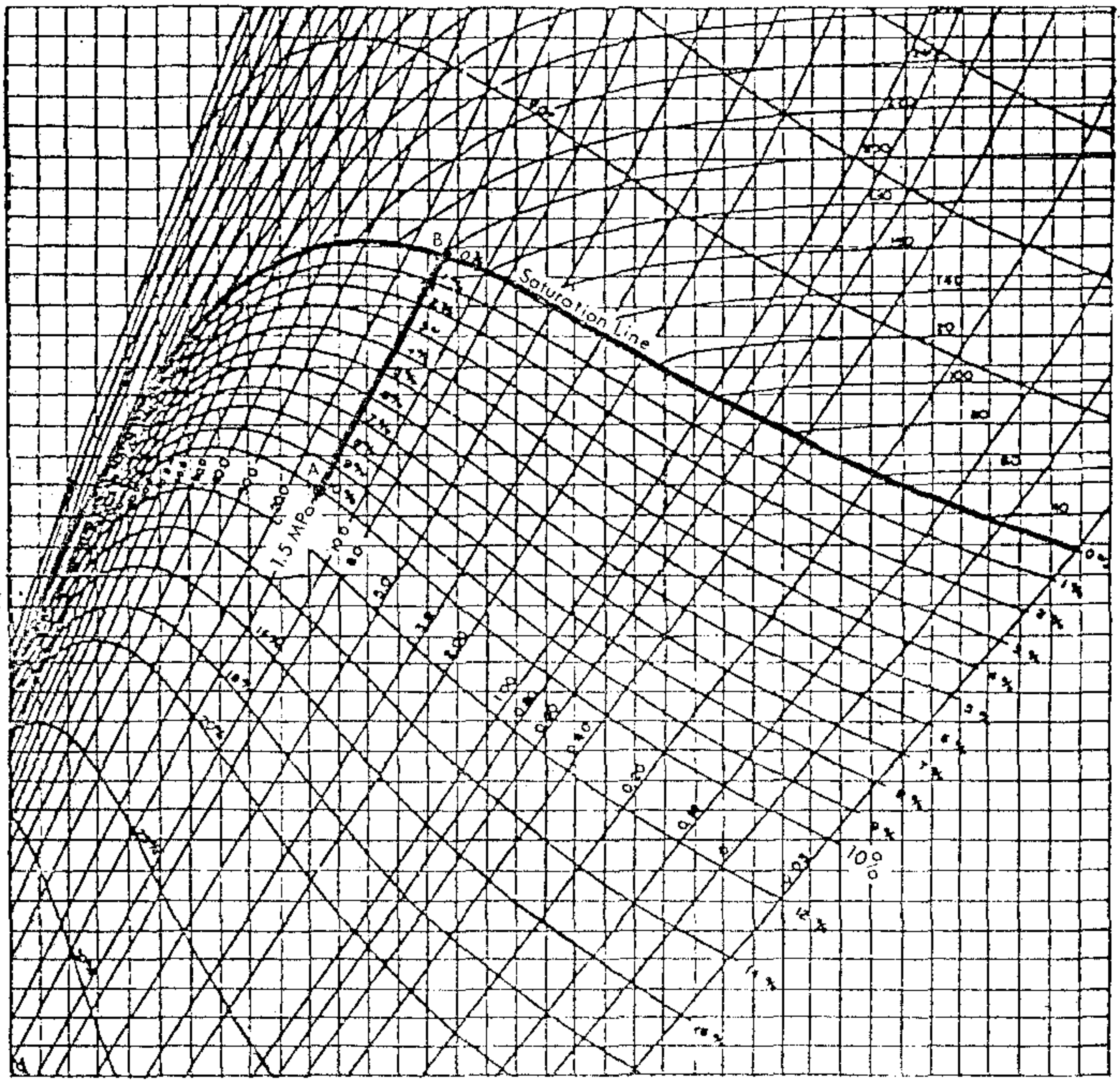
It is very useful to have a pictorial representation of the process. Question a) i) asks for a schematic diagram for the process and it would appear preferable to sketch the process itself; at least this way, there is some reinforcement of the process sequence which is occurring.

Using the Mollier diagram we can illustrate the total process sequence.

Moisture Separator

The moisture is removed at constant pressure. On the Mollier diagram this will be represented by moving up the 1.5 MPa(a) constant pressure line from 10% moisture to the saturation line, ie, 0% moisture.

Enthalpy, kJ/kg



Entropy, kJ/kg °C

Fig. 4.1.1

Point A is the exhaust from the high pressure turbine and the inlet to the moisture separator.

At Point A
1. Flowrate is 900 kg/s.
2. Pressure is 1.5 MPa(a).
3. Moisture content 10%.

Point B is the exhaust from the moisture separator and the inlet to the reheater.

At Point B

1. Flow rate is reduced by 10% due to the removal of the moisture. Thus flowrate ≈ 0.9 x 900 = 810 kg/s.
2. Ignoring the pressure drop in the moisture separator, there is no change in pressure.
3. The moisture content is 0%, ie, the steam is now saturated at 1.5 MPa(a).

Reheater

The reheater adds heat at constant pressure so we can continue up the 1.5 MPa(a) constant pressure line to some new point as determined by the heating steam supply to the reheater.

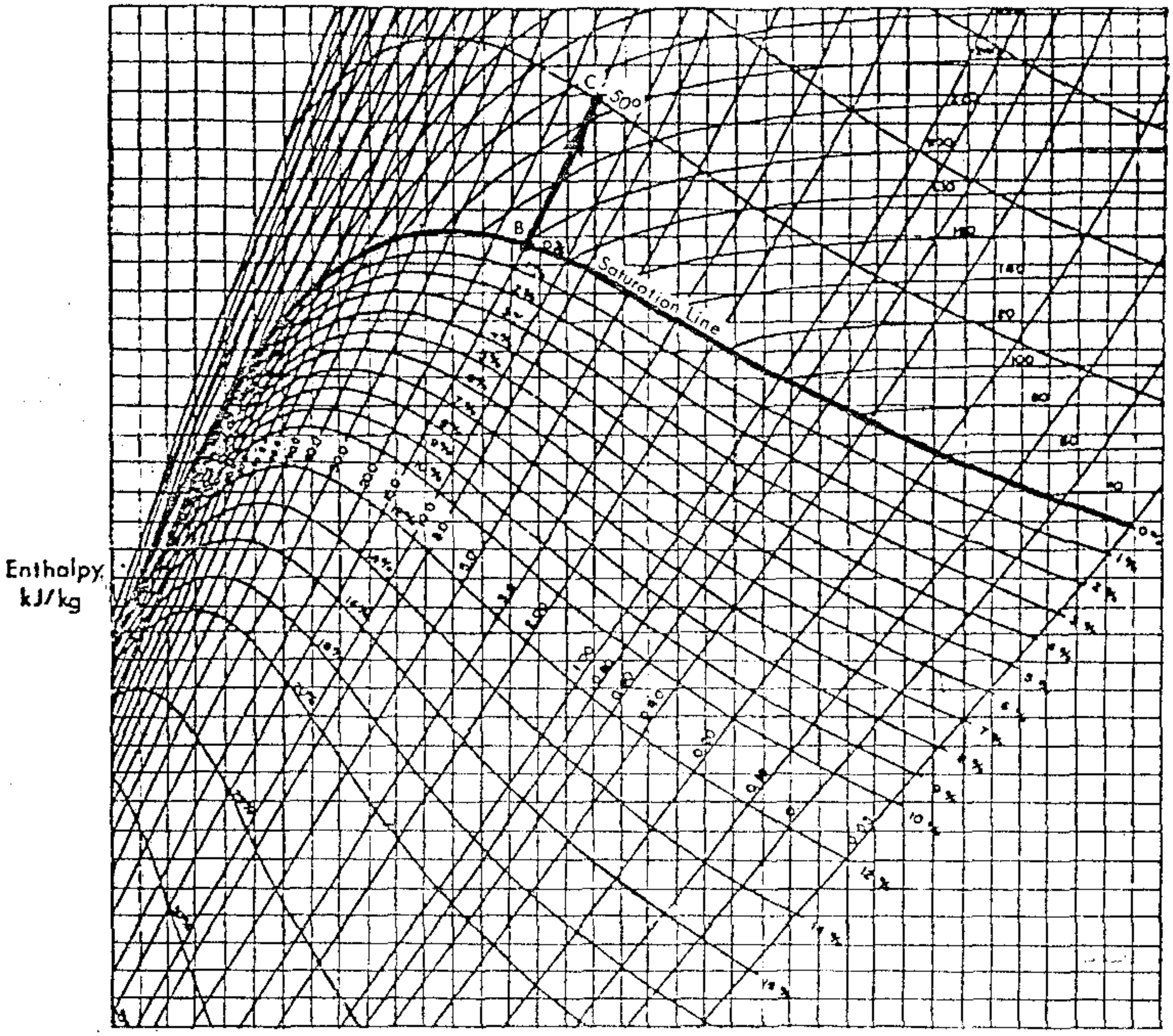


Fig.4.1.2

Point C is the exhaust from the reheater and is also the inlet to the lp turbine.

At point C flowrate is the same as at B = 810 kg/s. Pressure is 1.5 MPa(a). Moisture content is 0% because the steam is superheated.

If we want to tidy this up and present a complete picture, we can sketch the diagram and complete a table as shown below.

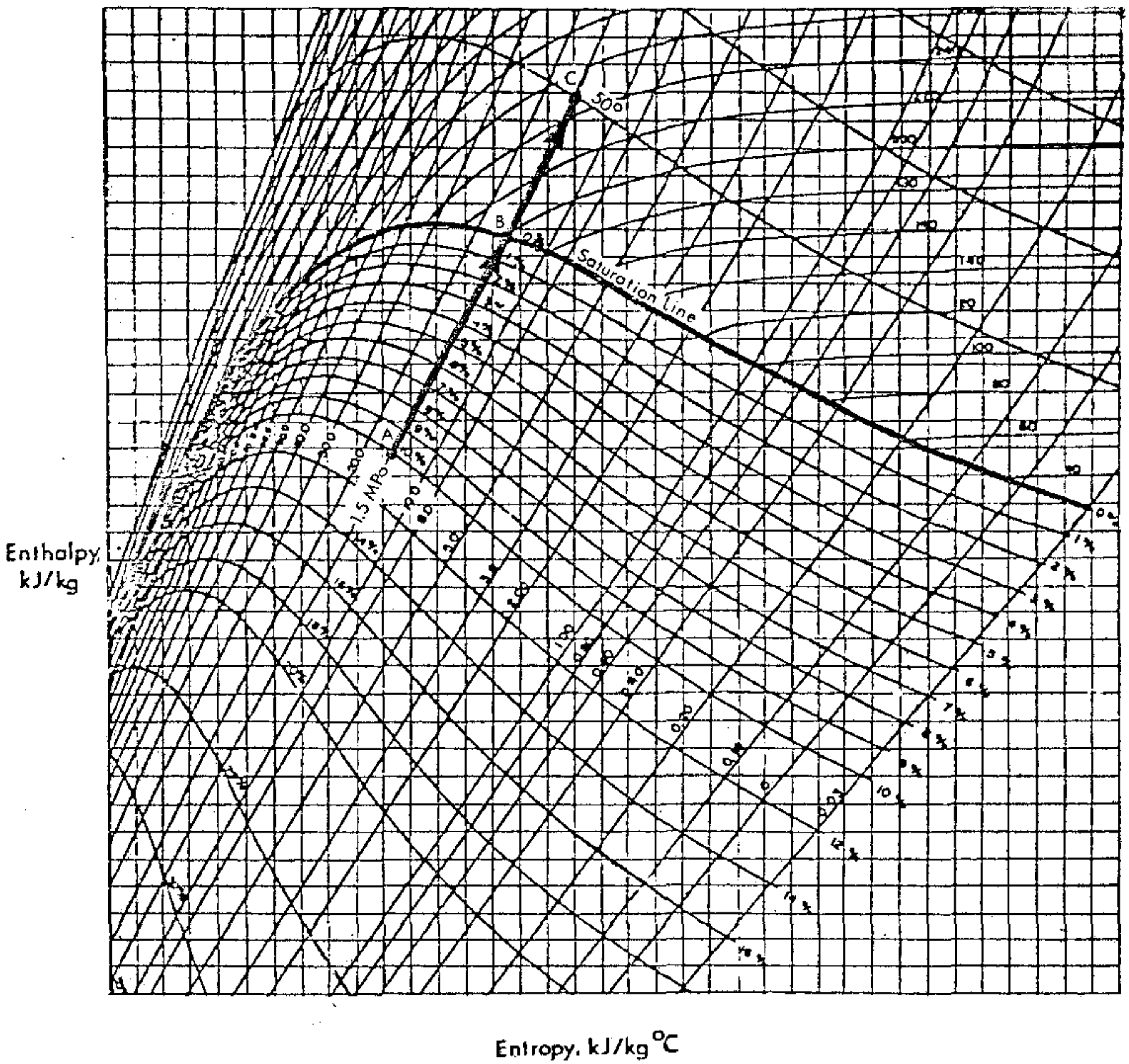


Fig. 4.1.3

Point	Flow	Pressure	Moisture
A	900 kg/s	1.5 MPa(a)	10%
B	810 kg/s	1.5 MPa(a)	0%
C	810 kg/s	1.5 MPa(a)	0%

Section a) ii) of the question asks us to determine the temperature of the steam leaving the reheater. There is no quick method of determining the temperature of the superheated steam. We have to calculate the amount of heat added to the process steam and then use steam tables to establish the temperature. The steam temperature changes with the addition of heat because it is superheated.

The basic approach to the reheater heat exchange is that the heat lost by the heating steam equals the heat gained by the process steam.

Heat Lost by the Heating Steam

The steam feeding the reheater is saturated steam and the condensate is not subcooled. The heat which has been removed from the heating steam is therefore the latent heat of vapourization at 4.5 MPa(a). We can see this clearly on the Temperature/Enthalpy diagram.

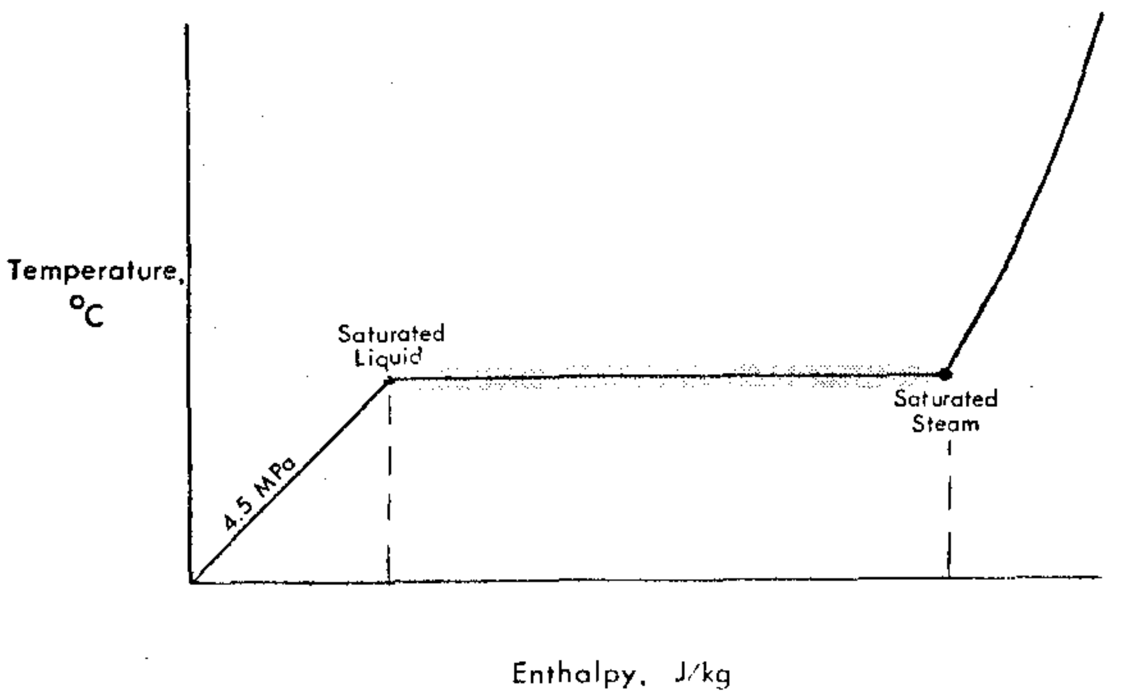


Fig. 4.1.4

The heat lost by the steam is the product of the mass-flow and the change in enthalpy. The decrease in enthalpy at 4.5 MPa(a) was from saturated steam h_g to saturated liquid h_f which is h_{fg}, the latent heat.

Mass Flowrate 65 kg/s

h_{fg} @ 4.5 MPa(a) = 1675.6 kJ/kg.

Thus heat lost = 65 x 1675.6 = 108,914

kg/s x kJ/kg = kJ/s.

This heat is gained by the process steam.

Using heat lost = heat gained, we can determine how much heat has been picked up by each kilogram of process steam.

Heat gained = process mass flowrate x increase in enthalpy. Heat gained = 108,914 kJ/s. Process mass flowrate through reheater = 810 kg/s. Increase in enthalpy is unknown.

Substituting

108,914 = 810 x increase in enthalpy.

$$\text{Increase in enthalpy} = \frac{108{,}914}{810}$$

$$= \underline{134.5} \text{ kJ/kg.}$$

The increased enthalpy is the enthalpy of the saturated steam at 1.5 MPa(a). h_g + 134.5 kJ/kg.

From tables h_g = 2789.9 kJ/kg.

New enthalpy = 2789.9 + 134.5 kJ/kg

= $\underline{2924.4}$ kJ/kg.

We must use the superheated steam tables at 1.5 MPa(a) to determine the temperature of the steam possessing the enthalpy of 2924.4 kJ/kg.

At 1.5 MPa(a) which is 15 bar, the enthalpy of the superheated steam is 2924 kJ/kg when the steam temperature is 250°C.

So the temperature of the steam leaving the reheater is 250°C.

Part b) of this question is designed to see if you can calculate the quality of the steam using the entropy values as we did in Module B.4.2.

Again a diagram is an asset and the process may be illustrated on a Mollier diagram, starting from the exit from the reheater which is the inlet to the low pressure turbine.

You should realize that if you made a mistake in calculating the temperature of the superheated steam in the previous section, then your answer to this section will also be incorrect even though you use the correct procedure.

The steam in the low pressure turbine expands isentropically, that is, at constant entropy. This is represented by a vertical line on the Mollier diagram. The line runs from the temperature of 250°C on the constant pressure line of 1.5 MPa(a) down until it strikes the constant pressure line of 10 kPa(a) as shown on the diagram.

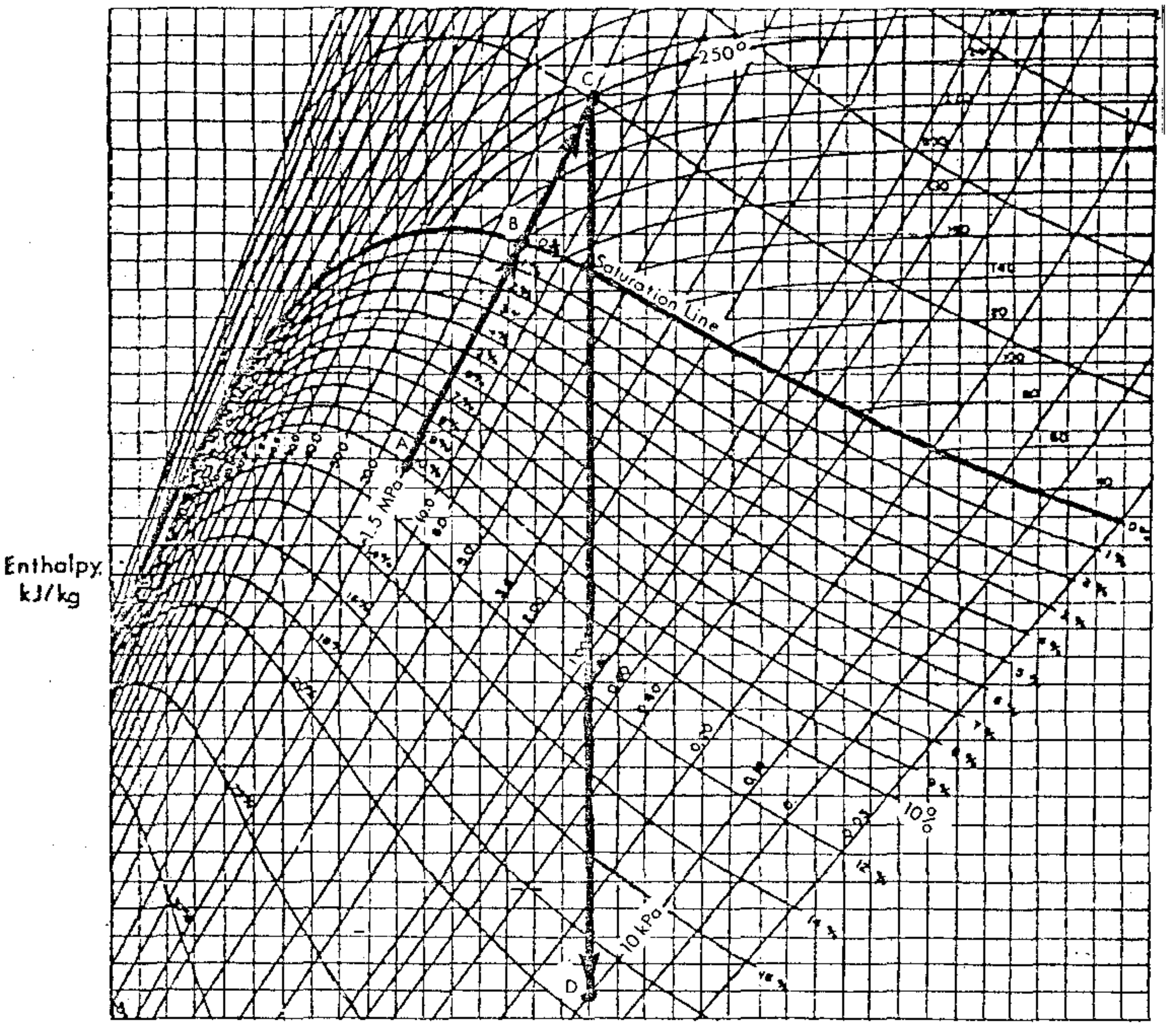


Fig. 4.1.5

The section on the diagram CD represents the isentropic expansion in the low pressure turbine.

We are asked to calculate the value of the moisture at point D and we will do this using the value of entropy which for this process is constant.

Using the superheated steam tables, we can look up the value of entropy at 1.5 MPa(a) and 250°C.

The value of entropy is 6.710 kJ/kg°C.

We know that this value remains constant throughout the expansion process down to 10 kPa(a).

We know that we have wet steam at 10 kPa(a) because the question tells us so. The entropy of the wet steam is found in exactly the same way as we find enthalpy.

Take the entropy of the liquid at 10 kPa(a).
S_f = 0.6493 kJ/kg°C. (10kPa(a) = 0.10 bar).

Now take the entropy from liquid to vapour at 10 kPa(a). S_{fg} = 7.5018 kJ/kg°C.

The actual entropy value of the wet steam depends upon the quality 'q' and is found using $S = S_f + qS_{fg}$.

We know S because that stays constant and the initial condition allowed us to determine that value. We have looked up S_f and S_{fg} - the only unknown is the dryness fraction or quality 'q'.

Substituting the values into $S = S_f + S_{fg}$, we get $6.710 = 0.6493 + q \times 7.5018$ kJ/kg°C,

thus $6.0607 = q \times 7.5018$

thus $q = \frac{6.0607}{7.5018}$

$= \underline{80.8\%}$.

This represents the vapour in the mixture, the moisture content is 1 - 0.808 = 0.192, or <u>19.2% moisture</u>.

This may appear to have been a lengthy process but you should realize that we have looked at a lot of detail, some of which you will have used on previous occasions.

The following examples are designed to reinforce the procedure we have just been through. Compare your answers to those at the end of the course.

B.4.1.3

Steam flows at 500 kg/s into a moisture separator. The steam has a dryness fraction of 88% and is at 1.0 MPa(a).

The moisture separator removes all of the moisture. The steam then enters a reheater where the heating steam is supplied at a pressure of 3.5 MPa(a) and a flowrate of 30.3 kg/s. The heating steam is saturated and the condensate is not subcooled. (Ignore any pressure drop through the moisture separator or reheater.)

a) Sketch a diagram of the process and list the values of flow, pressure and moisture content at each step.

b) Calculate the temperature of the steam leaving the reheater - show clearly how you proceed in the answer.

B.4.1.4

800 kg/s of steam enter a moisture separator at a pressure of 1 MPa. The moisture content is 13% at the inlet to the separator. Saturated steam leaves the moisture separator. The steam passes to a reheater using heating steam which is saturated at 3 MPa and which becomes subcooled by 6.8°C. The flowrate of heating steam is 41.5 kg/s.

Sketch the process on a Mollier diagram and determine the process steam temperature from the reheater. (Ignore any pressure drop in the moisture separator or reheater.)

B.4.1.5

Steam at 2 MPa(a) enters a low pressure turbine at 250°C. The steam expands isentropically and is exhausted to the condenser at 6 KPa(a).

Sketch the process on a Mollier diagram and calculate the moisture content of the steam leaving the low pressure turbine.

* * * * *

Turbine Pressure and Temperature Gradients

Under operating conditions the steam generator supplies steam to the turbine at a nominal pressure of 4 MPa(a). The steam is saturated and exists at the saturation temperature of 250°C.

The turbine exhausts wet steam to the condenser operating at a nominal pressure of 5.6 kPa(a). Again this is a saturation condition and the temperature of the exhaust steam from the turbine will be t_s at 5.6 kPa(a), ie 35°C.

No matter what happens in the turbine, the steam supply will be at 4 MPa(a), 250°C and the exhaust steam will be at 5.6 kPa(a), 35°C.

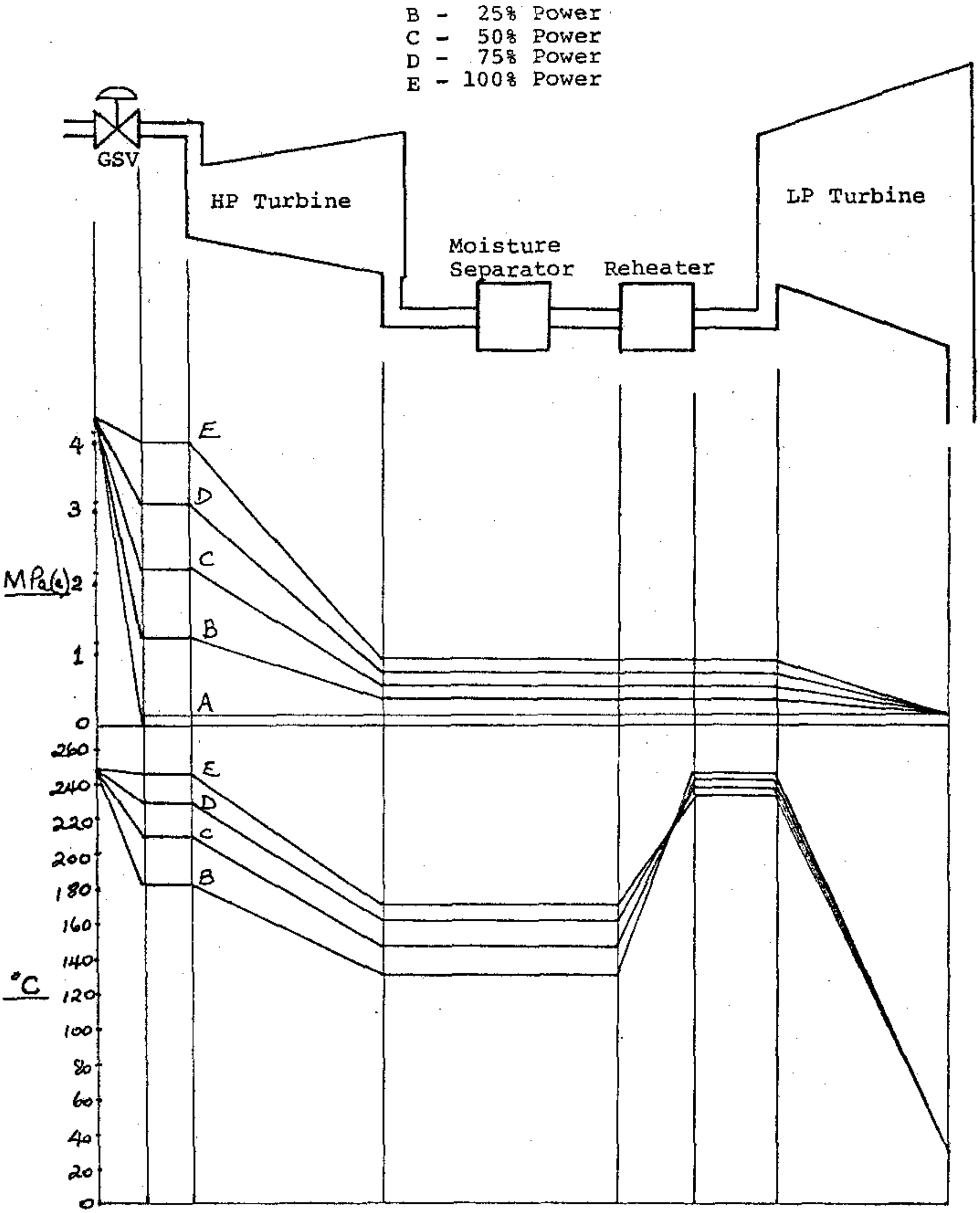
Consider the startup condition where the ESV's are shut, the turbine is on turning gear and the condenser is at its normal operating pressure of 5.6 kPa(a)

* * * * *

B.4.1.6

What do you know about the pressures in the low pressure turbines, reheater, moisture separators and high pressure turbine in this start up condition. Check your answer at the end of the course.

* * * * *


B - 25% Power
C - 50% Power
D - 75% Power
E - 100% Power
GSV
HP Turbine
Moisture Separator
Reheater
LP Turbine
MPa(a)
°C
E
D
C
B
A
4
3
2
1
0
260
240
220
200
180
160
140
120
100
80
60
40
20
0

This condition is illustrated on the diagram by line A. You can see at this point that the pressure upstream of the ESV/GSV is 4.3 MPa(a) whilst downstream the pressure is 5.6 kPa(a).

* * * * *

B.4.1.7

Steam at 4 MPa(a) passes through open ESV's and leaks past tripped GSV's into the high pressure turbine. The condenser pressure is 10 kPa(a). What is the temperature of the steam in the high pressure turbine.

Check your answer at the end of the module.

* * * * *

Suppose we have now run the turbine up to speed, synchronized and applied 25% load to the generator. In this situation the GSV's are open a small amount to admit slightly more than 25% full load steam flow. (At lower power less work is available per kg of steam due to throttling.)

This condition may be seen illustrated by time B on the diagram.

The pressure drop across the GSV is roughly 2.8 MPa so that the inlet pressure to the turbine itself is around 1.2 MPa(a). The saturation temperature corresponding to 1.2 MPa(a) is 188°C which is the temperature at which the steam is entering the high pressure turbine.

If the turbine is "cold" this does not present a problem but if the turbine is "hot" the admission of this low temperature steam will drastically cool the turbine and create high thermal stresses. This is the reason why block loading is employed for hot startup, to increase the steam temperature in the high pressure turbine casing to a value where no cooling occurs.

The change of inlet steam temperature of the turbine with increased GSV opening may be clearly seen from the temperature curves where the inlet temperature rises from 188°C at 25% load to 250°C at 100% load.

From the same series of temperature lines you can see also that the hp turbine exhaust temperature is increasing as the load increases. The exhaust temperature rises from 133°C at 25% load to 175°C at 100% load.

It is interesting to note that as the power on the turbine increases the temperature of the process steam, leaving the reheater, falls from 250°C to 239°C.

* * * * *

B.4.1.8

Why do you think the temperature of the process steam leaving the reheater, is highest at the lowest power levels?

Check your answer at the end of the module.

* * * * *

Well that's about it for this section. If you are confident about these questions, get the test from the Course/Shift Manager and write it. When you have written the test, ask for the self-evaluation sheet and compare with your test.

Take both the test and the self evaluation sheet to the Course/Shift Manager and when you are both satisfied with the result, have the Manager sign the progress summary sheet. If you identify some areas of weakness, return and practice some more and then try the test again.

When you are ready to progress, proceed to Module B.3.2 or B.2.

Answers

MODULE B.4.1

TURBINE WITH REHEAT

The initial moisture content was 9.4% and the final moisture content was 0.4% (100 - 99.6 = 0.4% you shouldn't have been caught here!).

The change in % moisture is 9.4 - 0.4 = 9%. So the new flowrate out of the moisture separator has been reduced by 9% of its original value, ie, to 91%. The original flowrate was 700 kg/s. Thus the flowrate out of the moisture separator is 700 x 0.91 = 637 kg/s.

B.4.1.2

a) High Pressure Turbine

The enthalpy will decrease as some of the heat energy is converted into work.

The temperature and pressure will decrease as the enthalpy is reduced. The flowrate will be reduced only if steam is extracted for feedheating. In this case, we will ignore steam extracted from hp turbine. The steam quality decreases as more work is produced from the steam.

b) Moisture Separator

The enthalpy of the steam will increase as the low enthalpy liquid is removed.

Ignoring the pressure drop, the pressure will remain constant.

The temperature of the steam will remain constant while the moisture is being removed.

The flowrate of steam from the moisture separator will be less than that at the inlet due to the removal of moisture. If steam is extracted from the moisture separator for feedheating, then this would also be taken into account when determining the new flowrate value.

The steam quality increases as the moisture is removed and the steam moves closer to the saturation condition.

c) Reheater

The enthalpy of the steam increases significantly in the reheater and the final steam has approximately 60°C of superheat.

Ignoring the pressure drop in the reheater the pressure remains constant.

The temperature of the steam increases to a value approximately 60°C above t_{sat} at the pressure in the reheater.

The mass flowrate through the reheater will remain constant since there is no extraction of steam.

The steam quality is raised from around 0.5% moisture to approximately 60°C of superheat.

d) Low Pressure Turbine

The enthalpy decreases as work is extracted from the steam.

The temperature and pressure fall with the decreasing enthalpy.

The flowrate decreases due to the steam extracted for feedheating.

The steam quality decreases due to the condensation produced by the reduction in enthalpy.

Item	Enthalpy	Temp.	Pressure	Flowrate	Steam Quality
HP Turbine	Decrease	Decrease	Decrease	Same	Decrease
Separator	Increase	Same	Same	Decrease	Increase
Reheater	Increase	Increase	Same	Same	Increase
LP Turbine	Decrease	Decrease	Decrease	Decrease	Decrease

B.4.1.3

In this question we do not have any turbine expansion after the reheat. Before doing any calculations, it is worth sketching the process so that there is a visual reference available as you work through the problem.

The process steam pressure is 1 MPa(a) and moisture separation to provide saturated steam, together with the reheating, both take place at constant pressure. On the Mollier diagram the process follows the constant pressure line upwards from the constant moisture line at 12% moisture.

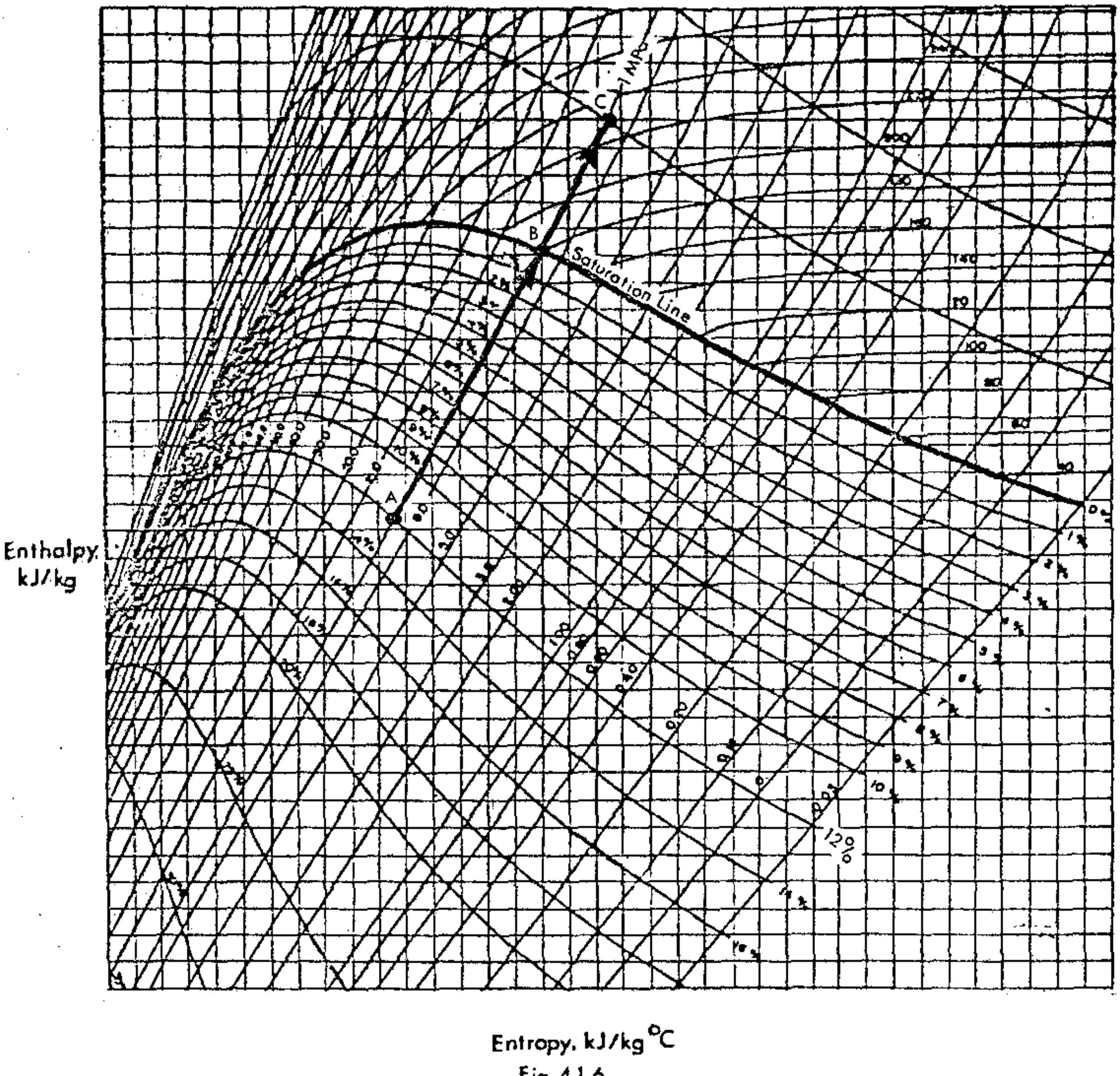


Fig. 4.1.6

Looking at the process points A, B and C, we can list the known values of pressure, flowrate and moisture content and calculate the unknowns.

Point	Moisture	Flowrate	Pressure
A	12%	500 kg/s	1 MPa
B	0%	440 kg/s	1 MPa
C	0%	440 kg/s	1 MPa

Point A All values are given.

Point B Steam is "saturated" so moisture is 0%. 12% of moisture has been removed at point B so flowrate deceases by 12%.

Point C Same values as point B.

The next part of the question asks for the temperature of the steam leaving the reheater. This part of the exercise is done by equating the heat gained by the process steam to the heat lost by the heating steam.

Heating Steam

This is initially saturated at a pressure of 3.5 MPa and the condensate remains at the saturation temperature because there is no subcooling. If we sketch the temperature enthalpy diagram, we can see that the heat lost is the latent heat at the pressure of 3.5 MPa(a).

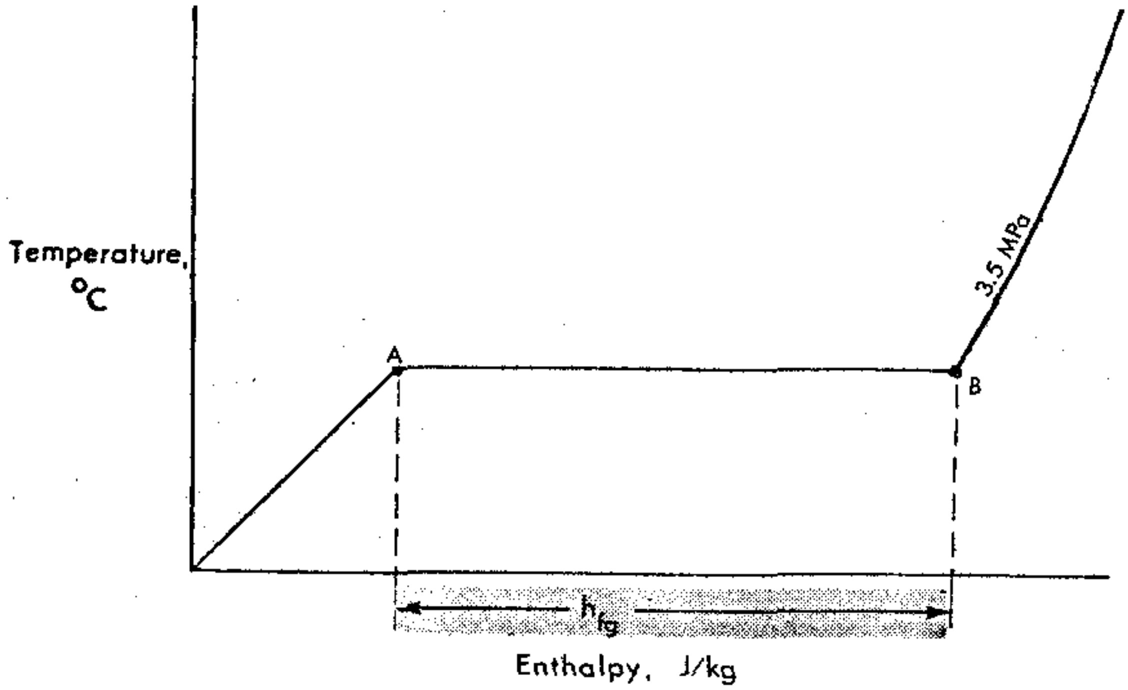


Fig. 4.1. 7

Point A represents the saturated liquid and point B represents the saturated steam.

h_{fg} at 3.5 MPa(a) = 1752.2 kJ/kg.

The heating steam flowrate is 31 kg/s.

So the total heat lost is the product of the enthalpy change, 1752.2 kJ/kg and the mass flowrate, 30.3 kg/s.

Heat lost by heating steam = 1752.2 x 30.3

= 53091.7 kJ/s.

This heat is given to the process steam <u>every second</u>. In every second there are 440 kg of process steam flowing through the reheater.

So each kg of process steam picks up 1/440 of the total heat lost by the heating steam = $\frac{53091.7}{440}$ = $\underline{120.7}$ kJ/kg.

The enthalpy of the saturated steam has been increased by 120.7 kJ/kg and we must look at the superheated steam tables to find the temperature of the steam that corresponds to this new value of enthalpy.

h_g at 1 MPa(a) = 2776.2 kJ/kg.

Enthalpy of superheated steam = 2776.2 + 120.7

= 2896.9 kJ/kg.

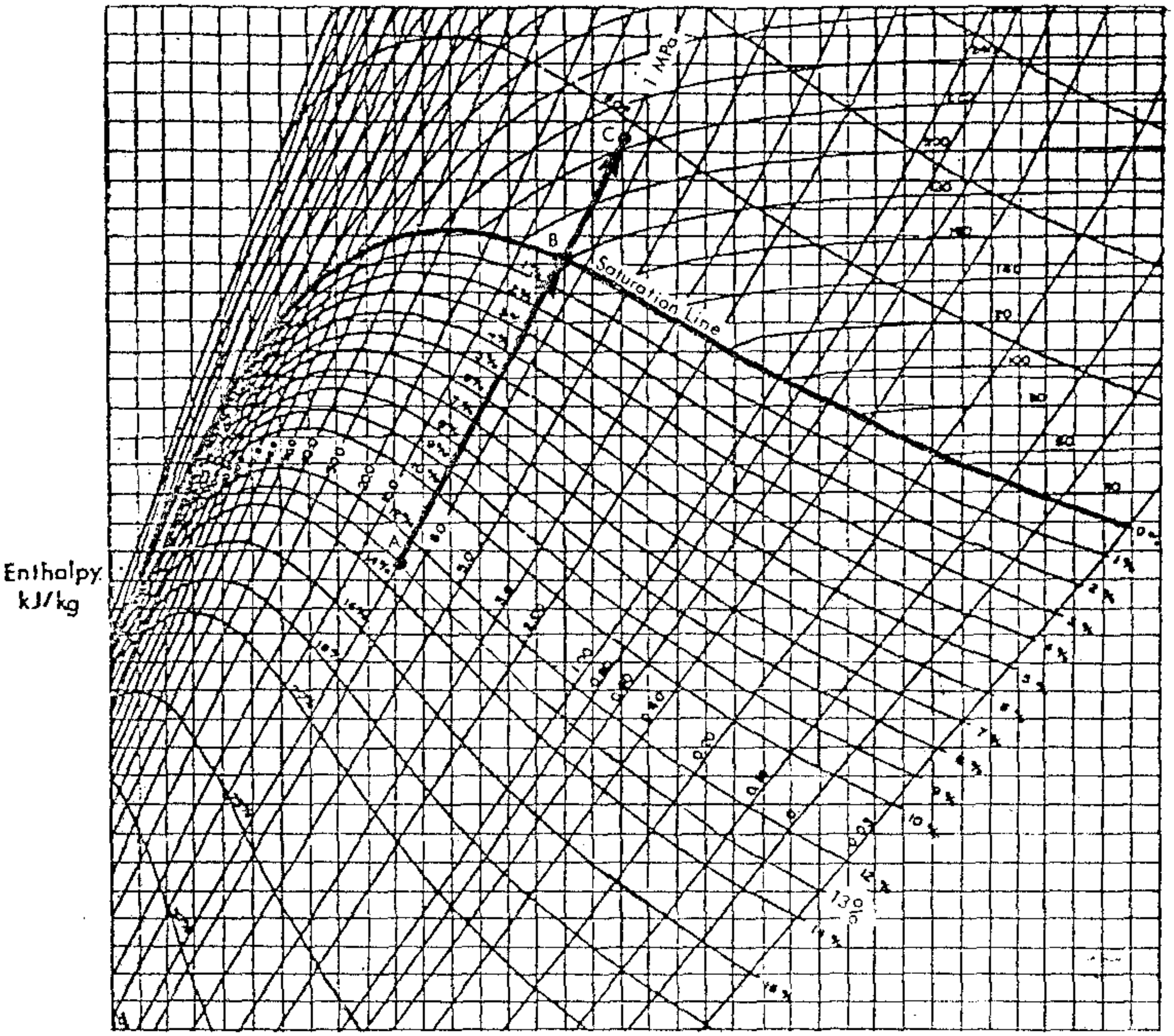
Using the superheated steam tables at 1 MPa we can see that at 200°C the enthalpy is 2827 kJ/kg and at 250°C the enthalpy is 2943 kJ/kg. So the temperature of the steam from the reheater is $\frac{70}{116}$ (50°C) + 200°C = 230°C.

B.4.1.4

This is a basic arrangement of the moisture separator and reheater operating at constant pressure.

The moisture separation process will appear as a line from the 13% moisture point, on the 1 MPa(a) constant pressure line, up to the saturation line.

The reheat process will appear as a continuation along this constant pressure line up into the superheat region.



Entropy. kJ/kg °C

Fig. 4.1.9

A - B is the moisture separation process.

B - C is the reheat process.

Moisture Separation

The only changes will be the reduction in mass flowrate as the steam quality improves to saturation conditions.

Steam flow reduces to 800 x 0.87 = 696 kg/s.

Reheat

In the reheater the heat gained by the process is lost by the heating steam.

The heating steam is saturated at 3 MPa(a) and the condensate becomes subcooled by 6.8°C. So we can determine the heat lost per kg of heating steam.

h_g at 3 MPa = 2802.3 kJ/kg, t_{sat} = 233.8°C.

The temperature of the condensate is t_{sat} - 6.8 = 233.8 - 6.8 = 227°C.

h_{f227} = 976.2 kJ/kg.

So the heat lost per kg of heating steam is 2802.3 - 976.2 = 1826.1 kJ/kg.

The total heat lost per second is the product of the mass of heating steam per second and the enthalpy change per kg,

= 41.5 x 1826.1

= 75783 kJ.

Each kg of the process steam receives 1/696 of the heat lost by the heating steam.

1 kg of process steam receives $\frac{75783}{696}$ = 109 kJ/kg.

The enthalpy of saturated steam entering the reheater at 1 MPa is 2776 kJ/kg.

The enthalpy of the superheated steam leaving the reheater at 1 MPa(a) is 2776 + 109 kJ/kg = 2885 kJ/kg.

Using the superheat steam tables at 1 MPa(a), we can find the temperature to which this enthalpy corresponds.

Enthalpy at 200°C and 1 MPa(a) = 2827 kJ/kg.
Enthalpy at 250°C and 1 MPa(a) = 2943 kJ/kg.

Difference for 50°C is 116 kJ/kg.

The enthalpy at the reheater outlet is 2885 kJ/kg which is 2885 - 2827 = 58 kJ/kg more than the enthalpy at 200°C.

Temperature increase above 200°C = $\frac{58}{116} \times 50 = 25°C$.

Steam temperature = 225°C.

B.4.1.5

In this problem the steam into the turbine is superheated so the entropy values for the initial steam condition will have to come from the superheated steam tables.

As in the previous question, the value of entropy remains constant during the expansion process. On the Mollier diagram the process will appear as a vertical line running down from the superheat region at 250°C and a pressure of 2 MPa to intersect the constant pressure line of 6 kPa(a).

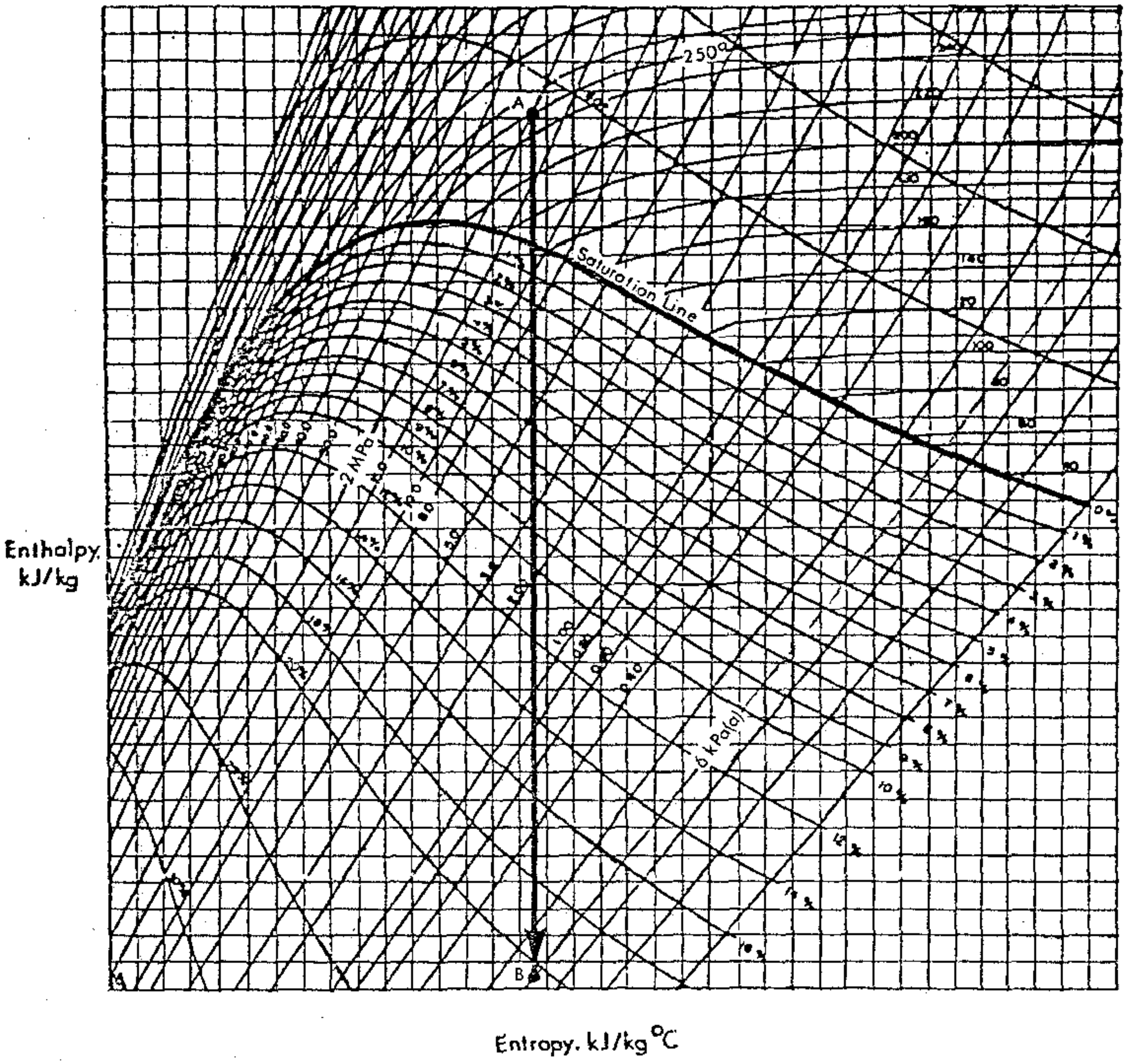


Fig. 4.1.11

Again we use the entropy value at the inlet condition to determine the condition of the exhaust steam.

From superheated steam tables, the value of entropy at 2 MPa(a) and 250°C is 6.545 kJ/kg°C.

At 6 kPa(a) S_f = 0.5209 kJ/kg°C
S_{fg} = 7.8104 kJ/kg°C.

The entropy of the superheated steam is equal to the entropy of the wet steam after expansion.

Thus $6.545 = 0.5209 + q\ (7.8104)$

$$6.0241 = q\ (7.8104)$$

$$q = \frac{6.0241}{7.8104}$$

$$= \underline{77.1\%}.$$

So the moisture level is 23%.

B.4.1.6

In this startup condition, prior to the admission of steam into the turbine, the whole of the turbine unit is at the same pressure, ie, the condenser pressure of 5.6 kPa(a). From the GSV through the hp turbine, moisture separators, reheaters and low pressure turbines the pressure is the same as that in the condenser.

B.4.1.7

Again in this condition the whole of the turbine unit is at the condenser pressure of 10 kPa(a).

The GSV are not isolating valves, they are control valves and are not designed to prevent total admission of steam to the hp turbine. Immediately after the GSV the pressure will have been throttled to 10 kPa(a). The temperature of this steam will be the saturation temperature corresponding to 10 kPa(a), ie, 46°C.

If the turbine was recently shutdown with the turbine "hot" this throttled steam entering the hp turbine can produce severe quenching of hp turbine rotor. This problem can be avoided by ensuring that the ESV's are always shut if there is any pressure in the steam lines.

B.4.1.8

If you look at the conditions of temperature and flowrate in the reheater you will observe the following:

a) Temperature of the heating steam remains constant over the whole power range (assuming constant boiler pressure).

b) The temperature of the process steam entering the reheater, from the hp turbine via the moisture separator, rises as the turbine power increases.

The temperature difference between the heating steam and the process steam which is being heated, becomes smaller as the turbine power increases, ie, from a ΔT of 121°C at 25% load to a ΔT of 79°C at 100% load.

With a smaller ΔT between the turbine steam and heating steam it would seem reasonable to suppose that the turbine steam temperature would more easily approach the heating steam temperature of 254°C.

What has changed besides the temperatures in the reheater as the load increases? The turbine steam mass flowrate has increased by approximately four times from 25% load to 100% load. This results in the process steam mass flowrate through the reheater increasing by a factor of four. The increased flowrate reduces the time that the steam is in the reheater by a factor of four. The process steam is not in the reheater long enough to be heated to the temperature of the heating steam. As the process steam flowrate increases, the difference between the heating steam temperature and turbine steam temperature at the reheater outlet, increases, due to the decreased time for heat transfer.

At 25% the difference between the heating steam temperature and the turbine steam temperature at the reheater outlet is 4°C. At 100% the difference is 15°C.

* * * * *

J. Irwin-Childs

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HEAT & THERMODYNAMICS

MODULE B.3.2

FEEDHEATER OPERATION

Heat & Thermodynamics

MODULE B.3.2

FEEDHEATER OPERATION

Course Objectives

1. Given a set of conditions, steam tables and a calculator, you will be able to perform simple calculations of heat transfer based on the principle that heat gained by the feedwater is equal to heat lost by the extraction steam.

2. You will be able to explain how the extraction steam is more efficiently used in feedheating than in producing further work in the steam turbine.

3. You will be able to support the rationale stated in Objective 2 using a simple numerical example.

Enabling Objectives

1. You will be able to explain how the extraction steam flow to a feedheater changes when feedwater flow conditions change.

Before we look at the feedheater as a heat exchanger, let's take a more global view of the whole system. The majority of our systems are concerned with heat transfer of one form or another. The systems are depending on each other and a change in condition in one system is reflected by changing conditions in another system.

Even in the "steady state" situation, conditions are fluctuating due to control systems, hydraulic transients, etc. How do we know what is within the normal fluctuation and what is abnormal? Are some parameters more reliable than others?

Two major questions then arise: "How do we know when we have lost control?" and secondly, "Do we know why control was lost?"

If we don't know the answers to these two questions, the chances of regaining control are very slim. You only have to examine the reports on Three Mile Island to see that this is true.

In any system, the "steady state" operation is reached when the supply satisfies the demand whether it is the supply of gold to satisfy the investor or the supply of electrical energy to satisfy the Grid requirements.

When the supply no longer satisfies the demand, conditions start to change, sometimes very rapidly. If we concentrate on the basic fluid systems within a nuclear station, there are two major parameters which will indicate changing conditions, TEMPERATURE & PRESSURE.

Let's consider these two parameters:

TEMPERATURE

Suppose we have a liquid/liquid heat exchanger; say the turbine lube oil cooler. Keep the oil flow constant and the cooling water flow constant and watch the cooler outlet oil temperature when the oil inlet temperature remains constant.

Will it change? Why doesn't the temperature change?

It will not change because the supply of cooling water and the supply of oil are constant and the steady state condition is created by the cooling water removing heat at the same rate as the cooling oil is supplying heat to the cooler.

Let's increase the flow of cooling water to the cooler.

What happens to the oil outlet temperature? Why did it start to fall?

The rate at which heat was being removed from the oil by the cooling water was greater than the rate at which heat was being added to the oil by the turbine bearings.

What happened to the outlet temperature of the cooling water?

The temperature became lower because, although overall more heat was being removed from the oil cooler; on a per kg base,each kg was removing less heat because there was less time for heat absorption in the cooler.

Did the pressure of the oil change as a result of reducing the temperature?

The pressure did not change because the pressure was being maintained by the oil pump.

B.3.2.1

Consider the following problem:

Suppose we had a closed cylinder and it was full of liquid at 300°C and at a pressure of 9 MPa. If we started to cool the cylinder, what would happen to the pressure?

Think about this and see if you agree with the response at the end of the module.

* * * * *

From this example, we can see that the first effect of cooling the cylinder was to reduce the temperature but because the temperature caused a change of volume within the system, the pressure also changed.

If the only change in the system had been the reduction of fluid temperature, then we could have measured this change by temperature or pressure measurements. A reduced pressure would lead us to deduce, quite correctly, that the temperature of the fluid was falling. Therefore, we could have used pressure to tell us that there was a mismatch in the system, ie, heat into the cylinder was less than heat out of the cylinder.

Before we move on to look at the feedheater, have a look at these two questions and compare your answers with those at the end of the module.

B.3.2.2

What happens to the pressure of the engine coolant in an automobile after the engine is shutdown? How is the effect you describe put to good use?

B.3.2.3

A tank of liquid propane is used for a period of time. The pressure in the tank falls and heavy frost forms on the outside of the propane tank. Explain why the pressure has fallen and why the frost has appeared.

* * * * *

Feedheater

The purpose of the feedheater is to raise the temperature of feedwater on its way to the steam generator. The feedwater flows through the tubes and receives its heat from steam in the heater body. The steam is extracted from suitable points on the steam turbine and may have high levels of moisture.

If the steam was condensed to saturated liquid only, then any small drop in pressure would cause the liquid to vapourize and vapour locking of drain lines would occur. Consequently, the condensate in a feedheater is sufficiently subcooled to prevent the drains flashing to vapour.

In a steady state condition, the heat gained by the feedwater is equal to the heat lost by the extraction steam and resulting condensate.

Any change in conditions on either side of the heater is going to appear as a temperature change or a temperature effect because Heat Out no longer equals Heat In.

Let's have a closer look at the conditions which exist and how they can affect heater performance.

Feedwater Side

The heat which is picked up by the feedwater is a function of the mass flow, in kg/s, and the change in enthalpy of the feedwater across the heater. This is the same as using the temperature difference except that by using the enthalpies, these values can be looked up immediately under the h_f columns in the steam tables.

Thus heat gained by the feedwater is:

flowrate (kg/s) x [Enthalpy Out ($h_{f_{out}}$)

- Enthalpy In ($h_{f_{in}}$)].

We will put some figures into this arrangement later on.

Steam Side

The heat which is lost by the steam is a function of the steam flow and the change of enthalpy of the steam entering the heater and the resulting condensate leaving the heater.

Again, we can use exactly the same approach of using enthalpies.

Thus, heat lost by the steam to the feedheater is:

flowrate (kg/s) x [Enthalpy In ($h_{steam\ in}$)

- Enthalpy Out ($h_{f_{out}}$)].

For any steady state operation, the heat gained by the feedwater will be equal to the heat lost by the extracted steam.

Heat Out Feedwater = Heat In Steam.

Feed Flow x Enthalpy Change = Steam Flow x Enthalpy Change.

Before we examine this equation in more detail, let's just consider flowrates. The feed flow requires a pump to be running; either the condensate extraction pump or the feed pump. It also requires that control valves (either the level control valves for the deaerator or the feedwater regulating valves for the steam generator) must allow the flow of feedwater.

The steam flow from the extraction steam belt on the turbine to the feedheater is not regulated by valves. The steam will only flow from the turbine to the feedheater if there is a pressure difference between the turbine and feedheater.

B.3.2.4

How is steam flow established to a feedheater? Why is the feedheater shell pressure normally lower than the turbine extraction point pressure?

B.3.2.5

How is the steam flow to the feedheater increased when the unit power changes from 50% to 100% power?

Check your responses with those at the end of the module.

Effect of feedwater conditions on extraction steam flow

Using the energy balance, heat in = heat out, we can examine the effects that changes in feedwater temperature and flowrate will have on the extraction steam flow to the feedheater.

Temperature

If the temperature of the feedwater into the heater changes, then this will affect the temperature rise of the feedwater across the heater.

The change in temperature means that the amount of heat removed from the feedheater will have changed. Assume that the feedwater flowrate is unchanged.

Suppose the feedwater inlet temperature drops. The amount of heat energy which is transferred is a function of the difference in temperature between the steam side and the feedwater side of the feedheater. Because of the larger temperature difference between the steam and the feedwater, more heat is being transferred and is being removed from the heater than before. The increased rate of heat removal has the effect of lowering the temperature in the steam side of the heater.

As the temperature in the heater shell falls, so does the pressure. This provides a larger pressure difference between the turbine extraction point and the heater, and more steam flows to the heater. The energy to and from the heater come back into equilibrium with a new set of operating conditions.

The new operating conditions will be:

a) lower pressure and temperature in the heater shell.

b) higher extraction steam flow.

c) increased ΔT across the heater on the feedwater side, although the outlet temperature will be less than previously.

Similarly, if the feedwater inlet temperature had risen, there would have been less heat removed from the heaterbecause there would have been a reduced temperature difference between the steam and feedwater.

The effect of reducing the heat removed by the feedwater would be that the temperature in the steam space would start to rise. As the temperature increased, the pressure would increase and the extraction steam flow from the turbine would reduce to a new level which satisfied the feedwater conditions.

The new operating conditions will be:

a) higher temperature and pressure in the heater shell.

b) reduced extraction steam flow to the feedheater.

c) the feedwater ΔT across the feedheater will have reduced although the feedwater outlet temperature will have increased.

The effect of keeping the feedwater inlet temperature constant and changing the feedwater flow produces the same results as changes in temperature. As the heat rate removal is increased, the temperature in the shell side falls, pressure falls, extraction steam flow increases, and the system moves back into equilibrium.

Try these questions and compare your answers with those at the end of the module.

B.3.2.6

Feedwater inlet temperature to a feedheater remains constant. Assuming that the supply steam temperature at the turbine remains constant, explain how the conditions of pressure, temperature and flowrates change at the heater when the feedwater flowrate is reduced.

B.3.2.7

A turbine has three feedheaters in series. Explain the changes you would expect to find on #3 heater if heater #2 is taken out of service.

B.3.2.8

A turbine has three feedheaters. Explain what changes in operating conditions you would expect from the heaters when the turbine power output is increased from 50% to 100%.

Heat Transfer

The heat gained by the feedwater in the heater is equal to the heat lost by the extraction steam. The only points that we have to watch are:

a) the steam to the feedheater may be very wet, up to 55%.
b) the condensate to the heater drains has a significant amount of subcooling, around 15 - 20°C.

Let's look at some examples and see how we can approach a feedheater calculation.

A feedheater is supplied with saturated steam at a pressure of 270 kPa(a) in the feedheater shell. There is no subcooling of the condensate. The feedwater inlet and outlet temperatures are 90°C and 118°C respectively. The feedwater flowrate is 588 kg/s. Determine the extraction steam flowrate.

There is nothing new in the approach to this problem. The only unknown is the extraction steam flow. If we use the relationship, heat gained by the feedwater = heat lost by the extraction steam, then we can find the one unknown.

Heat gained by the feedwater

This is equal to the mass flow per second multiplied by the change in enthalpy.

Inlet temperature is 90°C h_f = 376.9 kJ/kg.

Outlet temperature is 118°C h_f = 495.2 kJ/kg.

Change in enthalpy = $h_{f_{118}} - h_{f_{90}}$ = 495.2 - 376.9.

= $\underline{118.3}$ kJ/kg.

(The enthalpy of the feedwater is effectively only a function of the temperature, because the pressure effects are insignificant.)

The feedwater flowrate is 588 kg/s heat gained per second

= flow x enthalpy

= 588 x 118.3 = $\underline{69560}$ kJ

kg x kJ/kg.

Heat lost by extraction steam

The steam is saturated and there is no subcooling. If we look at the temperature/enthalpy diagram, we can see that the heat lost by the steam is in fact the latent heat of vapourization.

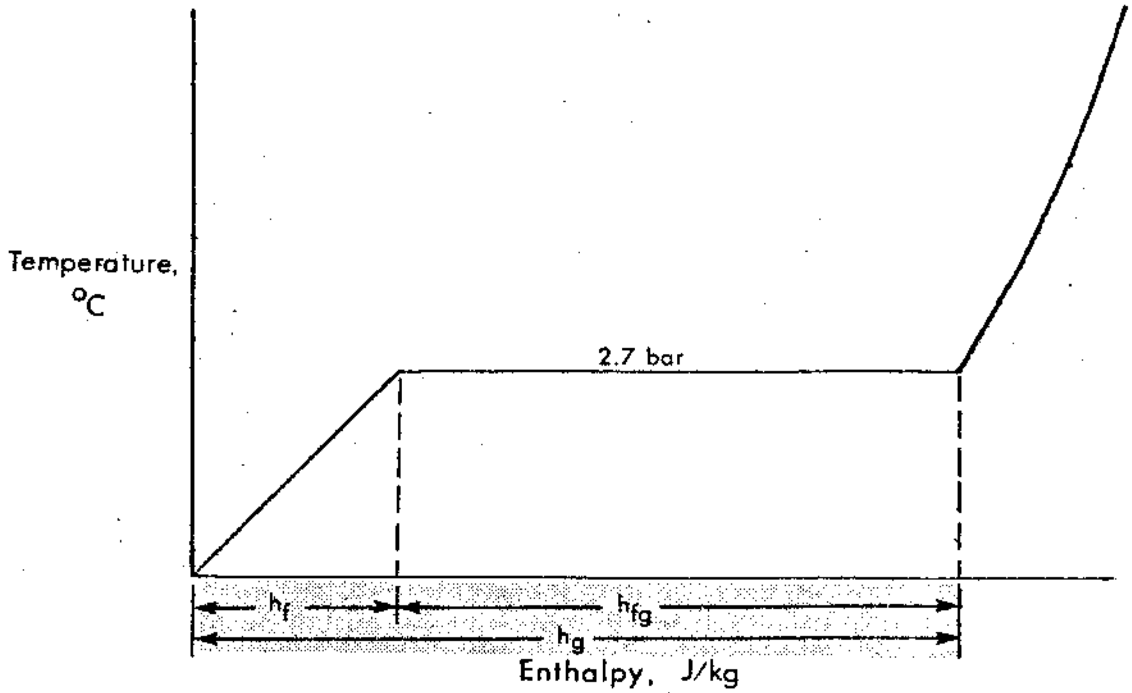

Fig. 3.2.1

At 270 kPa(a), ie, 2.7 bar, the value of h_{fg} = 2173.6 kJ/kg.

Heat lost by the steam per second is the product of the flow and the enthalpy change. Thus, heat lost by steam + $\overset{o}{m}$ x 2173.6 kJ per second, where '$\overset{o}{m}$' is the mass flowing per second.

Equating heat gained to heat lost:

$69560 = \overset{o}{m} \times 2173.6$ kJ

$\overset{o}{m} = 69560/2173.6$

$=$ <u>32 kg every second</u>.

In practice, the steam to the feedheater is usually 'wet' and the drains are subcooled. The only difference that this makes in the exercise is calculating the enthalpy drop of the extraction steam. Let's look at an example.

A feedheater is supplied with steam having a moisture content of 28%. The temperature in the feedheater shell is 103°C. The drains from the feedheater are at 87°C. The feedwater inlet and outlet temperatures are 58°C and 85°C and the flowrate is 521 kg/s. Determine the steam flow to the heater.

The heat gained by the feedwater per second is the product of the mass and the enthalpy change.

$$h_{f_{85}} = 355.9 \text{ kJ/kg}$$

$$h_{f_{58}} = 242.7 \text{ kJ/kg.}$$

$$\text{Change in enthalpy} = 355.9 - 242.7 \text{ kJ/kg}$$

$$= \underline{113.2} \text{ kJ/kg.}$$

Heat gained by the feedwater every second

$$= \text{mass x change in enthalpy}$$

$$= 521 \times 113.2 \text{ kJ}$$

$$= \underline{58977} \text{ kJ.}$$

The heat lost by the extraction steam which is initially 72% dry and is finally condensate, may be seen on the temperature/enthalpy diagram.

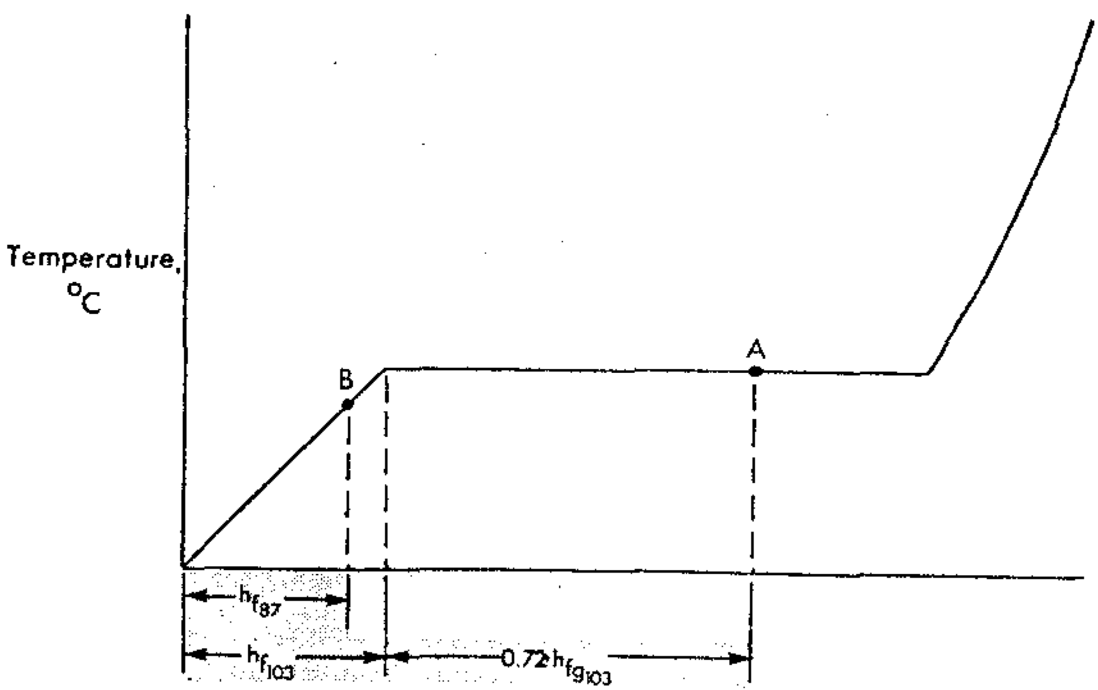

Fig. 3.2.2

$$\text{Enthalpy at point A} = h_{f_{103}} + 0.72\ h_{fg_{103}}$$
$$= 431.7 + 0.72 \times 2248.9$$
$$= \underline{2050.9}\ \text{kJ/kg.}$$
$$\text{Enthalpy at point B} = h_{f_{87}} = \underline{364.3}\ \text{kJ/kg.}$$
$$\text{Enthalpy change of steam} = 2050.9 - 364.3$$
$$= \underline{1686.6}\ \text{kJ/kg.}$$
$$\text{Heat gained by feedwater} = \text{Heat lost by steam.}$$
$$58977 = 1686.6 \times \overset{o}{m}\ \text{kJ.}$$
$$\overset{o}{m} = 58977/1686.6 = \underline{35}\ \text{kg/s.}$$

Try these problems and compare your answers with those at the end of the module.

B.3.2.9

A feedheater is fed with extraction steam from a turbine. The steam enters the heater shell at 180°C in a saturated condition. The drains from the heater are at 160°C. The feedwater inlet temperature is 150°C and the outlet is 174°C. The feedwater flowrate is 1000 kg/s.

Determine the steam flow to the feedheater.

B.3.2.10

Saturated steam enters a feedheater at 80°C and leaves as condensate at 66°C. The steam flowrate is 60 kg/s. The feedwater inlet temperature is 36°C and the flowrate is 850 kg/s.

Determine the feedwater outlet temperature from the heater.

Cycle Efficiency

The most efficient heat transfer in the steam generator occurs when the heat is transferred at constant temperature. In other words, when the steam generator is only supplying the latent heat of vapourization to change saturated liquid into saturated vapour.

In practice, this is not possible to achieve without a secondary source of heating. It follows that the greater the quantity of heat which has to be transferred in the steam generator to bring the liquid up to the saturation temperature, the more inefficient the cycle becomes.

If there was no feedheating, the steam generator would be fed with feedwater at around 35°C. This would mean that the steam generator would have to raise the temperature from 35°C to say 250°C before any latent heat could be added and therefore, before any vapour could be produced.

The feedheating system changes this picture considerably. It uses heat from the turbine to raise the temperature of the feedwater from 35°C to 175°C.

There is a second benefit in using feedheating. It is an opportunity to use thermal energy which would otherwise be rejected to the condenser cooling water system.

Around 70% of the reactor heat is thrown away in the CCW. This large quantity of heat is primarily accounted for by the remaining latent heat in the lp turbine exhaust, which must be removed to condense the large volume steam into a low volume liquid.

The steam turbine has a design limit of around 10 - 12% moisture beyond which rapid erosion would result.

The quality of steam entering a feedheater is of no significance from a heat transfer point of view. Consequently, the feedheater is able to handle moisture levels up to 50% and to raise the feedwater temperature using latent heat which is of no further use for producing work in the steam turbine.

B.3.2.11

a) If we can use the latent heat instead of rejecting it to the CCW, why don't we extract more steam from the turbine to heat the feedwater?

b) Maximum cycle efficiency occurs when the heat is added in the steam generator at 250°C. Why is the feedwater not heated to 250°C using extraction steam from the turbine?

B.3.2.12

If half of a nuclear power plant's feedheating capacity becomes unavailable, it might be necessary to reduce the electrical output. Explain two reasons why this might be necessary.

Compare your answers with the notes at the end of the module.

* * * * *

A numerical demonstration of the benefit of feedheating consists of making a comparison of the heat used in heating the feedwater compared with the heat lost as work from the turbine.

In this exercise, we have to make some assumptions and this is more easily done by trying to use conditions you would reasonably expect to find in a power plant. Let's have a look at a question of this type.

Demonstrate the benefits of using extraction steam. Compare the heat recovered with and without feedheating using saturated steam extracted from a turbine at 120°C. State any assumptions that are made.

Assumptions

1. Turbine exhaust temperature is 35°C.

2. 10% of the steam flow in the turbine is extracted for feed heating.

3. Assume turbine exhaust is 10% wet.

4. Assume no subcooling in the condenser.

In this question, we have two conditions to examine:

a) with no feedheater
b) with feedheating.

In both cases, we **must consider the turbine work as recovered heat.**

Case 1 No feedheating

In this case, we have the turbine work of 100% steam flow with saturated steam at 120°C expanding to 10% moisture at 35°C PLUS the heat in the condensate.

The change in enthalpy of the steam may be seen by looking carefully at the temperature enthalpy diagram. I say 'carefully' because you can save a lot of work by identifying the heat which is rejected from the system and the heat which is recovered.

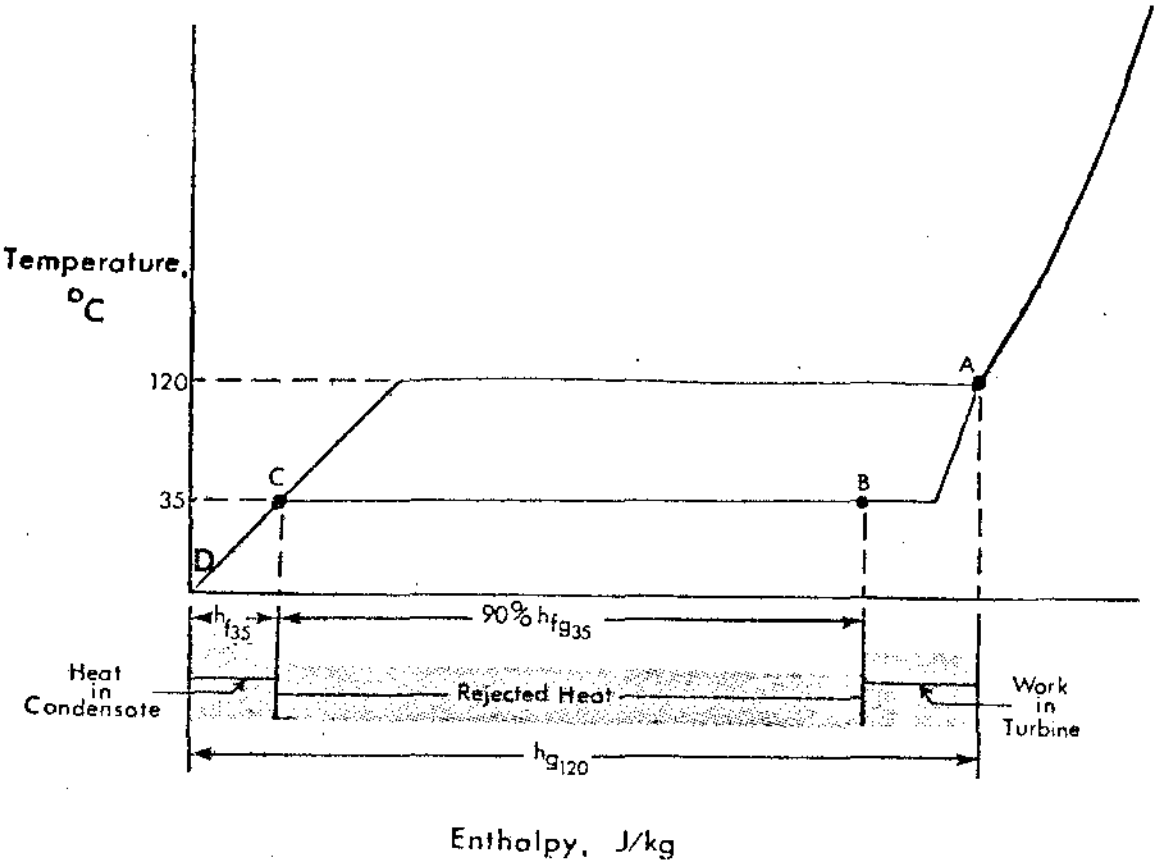

Fig. 3.2.3

The steam in the turbine at point A is saturated and expands to 10% moisture at point B. This change in enthalpy is recovered as work in the steam turbine. From point B to point C, heat is being rejected at constant temperature in the condenser as the remaining latent heat of vapourization is being removed. From point C to point D, nothing happens and this heat is returned to the feed system via the hotwell.

So you can see, the only heat which is lost from the system is the remaining latent heat of vapourization.

If we consider 1 kg of steam, the recovered heat is

$$h_{g_{120}} - 0.9\ h_{fg_{35}}$$

$$h_{g_{120}} = 2706 \text{ kJ/kg},$$

$$h_{fg_{35}} = 2418.8 \text{ kJ/kg}.$$

$$\text{Recovered heat} = 2706 - (2418.8)\ 0.9 \text{ kJ/kg}$$

$$2706 - 2176.9$$

$$= 529.1 \text{ kJ/kg of steam at } 120°\text{C}.$$

Case 2 With feedheating

This case is slightly more complicated because we have to consider 10% of the steam flowing to the feedheater and the remaining 90% to the turbine. We have already done the turbine portion so let's get that out of the way.

Still using 1 kg of steam, if we reduce the turbine steam to 90%, we will only get 90% of the recovered heat.

Heat recovered from turbine with feedheating is 90% of that recovered without feedheating.

Heat recovered = 0.9 x 529.1 kJ/kg

= 476.2 kJ/kg of steam at 120°C.

Consider the feedheater to which 10% of the steam is now flowing from the turbine. Again look at the temperature/enthalpy diagram for heat recovered.

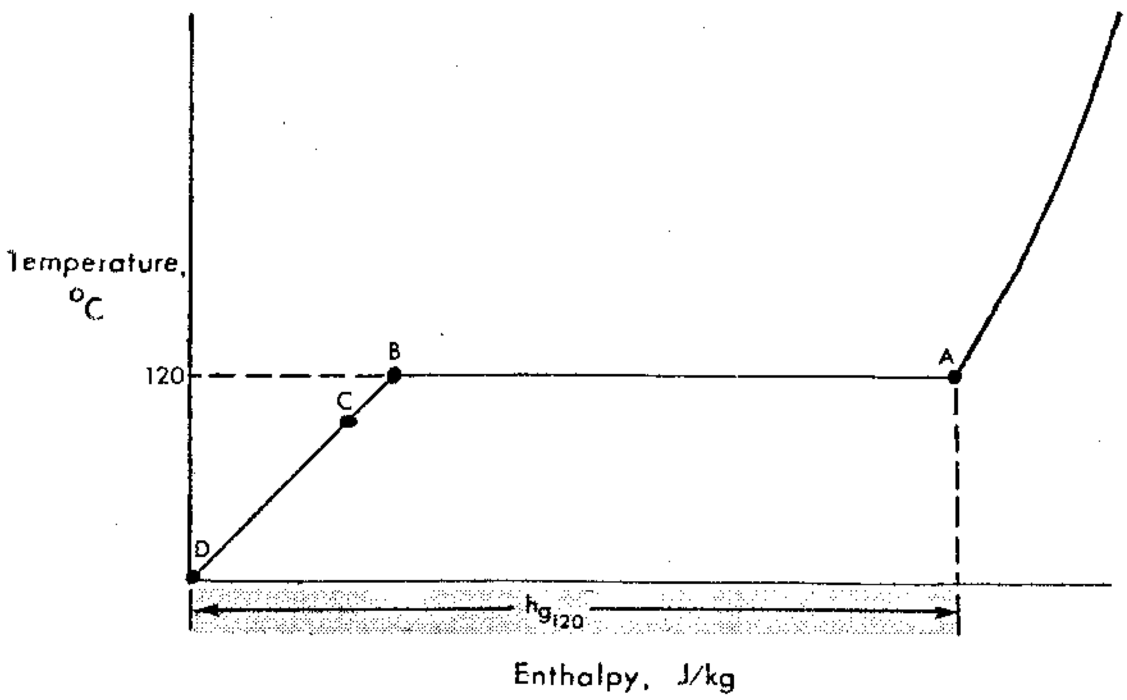

Fig. 3 2.4

The steam enters the heater at A and is condensed to point B if no subcooling or point C if subcooling occurs. The heat in the heater drains C-D remains in the feedwater system. So no heat is lost. All the heat sent to the feedheater is recovered. The heat in the steam is h_{g120} which is 2706 kJ/kg. If we consider one kg, we only have 10% of this heat. Consequently, the heat recovered in the feedheater is 270.6 kJ/kg.

Total recovered heat with feedheating is the turbine work plus heat recovered in the feedheater.

ie, 476.2 + 270.6

= 746.8 kJ/kg of steam at 120°C.

Primarily, we have gained on latent heat of vapourization which would otherwise have been rejected to the CCW. Heat recovered from turbine operation was reduced by 52.9 kJ/kg but the feedheating showed a recovered heat value of 270.6 kJ/kg.

If your immediate reaction is that we should do a lot more feedheating, remember my earlier remarks concerning numbers of heaters with increase in efficiency and use of high quality steam for heating. There is an optimum level above which an increase in feedheating capacity shows no increase in efficiency but the numerical exercise uses the thermodynamic principles upon which feedheating is based.

Try these questions and compare your answers with the notes at the end of the module.

B.3.2.13

Explain why steam is extracted for feedheating and not allowed to do further work in the steam turbine.

B.3.2.14

Saturated steam is supplied to a feedheater at 180°C. Demonstrate the benefit of feedheating by considering two cases:

a) a steam turbine without feedheating
b) a steam turbine with one feedheater and compare the heat recovered in each case. Use a temperature/enthalpy diagram to explain your reasoning.

Consider this one heater to utilize 20% of the steam entering the turbine. State all other major assumptions made.

* * * * *

When you feel that you are ready for the Criterion Test, obtain the test from the Course/Shift Manager. Upon completion of the test, request the self evaluation sheet and compare with your test. Finally, have the Manager review your work so that you may identify areas to be reinforced or progress to Module B.3.1.

Answers

MODULE B.3.2

FEEDHEATER OPERATION

B.3.2.1

The pressure in the cylinder would start to fall. The reason for this is that as the temperature of the liquid falls, so does the volume that the liquid occupies. The molecules do not vibrate so rapidly as the temperature decreases and they effectively occupy a smaller volume.

This is exactly the situation that we have with the PHT system and to overcome the problem of changing pressure, we remove some mass of D_2O when the temperature rises and we add some mass of D_2O when the temperature falls. This is done with the feed and bleed system.

B.3.2.2

If you said that the pressure increases or decreases you could be right but with qualification.

If you really thought about this from the moment you shut the engine down, you would have this sequence of events:

a) Initially, hot engine and then loss of coolant flow as water pump and fan are shut down.

b) Short term imbalance occurs due to the heat from the engine not changing dramatically whilst the heat rejection from the cooling water via the radiator decreases significantly. As a result, the temperature starts to rise.

c) As the temperature rises, the liquid expands and the system pressure increases until the pressure relief valve allows the system pressure to force the excess fluid into a reservoir.

d) As the engine starts to cool down, the coolant system is losing more heat than is being supplied because the engine is no longer supplying heat, being shutdown. As the temperature falls, so does the pressure. Eventually, the pressure in the coolant system becomes below atmospheric and atmospheric pressure is able to force fluid back into the coolant circuit to make up for the fluid contraction which has taken place.

This is a familiar pattern of events when looking at a closed fluid heat transfer system. How many closed fluid heat transfer systems could you come up with?!

B.3.2.3

In this example, the pressure is falling because heat is being removed from the system.

The propane vapour is generated by adding latent heat to the saturated liquid in the tank. The heat that vapourizes the liquid, flows into the tank from the outside. If the rate of vapour production uses latent heat at a greater rate than the heat is available from the atmosphere, then the temperature of the tank contents start to fall and of course, so does the pressure. If the usage is heavy, then the temperature will fall down to the dew point when condensation will appear on the tank and then down to the frost point when the moisture on the outside of the tank freezes. At this point, the system pressure is rapidly approaching atmospheric pressure when no gas flow would be available at all because there would be no pressure difference.

B.3.2.4

Consider a feedheater that is pressurized with steam from the turbine but has no feedwater flow. In this situation, no heat is being transferred from the extraction steam to the feedwater.

If the feedwater flow is established, the extraction steam will condense on the feedheater tubes as the latent heat is removed. This condensation process results in a local reduction in pressure around the tubes and initiates some steam flow.

This process of condensation continues to lower the heater shell pressure and temperature until the extraction steam reaches a flowrate when the heat provided by the steam from the turbine matches the heat removed by the feedwater.

At this point, the temperature and pressure in the feedheater will be at lower values and the feedwater temperature will have increased.

This process is happening all the time creating a self regulation effect so that the heat removed always balances the heat supply.

B.3.2.5

As the unit power is raised from 50% to 100%, two major changes take place on the feedheater. As the steam flow through the turbine increases so do the extraction steam pressures which means that the temperatures in the shell of the heaters have also increased.

Secondly as the steam flow increases, so does the feedwater flow to the steam generator and so heat is being removed at a greater rate than before.

Both these causes will create a larger extraction steam flow to the heaters together with a significant increase in feedheating.

B.3.2.6

It is probably easier to draw up a table of heater conditions and then write an explanation for the changes.

		Feedwater	Steam
Flowrate		Decrease(G)	Decrease
Inlet Temp	1	Same(G)	Increase
Outlet Temp	2	Increase	N/A
Feedwater $\Delta T(2-1)$		Increase	N/A
Pressure		N/A	Increase

(G) Information Given

The rate of heat removal from the feedheater decreases with the reducing feedwater flowrate. The effect is an energy imbalance because the extraction steam is providing more thermal energy than is being removed.

As a result, the temperature in the steam space starts to rise. As the temperature rises, so does the pressure. The effect of the rising pressure is to reduce the pressure differential between the turbine and the feedheater and the extraction steam flow is reduced as a result.

Why does the feedwater outlet temperature rise in this situation? There are two reasons, one more significant than the other. In any heat transfer operation, the amount of heat which is transferred is a function of temperature difference and time.

At the lower flowrate, the feedwater velocity is slightly reduced which means that there is slightly more time available for the feedwater outlet temperature to move towards the feedheater steam temperature.

More significantly, as the temperature in the steam side of the feedheater rises, there becomes a larger difference between the steam temperature and the average feedwater temperature and more heat is transferred. In this way, the ΔT for the feedwater has increased across the heater although the inlet temperature remained constant and the feedwater flowrate decreased.

B.3.2.7

In this exercise, the feedwater flowrate is going to remain constant. If we remove the number two heater, the number 3 heater will receive feedwater at a temperature much lower than normal. The effect of this low inlet temperature will be that heat energy will be transferred at a higher rate from the high temperature in the steam space to the lower temperature feedwater.

There is now an energy imbalance where more heat is being removed from the feedheater than is being supplied and the temperature in the steam space starts to fall. As the temperature in the steam space drops, so does the pressure and more extraction steam flows from the turbine to the heater.

In summary conditions on #3 heater will be as follows:

1. Heat transfer and extraction steam flow will increase.
2. Temperature and pressure in the steam space will decrease.
3. Feedwater outlet temperature will fall.
4. Feedwater temperature rise across the heater will increase.

B.3.2.8

Some significant changes occur with the extraction steam and the feedwater when the turbine power is raised from 50% to 100%.

As the governor steam valves open up, less and less throttling takes place until the point is reached when the GSVs are fully opened and there is no throttling at all across the GSVs.

At this point the steam pressure at the emergency stop valves is being evenly dropped across the whole of the turbine down to condenser pressure instead of having a major pressure drop across the GSVs.

As a result of this change, all the stage pressures in the turbine have increased including those at the extraction steam points.

A higher pressure differential now exists to the feedheaters. More extraction steam flows to the heaters which means that more heat is being supplied to the feedheaters than is being removed by the feedwater and the shell temperature rises which means that the shell pressure also rises.

The higher temperature in the steam space increases the heat transfer to the feedwater and the feedwater outlet temperature on all the heaters increases.

As a result of increasing the steam flow through the turbine, there will be a demand for higher feedwater flow into the steam generator.

The effect of increasing the feedwater flow through the heaters will further increase the rate of heat transfer and the extraction steam flow will increase further to match this new thermal load.

In practice, these two conditions are happening at the same time. Probably the only parameter which does not change dramatically is the condensate temperature from the condenser.

In summary, the extraction steam flows will increase, the feedwater flow will increase, the feedwater outlet temperatures from the heaters will increase, the feedwater temperature rise across the heaters will increase, the pressure and temperature in the steam space of the heaters will increase.

B.3.2.9

Using the temperature/enthalpy diagram, we can see that the heat lost by the steam is the difference between h_{g180} and $h_{f160°C}$.

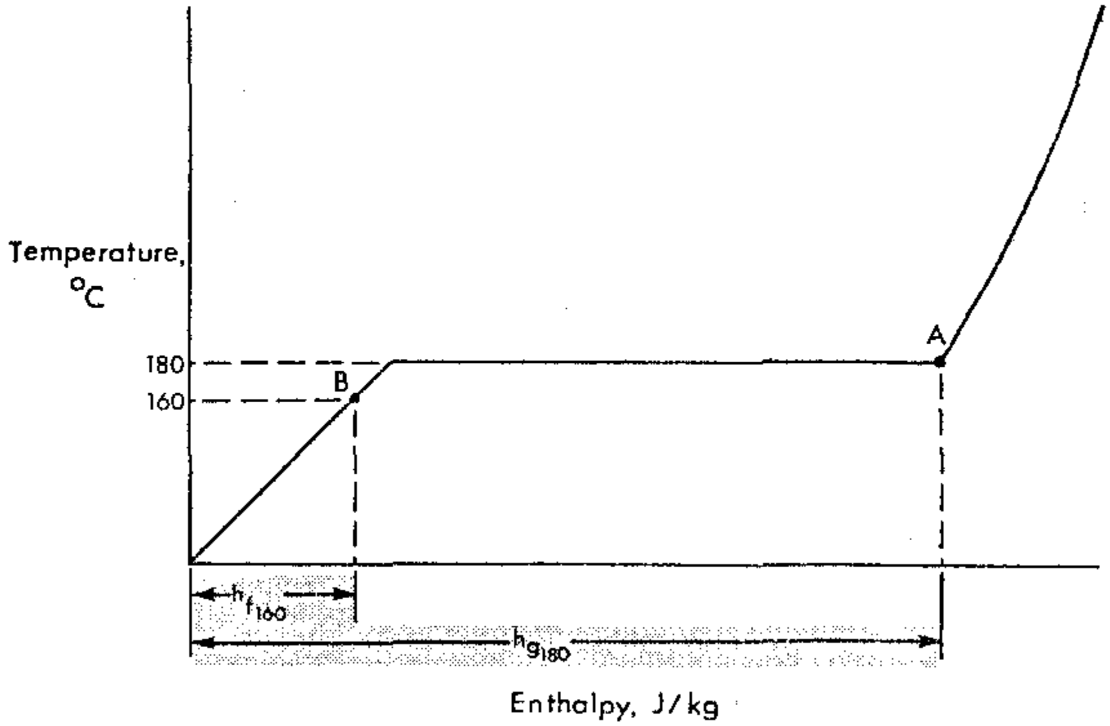

Fig.3.2.5

Enthalpy difference of the steam $= h_A - h_B$

$= h_{g180} - h_{f160}$

$= 2776.3 - 675.5$

$= \underline{2100.8}$ kJ/kg.

Heat lost by steam $= \underline{\overset{o}{m} \times 2100.8}$ kJ per second.

Heat gained by the feedwater $= h_{f174} - h_{f150}$

$= 736.7 - 632.1$

$= \underline{104.6}$ kJ/kg.

Heat gained per second = Mass x enthalpy change

$= 1000 \times 104.6$

$= 104600$ kJ.

The heat lost by the steam = heat gained by the feedwater

$$\overset{o}{m} \times 2100.8 = 104600 \text{ kJ}$$

$$\overset{o}{m} = 104600/2100.8$$

$$\overset{o}{m} = \underline{49.8} \text{ kg/s.}$$

B.3.2.10

In this example, we know everything about the steam and have to find the feedwater temperature.

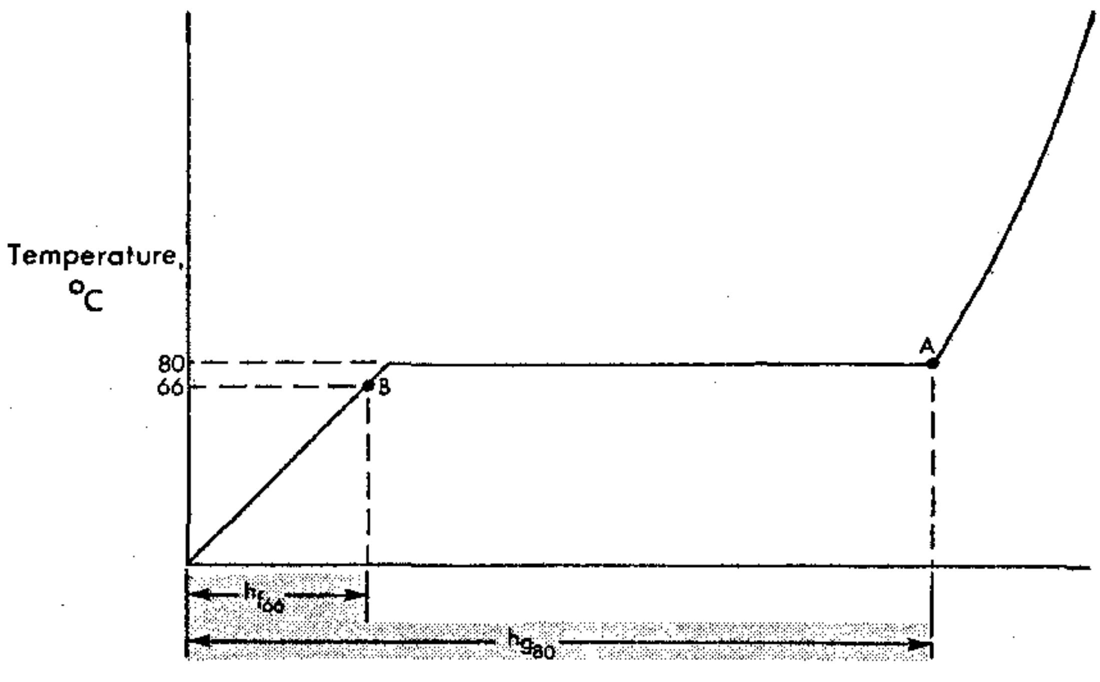

Fig. 3.2.6

Change in enthalpy of steam to condensate is $h_{g_{80}} - h_{f_{66}}$

$$h_g = 2643.8 \text{ kJ/kg}$$

$$h_{f_{66}} = 276.2 \text{ kJ/kg.}$$

$$\text{Change in enthalpy} = 2643.8 - 276.2$$

$$= \underline{2367.6} \text{ kJ/kg.}$$

Heat lost by steam per second

$$= \text{mass x enthalpy change}$$

$$= 60 \times 2367.6$$

$$= \underline{142056} \text{ kJ.}$$

Heat gained per second by the feedwater

$$= \text{mass x enthalpy change}$$

$$= \text{mass x } (h_{f_x} - h_{f_{36}})$$

$$= 850 \times (h_{f_x} - 150.7) \text{ kJ.}$$

$$\text{Heat lost by steam} = \text{Heat gained by feedwater}$$

$$142056 = 850 \times (h_{f_x} - 150.7) \text{ kJ}$$

$$142056/850 = h_{f_x} - 150.7 \text{ kJ}$$

$$167.1 = h_{f_x} - 150.7$$

$$\therefore h_{f_x} = \underline{317.8} \text{ kJ/kg.}$$

'x' is temperature corresponding to a liquid enthalpy value of 317.8 kJ/kg.

From table 1, x = 76°C when h_f = 318 kJ/kg.

B.3.2.11

a) Although there is a lot of low temperature heat available that would normally be rejected to the CCW, it is of little use in heating the feedwater. The reason for this is simply that the temperature of the steam is very close to that of the condensate so the amount of heat which may be transferred is extremely limited.

To obtain better heat transfer, we can use higher temperature steam but as steam is extracted at higher and higher temperatures, the turbine work lost to feedheating increases. There is an economic point beyond which feedheating is of no further benefit. In the Candu system, this optimum occurs when the feedwater temperature is around 175°C.

b) Before we examine this principle any closer, let's make a statement of fact.

"It is impossible to raise the temperature of the feedwater to 250°C using heating steam which is also at 250°C."

So, why can't we heat the feedwater to 240°C? In practice, the feedwater outlet temperature is roughly 4°C *below the extraction steam temperature to the heater*. If we wanted feedwater at 240°C, then we would have to use steam at 244°C.

This situation creates a conflict of interest. We want to maximize the cycle efficiency by raising the feedwater temperature but we also want to use the high temperature steam in the turbine where it is of most benefit in producing work.

B.3.2.12

The action that would follow a significant loss of feedheating capacity depends largely upon where in the feedheating cycle the loss occurs.

If the loss occurs in the early part of the feedheating system, then it is possible for a large proportion of the heat loss to be picked up in the following heaters.

It should be realized that this will dramatically change the extraction steam flow distribution and more high quality steam will be used for feedheating instead of turbine work. Thus, it may be possible to maintain a reasonable feedwater temperature into the steam generator but at the expense of power in the higher pressure end of the turbine and consequently, electrical power would be reduced.

The main point to consider is the thermal shock to the steam generator feedwater nozzles. When the temperature difference is large between the steam generator temperature and the feedwater temperature, the thermal stresses become an *overriding parameter. An operating limit, of temperature* difference, ensures that permanent damage does not result. A reduction in steam flow and hence feedwater flow is the only way to reduce the temperature difference at the feedwater nozzles. This reduces the feedwater flow through the feedheaters which raises the feedwater temperature.

If the feedheating was unavailable at the high temperature end of the system and temperature differences in the boiler were not a problem, the loss of heating would have to be provided by the PHT system in the steam generator. The average temperature and pressure in the steam generator would fall, assuming reactor power is constant and in a reactor leading program, the BPC program would sense a mismatch and reduce the turbine load.

The loss of feedheating would provide more steam flow to the condenser and would cause a mismatch between the heat lost by the steam and the heat gained by the CCW system. Even if the vacuum deloader did not operate, an increased pressure in the condenser would reduce the steam flow through the turbine. Would the turbine power level change?!

B.3.2.13

When the steam is exhausted from the turbine, it still possesses around 80% of its heat, the majority of which will be rejected to the CCW in the condenser and the rest will be returned to the system in the feedwater.

If we can use some of the heat which is going to be rejected to the CCW, then the savings are obvious. We can show by simple calculation that although a small amount of turbine work is lost, a considerable amount of heat is gained from the extraction steam.

As the steam temperature increases, the penalty in lost turbine work also increases when using high temperature steam for feedheating.

The closer the feedwater is to the saturation temperature in the steam generator, the more efficient the cycle becomes. Typically, the saturation temperature is 250°C but it is not only impossible to heat the feedwater to 250°C using steam at 250°C but is is not economically viable to heat it above 175°C. The temperature of 175°C represents the economic cut-off temperature above which the penalty of using high temperature steam becomes unacceptable.

B.3.2.14

First of all, state your assumptions - all of them!

a) Turbine exhaust temperature is 35°C.

b) Turbine exhaust moisture is 10%.

c) No subcooling occurs in the condenser.

d) 20% of the steam flow in the turbine is extracted for feedheating.

Case 1 No feedheating

The conditions may be shown on a temperature/enthalpy diagram showing saturated steam at 180°C expanding to 10% moisture at 35°C.

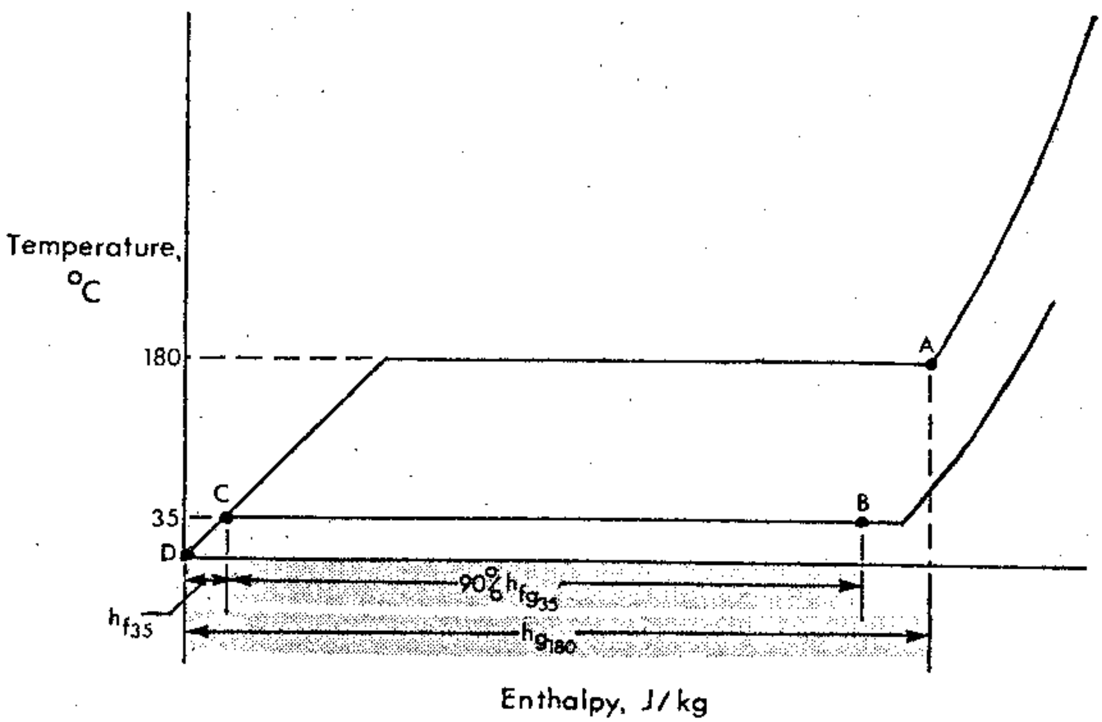

Fig. 3.2.7

The enthalpy change from point A to point B represents the work done in the turbine. The enthalpy drop from point B to point C is the heat rejected to the CCW system and the enthalpy C-D is the heat energy remaining in the condensate in the hotwell and is returned to the feedwater system.

The loss of heat is the 90% of the latent heat at 35°C. So the recoverable heat is $h_{g_{180}} - 0.9\ h_{fg_{35}}$

$= 2776.3 - 0.9\ (2418.8)$

$= 2776.3 - 2176.9$

$= \underline{599.4}$ kJ/kg of steam at 180°C.

This represents both the heat in the condensate and the work done in the turbine.

Case 2 With feedheating

There are two areas to cover:

a) the turbine work and condensate.
b) the feedheater operation.

a) Turbine Work and Condensate

If the flow through the turbine is reduced by 20%, then the work and condensate will show a 20% reduction of recoverable heat.

Recoverable heat from the turbine and condensate with 20% extraction steam = 0.80 x 599.4

$= \underline{479.5}$ kJ/kg of steam at 180°C.

b) The Feedheater

We can see how much recoverable heat is available from the feedheater by drawing the temperature/enthalpy diagram.

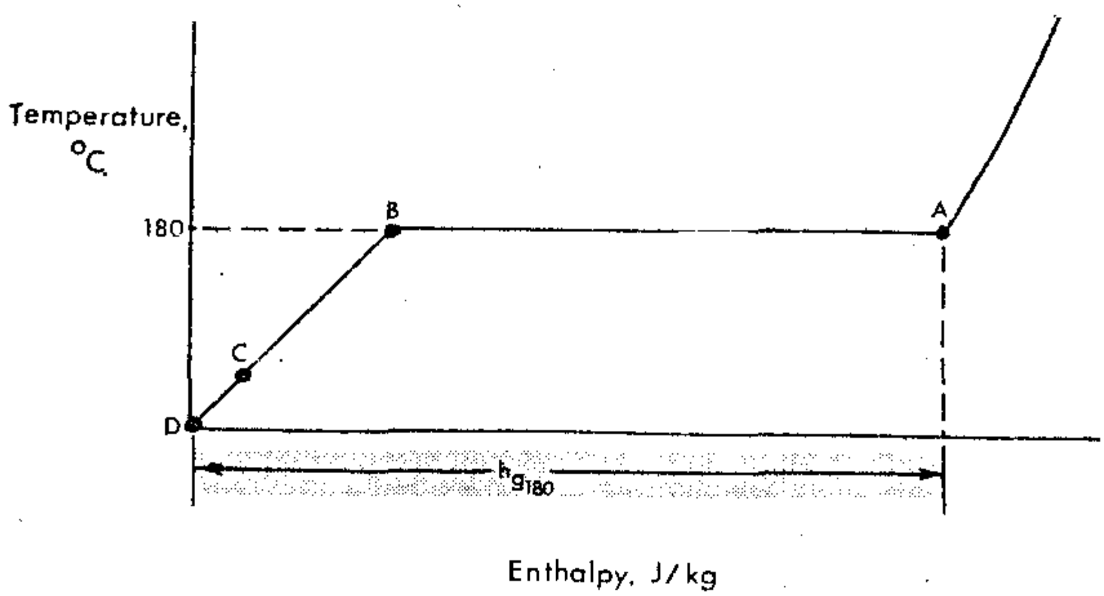

Fig. 3.2.8

The enthalpy change from point A to point B is the heat gained by the feedwater and lost by the steam. The enthalpy change from point B to C represents the heat given to the feedwater and subcooling the heater drains. The enthalpy C-D is the remaining heat in the drains from the heater and this remains in the system. So the total heat in the steam is recovered.

$$h_{g_{180}} = \underline{2776.3} \text{ kJ/kg.}$$

The heat gained for 20% of 1 kg is

$$0.20 \times 2776.3 = 555.3 \text{ kJ.}$$

Thus the total recoverable heat with feedheating per kilogram of steam entering the turbine is

$$479.5 + 555.3 = \underline{1034.8} \text{ kJ}$$

compared with 599.4 kJ without feedheating.

J. Irwin-Childs

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HEAT & THERMODYNAMICS

MODULE B.3.1

CONDENSER PERFORMANCE

Heat & Thermodynamics

MODULE B.3.1

CONDENSER PERFORMANCE

Course Objectives

1. You will be able to explain four advantages of using a condenser instead of rejecting the exhaust steam to atmosphere from a steam turbine.

2. You will be able to explain the changes which occur to pressure and temperature when steam or CCW flowrate conditions change in the condenser.

3. You will be able to list a sequence of steps designed to eliminate the causes of increased condenser pressure. You will be able to explain the reasoning for each step.

4. You will be able to explain two undesirable consequences for each of the following conditions:

   a) operating the condenser above design pressure
   b) operating the condenser below design pressure.

5. Given condenser conditions relating to steam and cooling water, you will be able to calculate either the CCW flow or the steam flow.

In this module, we will be looking at condenser performance and examining some of the basic concepts of condenser operation. In many respects, the feedheater and condenser have a lot in common. They both remove heat from steam using a liquid coolant.

Why do we need a condenser? It's a simple question that has a more complicated answer. You may say that the condenser is in the design to allow the cycle efficiency to be optimized. That's not altogether true! The fact that we do use a condenser does allow us to maximize the efficiency of the cycle, but that is not the prime reason for using a condenser.

If we did not bother to collect the exhaust from the turbine and return it to the system, the costs of operating a unit would be very high.

We would be throwing away hot demineralized water at the rate of around 1000 kg every second. This is obviously an impractical situation. The size of the water treatment plant and storage would be enormous.

It is an advantage to retain the working fluid within the system. The need for phenomenal quantities of treated water is eliminated and some of the remaining heat in the cooling fluid is recovered.

After the steam turbine, the working fluid is returned to the boiler for heating. The boiler is at a much higher pressure than the turbine exhaust so we must raise the pressure of the working fluid to a higher pressure than the boiler in order that the working fluid can flow into the boiler.

This creates a basic problem. The exhaust steam from the turbine exhaust has a very large volume, even at atmospheric pressure and the easiest way of raising the pressure of the exhaust steam is to use a compressor. The problem with this concept is that the compressor would be extremely large, due to the large steam volume, and would consume vast quantities of power.

If we could reduce the volume of the working fluid and pump liquid instead of vapour, the problems would be much more acceptable.

The condenser allows the volume of the working fluid to be reduced dramatically; a reduction in volume of around 28000 to 1, ie, 1 kg of steam at low condenser pressure occupies around 28000 liters. When condensed, the final volume is 1 liter.

The price that we have to pay for this reduction in working fluid volume is that we must reject around 66% of the total reactor power or sensibly twice the turbo-generator power. This heat which appears in the CCW is the latent heat of vapourization from the turbine exhaust steam which had to be removed for condensation to saturated liquid to occur. We do manage to keep the remaining sensible heat in the resulting condensate in the condenser hotwell.

Before we move on, answer the question below and check your answer with the notes at the end of the module.

B.3.1.1

Explain the function of the condenser and describe three advantages that arise from a plant design using a condenser.

* * * * *

Cycle Efficiency

Having made a decision to use a condenser, we are now faced with another problem. At what temperature should the condenser operate?

Thermodynamically, we can get the best use from the steam when the temperature difference between the steam in the steam generator and the steam in the condenser is at maximum.

In practice, the type of nuclear fuel that is used dictates that the steam temperature is around 250°C as we will discuss in more detail in Module B.1. When we look at making the exhaust temperature in the process as low as possible, we find that there are constraints on this option as well.

It is a fact that we cannot condense the exhaust steam at a lower temperature than the cooling water. In the summer time, the CCW inlet temperature may be fairly high in relation to winter when the temperature may hover around the freezing mark. These two conditions represent the range of temperature that we would expect to see. In practice, the system is designed around some temperature between the two extremes.

Suppose the mean temperature, ie, the average between the CCW inlet and outlet temperatures, was 15°C. Does this mean that the temperature of the steam in the condenser will be 15°C under operating conditions? The answer is that if condensation is to occur, the latent heat of vapourization has to "flow" from the condenser steam space to CCW system. Therefore, there has to be a temperature difference between the steam and the average CCW temperature.

In practice, the lowest temperature in the condenser is around 33°C and this is the temperature for which the condenser heat transfer will be designed.

The potential cycle efficiency is now fixed based upon a maximum temperature of 250°C steam and an exhaust temperature of 33°C. Obviously, these temperatures will vary from station to station but the principle is still valid.

You can see now why I said that having the condenser to maximize the efficiency wasn't altogether the true picture. We needed the condenser to return the working fluid to the steam generator, and having made that choice, we then were able to optimize the efficiency.

Answer the following question and check your answer with the notes at the end of the module.

B.3.1.2

Explain why steam is not expanded to 10°C in the turbine when the CCW inlet temperature is 0°C.

* * * * *

Heat Transfer

I am going to look at the condenser in exactly the same way as we examined the feedheater. I will use a single condenser tube to illustrate the ideas so that we can visualize what is happening in practice.

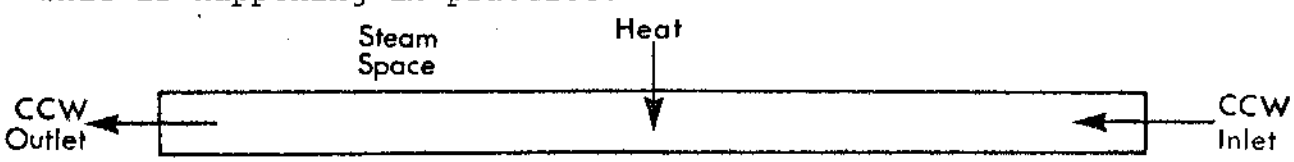


Fig. 3.1.1

Let's just take a look at the diagram. The tube represents one condenser tube through which the CCW is travelling and through the walls of which the heat flows from the steam to the CCW. The amount of heat which is able to flow from the steam space in the condenser to the CCW depends upon the difference which exists between the steam temperature and the average temperature of the CCW. In practice, the heat transfer is more complex than this but a simplistic approach will allow a clearer understanding of the concept.

The average CCW temperature = $\frac{\text{Outlet + Inlet}}{2}$.

Consider the steady state situation in the tube. The temperature in the steam space is T_s and the average temperature of the CCW is T_{wa}. T_s is greater than T_{wa} and heat is flowing from the steam space to the CCW in proportion to ($T_s - T_{wa}$).

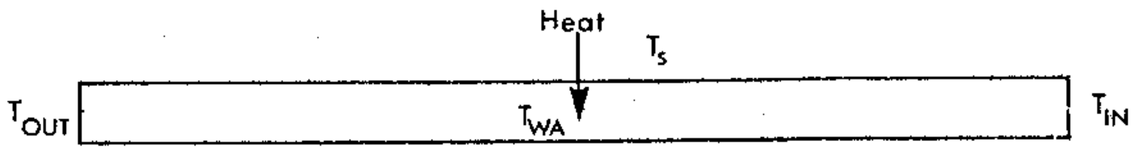


Fig. 3.1.2

The temperature rise across the condenser tube is $T_{out} - T_{in}$. The pressure which exists in the steam space is the saturation pressure for temperature T_s.

Let's consider several changes in the system and examine the effects on the rest of the system.

CCW Inlet Temperature Increases

Initially, the heat transferred will stay constant. Suppose the CCW inlet temperature rose by 4°C, then the outlet temperature would rise by the same amount because initially, the same amount of heat would be transferred. What happened to the average CCW temperature T_{wa}? If the inlet temperature rose by 4°C and the outlet temperature rose by 4°C, then T_{wa} would rise by 4°C.

What has happened to the temperature difference ($T_s - T_{wa}$)? As the average CCW temperature has risen, so the temperature difference has decreased and less heat is being transferred.

Exhaust steam is still entering the condenser at the same rate but the heat rejection rate to the CCW has decreased. What will be the effect of this energy imbalance? How does it affect the condenser? The temperature in the steam space will rise. What will happen to the condenser pressure? It will rise with the rising temperature to maintain the saturation pressure corresponding to the temperature.

As the condenser pressure rises, the difference in pressure from the GSVs to the condenser decreases which means that the steam flowrate through the turbine decreases until the heat entering the condenser is once again equal to the heat leaving via the CCW system.

The changes may be reflected by recording in table form.

	Steam	CCW
Flowrate	Decrease	Same
Inlet Temp	X	Increase
Outlet Temp	X	Increase
Ave Temp	Increase	Increase
Pressure	Increase	X

Answer this question and compare your response with the notes at the end of the module.

* * * * *

B.3.1.3

Explain how temperatures, pressure and flowrates are affected in a condenser when the CCW inlet temperature falls. Summarize your answer in table form.

CCW Flowrate Increases

To examine the effect of change, we initially must assume that the rest of the system remains at the same level of operation. If the CCW inlet temperature remains constant and the heat rejected from the condenser remains constant, the effect of increasing the CCW flowrate will be to lower the CCW outlet temperature. This is because with the increased flowrate, each kilogram of CCW will pick up less heat and therefore there will be less temperature rise.

The falling CCW outlet temperature lowers the average CCW temperature which increases the temperature difference between the CCW and the condenser steam space and more heat flows to the CCW. There is now an inequilibrium because heat is being removed at a greater rate than it is being supplied and the temperature in the steam space starts to fall. The condenser pressure falls with the temperature and the steam flow into the condenser increases because of the larger pressure differential across the turbine.

The system finds a new operating point with a lower CCW outlet temperature, lower condenser pressure and temperature, together with an increased steam flow.

	Steam	CCW
Flowrate	Increase	Increase
Inlet Temp	X	Same
Outlet Temp	X	Decrease
Ave Temp	Decrease	Decrease
Pressure	Decrease	X

Answer the following question and compare notes at the end of the module.

B.3.1.4

The steam flow into a condenser is increased from 50% to 100% whilst the CCW inlet temperature and flowrate remain constant. Explain the changes you would expect and list the changes in table form.

* * * * *

A condenser is designed to operate at a particular pressure. This pressure is used to optimize the turbine performance. Deviations from the design value of condenser pressure can create problems as we will see later on. One of the first indications of change in the condenser performance is a change in condenser pressure for which there may be several reasons.

Reduction of CCW Flowrate

This situation may occur because the condenser tubes are blocked or because of the loss of a CCW pump. The result will be an increased CCW outlet temperature which will raise the CCW average temperature and result in a higher temperature and pressure in the steam space. There will be no difference between the condensate temperature and the condenser exhaust temperature.

This may also be due to accumulated gas in the water boxes which may be determined by checking the vacuum priming system.

Fouling of the Heat Transfer Surfaces

Fouling is due to contaminants being deposited on the heat transfer surfaces. Contaminants may be oil, corrosion scale, or other deposits on either the CCW side or the steam side of the condenser tubes.

The effect of fouling means that a larger temperature difference is required to overcome the increased thermal resistance. The CCW outlet temperature does not change significantly, but the temperature and pressure in the steam space will have increased. There will be no difference between the condensate temperature and turbine exhaust temperature.

Change in CCW Inlet Temperature

The change in inlet temperature will be seen by a corresponding change with the CCW outlet temperature and a corresponding change in the CCW average temperature.

If the CCW inlet temperature rises, then the CCW outlet temperature and CCW average temperatures also rise. This results in an increase in pressure and temperature in the steam space. There will be no difference between the condensate temperature and the exhaust temperature.

Air Ingress

If air is drawn into the condenser, it impairs the heat transfer on the steam side because the air collects around the condenser tubes where it was left by the condensing steam. If air leakage does occur, it will reduce the cooling surface area available for condensing the steam.

The pressure in the condenser is equal to the sum of the partial pressures due to all the gases and vapours. In normal circumstances, there is so little air and other gases, the pressure is sensibly only due to the steam.

If air is now introduced, the pressure rises and the condenser pressure is due to the pressure of the steam plus the pressure due to the air. The saturation temperature for the steam only depends upon the partial pressure due to the steam. This provides a means of checking whether the increase in condenser pressure is due to air or some other cause.

If there was no subcooling, as there should not be in the condenser, the temperature of the condensate would be equal to the saturation temperature corresponding to the pressure.

If air has entered the condenser, the pressure will be higher than that indicated by the condensate temperature. If the condensate temperature was 35°C and the condenser pressure was 70 kPa(a), then there is a very strong possibility that air has entered the condenser and is impeding heat transfer. If there was no air present, the condensate temperature would be t_{sat} at 70 kPa(a), t_{sat} = 39°C.

Another indication of air ingress is a decrease in the exhaust temperature into the condenser although the condenser pressure will have risen. The greater the % air in the condenser, the more exaggerated this effect becomes.

A giveaway for air ingress is a marked increase in dissolved oxygen in the condensate.

Flooding of Condenser Tubes

If a problem of level control arises in the hotwell, the heat transfer surfaces may become flooded with condensate. This flooding produces two effects:

a) There is a significant degree of subcooling of the condensate.

b) There is a reduction in the heat transfer surface available for condensing the steam.

This event would result in an increase in temperature and pressure in the steam space. The CCW outlet temperature would be increased and the condensate would be well subcooled.

A table of changes, relative to the "normal" condenser conditions may be a useful guide to determining cause for the increase in condenser pressure. The table assumes that nothing else has changed in the system.

Changing Condition	1 CCW Inlet Temp.	2 CCW Outlet Temp.	2-1	3 Cond. Press.	4 Turbine Exhaust Temp.	5 Cond. Temp.	4-5
CCW Flowrate Decrease	Same	Incr.	Incr.	Incr.	Incr.	Incr.	Zero
Condenser Tube Fouling	Same	Same	Same	Incr.	Incr.	Incr.	Zero
CCW Inlet Temp. Increase	Incr.	Incr.	Decr.	Incr.	Incr.	Incr.	Zero
Air Ingress	Same	Decr.	Decr.	Incr.	Decr.	Decr.	Incr
Tube Flooding	Same	Incr.	Incr.	Incr.	Incr.	Decr.	Incr

B.3.1.5

The pressure in a condenser is normally 5 kPa(a) and has risen to 7 kPa(a). Describe the steps you would follow to quickly eliminate some of the possible causes for the increase in condenser pressure. Explain why you are considering each parameter.

* * * * *

Earlier in the module, I said that deviations from the design condenser pressure could result in problems. Let's examine the effect of operating with a condenser pressure lower than design, ie, a higher vacuum.

Suppose we have steam at 800 kPa(a) with 50°C superheat entering a low pressure turbine which exhausts to a condenser at a pressure of 60 kPa(a). (You will recognize that the exhaust pressure is not realistic but allows the process to be easily illustrated on the Mollier diagram.) For simplici-

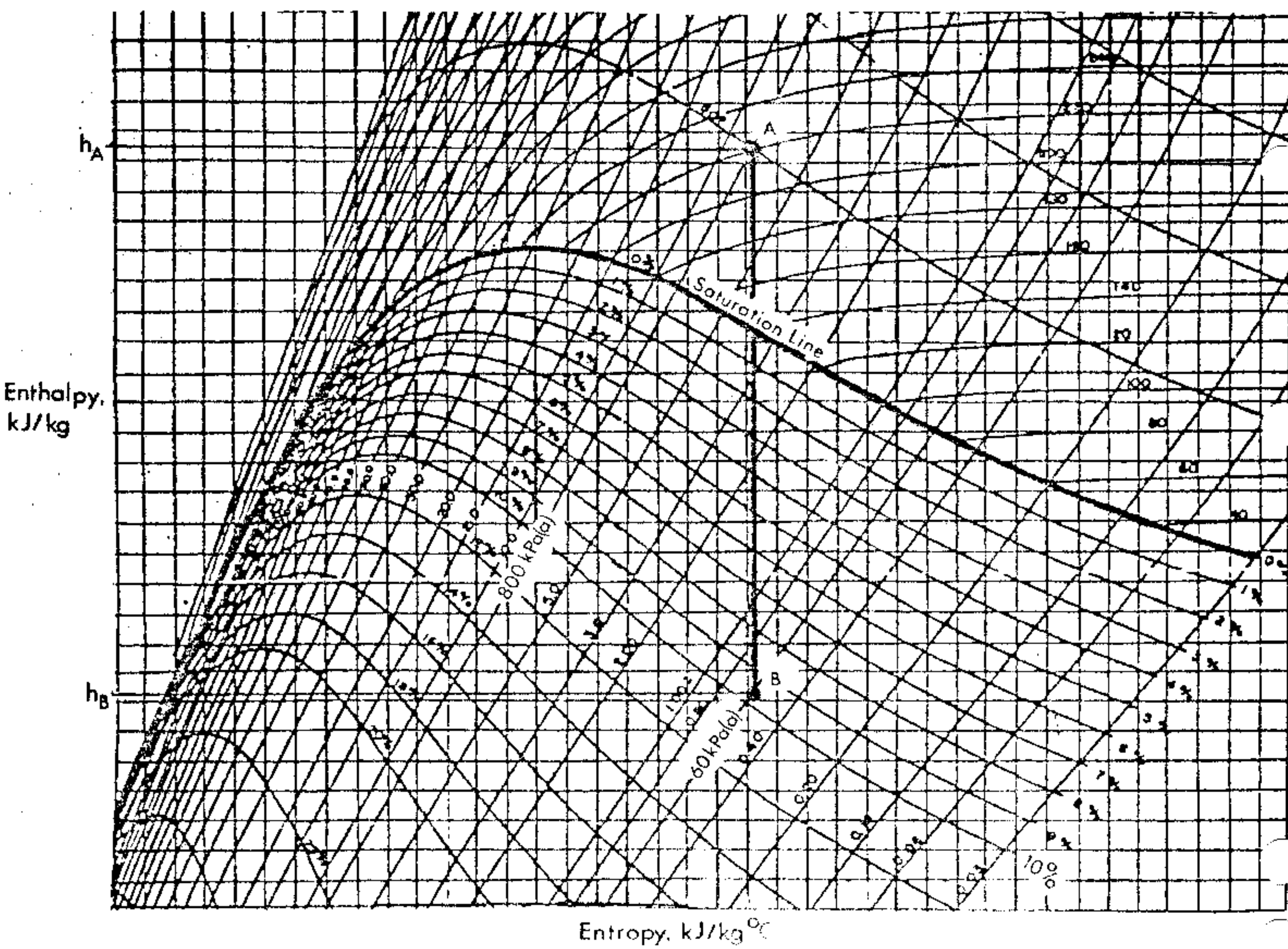


Fig. 3.1.3

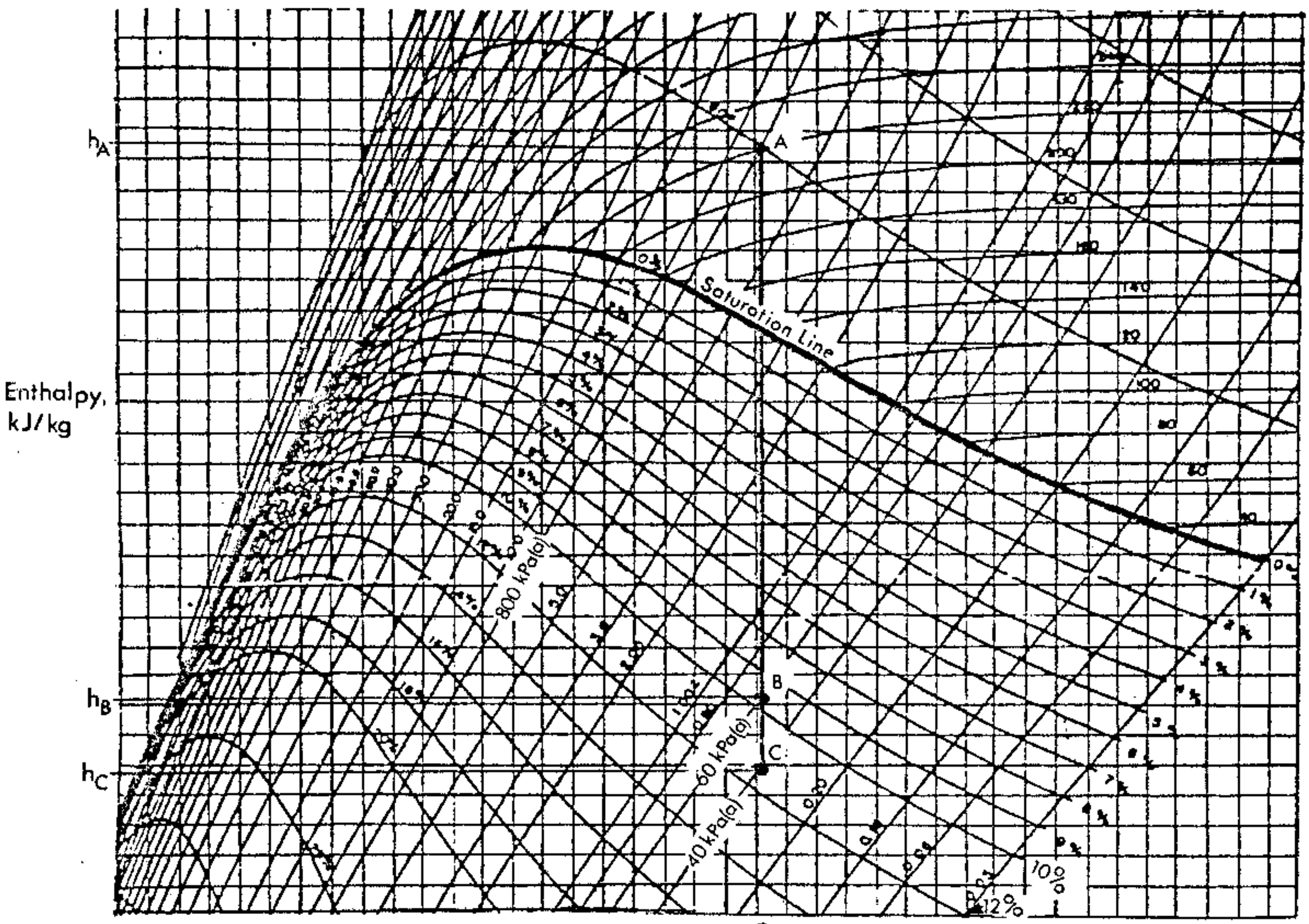
ty, we'll assume that the turbine expansion is isentropic which means that the expansion is represented by a vertical line on the diagram.

From the diagram, you can see that the exhaust moisture is around 10%. The ideal work done in the turbine is equal to the enthalpy drop from point A to point B.

Thus the turbine work is:

$H_A - H_B$.

Suppose the CCW conditions are such that we can obtain a vacuum of 40 kPa(a). Let's look at the Mollier diagram and see how this changes the previous operating condition.



Entropy, kJ/kg °C

Fig. 3.1.4

There is an obvious difference when looking at the amount of enthalpy that is converted into work in the turbine. This work has increased to $H_A - H_C$ which represents an additional 13% turbine power.

A second effect of the lower condenser pressure is to increase the steam flow through the turbine which also contributes to increasing the turbine power.

Why does this present a problem operationally? You have probably already noticed the new exhaust condition from the low pressure turbine. The moisture level has increased by around 2%. If this increased moisture level is experienced for any length of time, there will be a significant increase in the rate of erosion on the turbine blading which will increase stresses and accelerate failure due to fatigue.

The second aspect of this problem is also related to blade stresses. The turbine output power has been increased due to the increased enthalpy drop through the turbine and to the increase in steam mass flowrate due to the larger pressure difference between the turbine GSVs and the condenser. This increased turbine power level puts more stress on the turbine blading and will significantly reduce blading life.

Everything has its price and the price that is paid for operating the turbine at exhaust pressures below design values is reduced blading life. This reduced blading life is due to increased stresses as a result of accelerated erosion and overpowering of the turbine.

Let's look at the other condition of operating a turbine with a higher pressure than design, ie, a lower vacuum.

From the previous example, it will be no surprise to find that the turbine power has been reduced due to:

a) a lower enthalpy drop available from the steam.
b) a reduced steam flowrate due to the lower pressure difference which exists between the GSVs and the condenser.

The loss of turbine power is obviously undesirable but the story does not end here. Less work is done per kilogram of steam which reduces the cycle efficiency.

A more immediate concern relates again to the turbine blading. The velocity of the low pressure blade tips is approaching 800 m.p.h. As the pressure of the steam in the condenser increases, so the density of the steam increases. The increase in density results in an increase in frictional effects on the turbine blading which results in heating.

Permanent blade distortion due to creep effects is significantly affected by temperature. If the temperature is allowed to rise to a critical value, the low pressure blades will permanently stretch in the radial direction and in so doing, close up the radial tip clearances.

In the event of a high condenser pressure, the vacuum unloader reduces the turbine load to control the heating effect on the long low pressure turbine blades.

If reducing the turbine power via the vacuum unloader does not have the desired effect, the vacuum trip will operate at a condenser pressure of around 25 kPa(a).

It should be restated that there is no long term advantage to be gained in operating a turbine at exhaust conditions other than those for which the machine is designed.

Do these questions and check your answers at the end of the module.

B.3.1.6

It appears that the power output of a turbogenerator may be increased to 110% of rated continuous full power. The increase in available power is dueto low CCW inlet temperatures. Describe two turbine related problems which would result from operating at this condition for any significant length of time.

B.3.1.7

If you were faced with the situation in question B.3.1.6, what would be your recommendations for operating the turbine?

B.3.1.8

Explain why a vacuum unloader and vacuum trip facilities are considered necessary protective deviceson a steam turbine exhausting to a condenser.

* * * * *

Steam Flowrate and CCW Flowrate

The approach to numerical problems relating steam flow and CCW flow is exactly the same as the approach we used for the feedwater. Heat lost by the exhaust steam = Heat gained by CCW. For example, a condenser is supplied with cooling water at an inlet temperature of 4°C. The temperature rise across the condenser is 10°C.

Steam at 36°C enters the condenser at 12% moisture and a flowrate of 680 kg/s.

Assuming that there is no subcooling of the condensate, determine the CCW flowrate.

Heat Lost by Exhaust Steam

A sketch of the temperature enthalpy diagram will quickly confirm how much heat is lost by the steam.

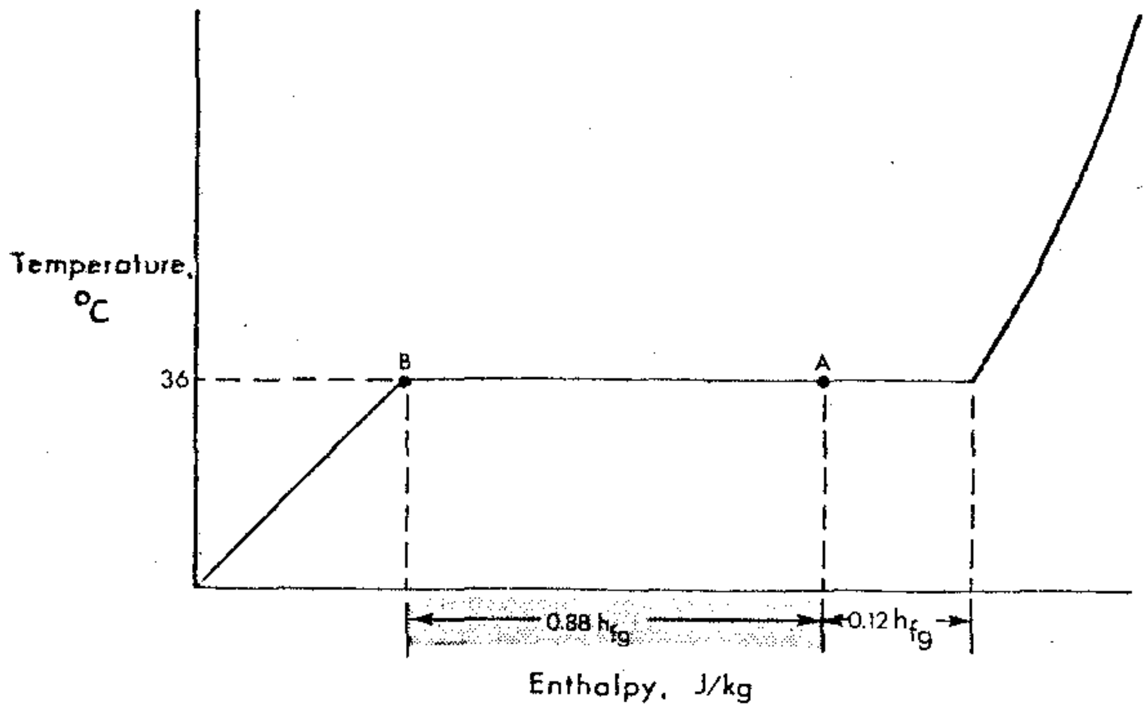


Fig. 3.1.5

At point A, the steam has lost 12% of its latent heat because it is 12% moisture. The condensate is <u>not</u> subcooled and is therefore, saturated liquid at 36°C.

From the diagram, we can see that the heat to be removed from 1 kg of steam is the remaining latent heat, ie, 0.88 $h_{fg_{36}}$.

From Table 1 h_{fg} at 36°C = 2416.4 kJ/kg

$$0.88 \times 2416.4 = 2126.4 \text{ kJ/kg.}$$

The total heat lost by the steam per second is found by multiplying the heat lost per kg by the mass flowrate 2126.4 x 680 = 1445952 kJ per second.

Under steady state conditions, this is the heat gained by the CCW.

Heat gained per kilogram of CCW is the enthalpy of the liquid at the outlet temperature (4 + 10 = 14°C) less the enthalpy of the liquid at the inlet temperature (4°C).

$$\begin{aligned} \text{Heat gained} &= h_{f_{14}} - h_{f_4} \\ &= 58.75 - 16.80 \\ &= 41.95 \text{ kJ/kg.} \end{aligned}$$

Every kilogram of CCW picks up this amount of heat in the condenser until the total of 1445952 kJ has been removed every second. If 1 kg removes 41.95 kJ of heat, then 1445952/41.95 kg of CCW are required to remove 1445952 kJ of heat = 34468 kg.

Every second 34468 kg of CCW are required to remove the heat lost by the condensing steam.

Try these examples and check your answers at the end of the module.

B.3.1.9

A condenser operates at a pressure of 6 kPa(a) and receives steam at a flowrate of 710 kg/s which is 92% dry. The CCW outlet temperature is 12°C and the temperature rise across the condenser is 10°C. Assuming no subcooling of the condensate, determinethe CCW flowrate required.

B.3.1.10

45 x 10^3 kg/s of CCW flow through a condenser with an inlet temperature of 3°C. The CCW temperature rise is 9°C.

Saturated steam is condensed to saturated liquid at 35°C. Determine the steam flow into the condenser.

* * * * *

This completes the module on condenser performance. When you feel you are ready for the test, ask the course/ shift manager. When you have written the test, ask for the self-evaluation sheet and look at the notes. Discuss your answers with the course/shift manager and when you are both satisfied, have the manager sign your progress summary sheet.

Proceed to Module B.4.2 or B.2.

Answers

MODULE B.3.1

CONDENSER PERFORMANCE

B.3.1.1

It is obviously wasteful to reject the working fluid from a system at the end of a process. This is particularly true if the fluid has some economic value, eg, contains some heat and has already been processed as in the water-treatment plant.

Having made the decision to retain the working fluid at the end of the process and return it to the system presents a problem. The exhaust at the end of the process is a mixture of water as vapour and liquid. How do you pump this mixture into the steam generator? You could use a compressor but because of the very large specific volume of exhaust steam, the size of the compressor would be equal to the size of the turbine and probably consume more power than the turbine produces.

So we can use a pump. The only problem is that most pumps are designed to handle liquids and not liquid/vapour mixtures. The only way that we can produce liquid is to condense the steam by removing the remaining latent heat of vapourization. This is the reason for the condenser to change the state of the working fluid from vapour to liquid, thereby reducing the volume significantly and allowing the working fluid to be pressurized using a conventional pump.

Three immediate benefits that arise from using the condenser are:

1. Use of a small pump instead of a compressor as already stated.

2. Some of the turbine exhaust heat is recovered as sensible heat in the condensate.

3. A significantly reduced treated water usage and plant incurs a much lower capital and operating expense.

B.3.1.2

There are two aspects of this question. The first point is that there has to be sufficient temperature difference between the Steam and the CCW to be able to reject the heat from the steam to achieve condensation. In practice, the rough difference is 25°C above the mean CCW temperature. This is only a guide but it serves to illustrate that this temperature difference does not exist in the question as stated.

The second point concerns the seasonal variation of CCW temperature. Suppose the condenser design was fine tuned to achieve the stated performance.

As the temperature of CCW inlet rose in the summer, the CCW flowrate would have to be increased in proportion to compensate. In practice, there would be insufficient CCW capacity and the unit would have to be derated. So we would have gained during the winter but lost that advantage during the summer.

B.3.1.3

We can apply exactly the same rationale as before. Initially, the heat rejected from the steam in the condenser will remain constant. As the CCW inlet temperature falls, so the CCW outlet temperature will also fall. At the same time, the average CCW temperature will fall.

The effect of the lower average CCW temperature will increase the temperature difference between the steam in the condenser and the CCW and more heat will flow to the CCW.

There is now an imbalance. The CCW is removing more heat than is being supplied to the condenser and the average temperature in the condenser falls. As a result of the falling temperature, the pressure in the condenser also drops.

The effect of the lower condenser pressure is to increase the pressure difference between the GSVs and the condenser and more steam flows.

The system settles out with lower CCW temperature, lower condenser temperature and pressure and a larger steam flowrate to the condenser.

	Steam	CCW
Flowrate	Increase	Same
Inlet Temp	X	Decrease
Outlet Temp	X	Decrease
Ave Temp	Decrease	Decrease
Pressure	Decrease	X

B.3.1.4

As soon as the steam flow into the condenser starts to increase, there will be an imbalance in the heat input to the condenser and the heat rejected to the CCW. As a result of the increased steam flow to the condenser, the temperature in the steam space will start to rise because with the existing temperature differences between the steam and the CCW, the CCW is not able to remove the extra heat energy.

As the temperature in the steam space rises, so the temperature difference between the steam and the CCW increases. This increased differential allows more heat to flow to the CCW and is seen by a higher CCW outlet temperature.

This temperature in the condenser continues to rise until the temperature difference between the steam and the CCW rises to a level when all the extra heat energy is being transferred to the CCW. The condenser pressure will, of course, rise with the temperature in the steam space.

	Steam	CCW
Flowrate	Increase	Same
Inlet Temp	X	Same
Outlet Temp	X	Increase
Ave Temp	Increase	Increase
Pressure	Increase	X

B.3.1.5

In this exercise, we are not concerned with the remedial action to be taken. Knowing the possible causes of the loss of back pressure, the procedure is essentially to rule out as many options as we can. A word of caution - in practice, conditions may be greatly different upon closer examination than at first glance. The fact that a possible cause for the high pressure is determined in this exercise, does not mean that you stop before completion. There may be more than one cause. Having identified the probable causes, someone would then have to calculate whether these probable causes would account for the total change in condenser pressure. We don't have to do this part of the exercise.

a) So let's start the exercise. Before we stride into the problem, we have to have a reference from which to work. The safest reference is to check the CCW inlet temperature. If this has increased, then this will account of some or all of the pressure increase due to the increase in average CCW temperature and therefore an increase in the steam space average temperature. If the CCW inlet temperature is the same as before the pressure rise, this option is eliminated.

b) The next possibility is so obvious that we often forget to consider it! Has the turbine power changed? Has there been a reduction in steam extracted from the turbine? An increase of 10% steam flow will raise the CCW outlet temperature by approximately 1°C if the full CCW flowrate is passing through the condenser.

The increased steam flowrate would have produced an imbalance in the energy into the condenser/energy out of the condenser. As a result, the average temperature in the steam space would have increased to transfer a greater quantity of latent heat to the CCW system.

If the steam flow has not increased, this option is eliminated.

c) Has the CCW flowrate through the condenser dropped? This could be due to a CCW pump having tripped or tube blockage occurring.

If all the temperatures apart from the CCW inlet temperature have increased including the condensate temperature, then having followed the process to this point, this is a likely cause. You must watch that the condensate temperature increases as well because this option is very similar in its effect to that of flooding the tubes with the exception of the condensate temperature.

The reduced flowrate would result in a higher CCW outlet temperature and therefore a higher CCW average temperature. This would mean that the steam space temperature would have to rise to maintain the same temperature difference in order to transfer the same quantity of heat to the CCW.

d) The next possibility is that of air ingress. If this has occurred, the air will act as an insulating blanket and reduce the heat transfer in the condenser which will be seen by a lower CCW outlet temperature. This will occur even though the condenser pressure has risen. It is quite likely that the partial pressure of the steam will have fallen as well and this would reduce the temperature of the steam space in the condenser but the condensate temperature would be below that of the condenser exhaust temperature. The real giveaway is a marked jump in the dissolved oxygen level in the feedwater.

e) Tube flooding is a possibility but does not happen very often. The giveaway for tube flooding is a significant drop in the condensate temperature leaving the hotwell. The subcooling has resulted from the condenser tubes being immersed in the condensate.

f) Tube fouling that impedes the heat transfer, as opposed to tube blockage which restricts the CCW flow, is unlikely to happen suddenly. This situation usually deteriorates with time. However, it is conceivable that an oil slick could be drawn in through the CCW system or some similar contamination could occur within the steam side of the condenser.

In this situation, you would not expect to see any significant change on the CCW circuit. The problem is one of higher thermal resistance to the transfer of the same amount of heat from the steam to the CCW. This resistance is overcome with a higher temperature difference between the steam and the CCW which results in the higher condenser pressure.

If you followed this exercise and did not find at least one possibility for the increased condenser pressure, you should consider checking the validity of the readings you are using. There are some things which we have to accept and I have accepted that the increase in condenser pressure indication was real and not a fault on the data system.

B.3.1.6

There are two turbine related problems which will arise from operating a turbine above full rated power due to a lowering of condenser pressure.

The lower condenser pressure allows more work to be extracted from the steam which looks like something for nothing. However, the only way that more heat may be extracted from the steam is to allow more latent heat to be removed and more steam to condense in the turbine. The increased moisture will accelerate erosion of the blading and will result in premature fatigue failure of the turbine blading.

In the second aspect we are concerned with the increased work done by the blades due to the drop in condenser pressure and the extra steam flow which arises as a result of the larger pressure difference between the GSV and the condenser.

The extra work from the turbine increases the mechanical loading on the blades. This extra loading will result in premature blade failure as a result of the higher stresses.

B.3.1.7

Before you can make a recommendation, you must to sure that you know why the turbine unit is now operating in this condition.

The turbine is operating at full rated power and because the CCW conditions have changed, we now have the opportunity of overpowering the turbine which may be desirable in the very short term but is undesirable in principle. How can we restore the condition to 100% power at design vacuum?

If you feel you want to advocate reducing turbine power to 100%, RESIST this temptation!

Let's have a look at this situation from the start. How did the turbine conditions change in the first place? Quite simply - the CCW inlet temperature dropped which lowered the average CCW temperature and allowed more heat to be removed from the condenser than was being supplied by the steam.

If we reduce the turbine load, will the condenser pressure increase or decrease? Reducing the amount of heat entering the condenser will cause an even greater mismatch between heat lost by exhaust steam and heat gained by the CCW. In this situation, the condenser pressure would fall further as the average temperature in the condenser approached the CCW inlet temperature. The moisture in the exhaust steam would also rise.

The solution to the condition is to reverse the effect of the CCW inlet temperature. If each kilogram is capable of removing more heat, then to maintain the previous operating condition the condenser needs a lower CCW flow. How this is achieved in practice depends upon the condenser design. It may be possible to reduce the number of CCW pumps on the unit or it may be possible to reduce the CCW flow from the water boxes with a CCW outlet valve.

Whichever technique is employed, a reduction of CCW flow will restore the turbine power to 100% at design vacuum.

B.3.1.8

If the pressure in the condenser starts to rise, this is an obvious indication of a mismatch between the heat being rejected by the exhaust steam and the heat being gained by the CCW.

In this case, the heat being rejected by the steam exceeds the heat being gained by the CCW. As a result the temperature and pressure rise in the condenser.

The tips of the low pressure blades are travelling around 800 mph and the frictional skin heating effects on the rotating blades become very significant as the temperature and pressure rise.

The centrifugal force is trying to elongate the moving blades. As the temperature of the blades rises, the resistance to elongation becomes less. If the blades did stretch, they would close the radial blade clearances with the turbine casing and the results could be catastrophic.

To prevent this event occurring, we try and restore the equilibrium across the condenser by reducing the amount of steam entering the condenser. This is done in practice using the vacuum unloader which reduces the oil pressure to the GSVs. If the pressure continues to rise in spite of the vacuum unloader action, then the turbine is tripped on condenser high pressure using the vacuum trip at which point the heating of the low pressure turbine blades ceases.

B.3.1.9

The heat lost by the condensing steam is equal to the heat by the CCW.

Heat Lost by the Condensing Steam

A sketch of the temperature/enthalpy diagram is of help in presenting the initial and final steam conditions.

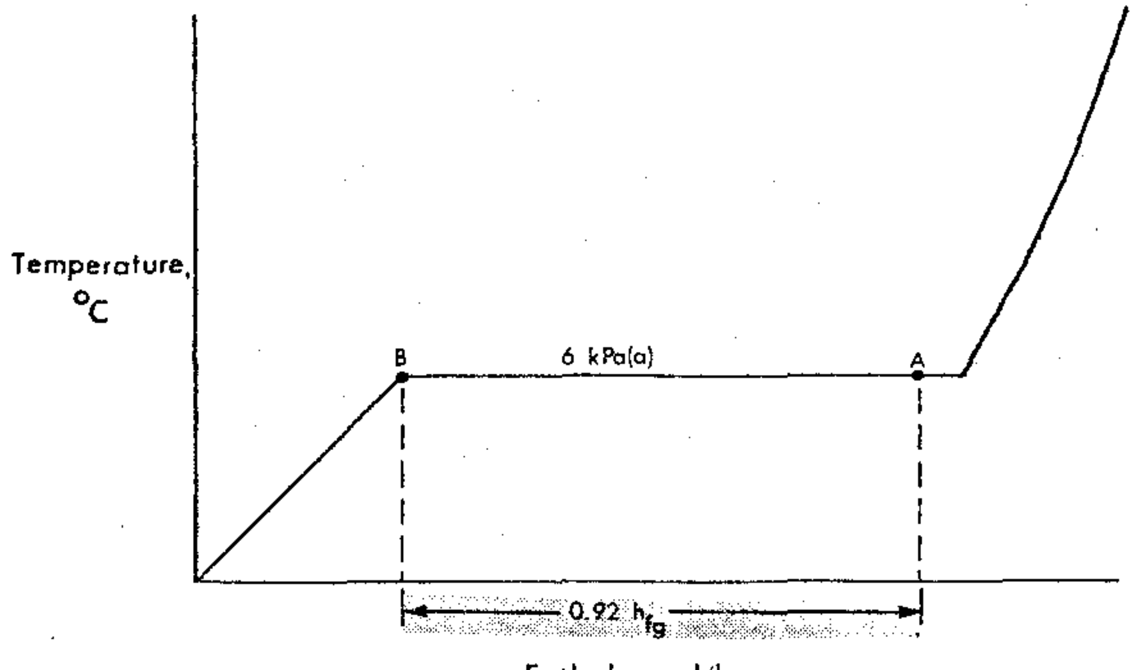


Fig. 3.1.6

The steam entering the condenser at point A, has already lost 8% of its latent heat of vapourization. The condensate at point B is saturated liquid when it leaves the condenser. The heat which has been removed between points A and B is the remaining latent heat of vapourization at 6 kPa(a).

From table 2, h_{fg} at 6 kPa(a) = 2416 kJ/kg

Heat lost per kg of steam = 0.92 x 2416

= 2222.7 kJ.

Total heat lost by steam in the condenser equals the change in enthalpy (2222.7 kJ/kg) multiplied by the mass flowrate (710 kg/s).

Total heat lost per second = 2222.7 x 710

= 1578131 kJ.

This heat is gained by the CCW. The outlet temperature is 12°C and the inlet temperature is 2°C (12°C - 10°C).

$$\text{Thus heat gained per kilogram of CCW} = h_{f_{12}} - h_{f_2}$$
$$= 50.38 - 8.39$$
$$= \underline{42}\ \text{kJ/kg.}$$

Every kg of CCW removes 42 kJ of heat until 1578131 kJ have been removed every second.

$$\text{CCW flow required to remove 1578131 kJ} = \frac{1578131}{42} = \underline{37584}\ \text{kg/s.}$$

B.3.1.10

This time we know the CCW flow and have to find the steam flow. The approach is exactly the same.

Heat gained by CCW = Heat lost by steam.

Heat Gained by CCW

Outlet temperature = 12°C (3°C + 9°C).

Inlet temperature = 3°C.

$$\text{Heat gained per kg of CCW} = h_{f_{12}} - h_{f_3}$$
$$= 50.38 - 12.60$$
$$= 37.8\ \text{kJ.}$$

Total heat gained by CCW equals enthalpy rise (37.8 kJ) multiplied by the CCW flowrate (45×10^3 kg/s).

$$\text{Total heat gained by CCW} = 37.8 \times 45 \times 10^3$$
$$= 1.7 \times 10^6\ \text{kJ/s.}$$

This is equal to the heat lost by the condensing steam in the condenser. The heat lost is uncomplicated in this example.

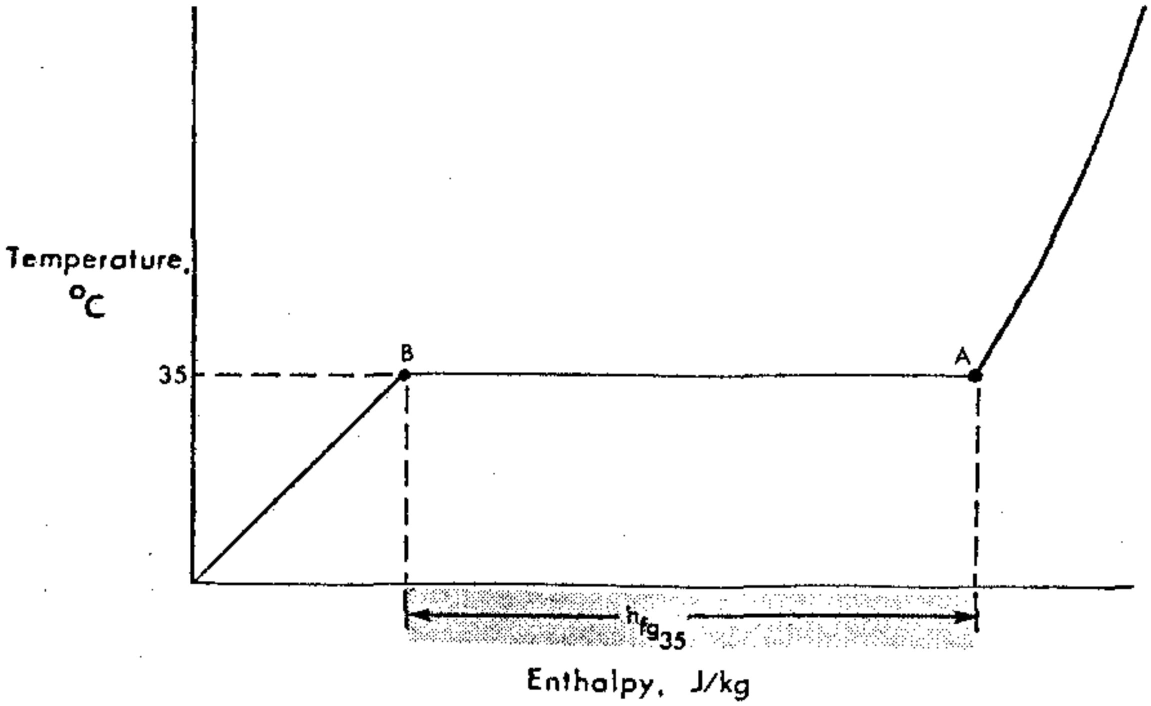


Fig. 3.1.7

The steam enters the condenser as saturated steam at point A and leaves as saturated liquid at point B. The heat which has been removed in the condenser is all the latent heat of vapourization at 35°C.

From table 1 h_{fg} at 35°C = 2418.8 kJ/kg.

This heat is gained by the CCW and steam is continually condensed giving up 2418.8 kJ/kg until 1.7×10^6 kJ of heat are transferred to the CCW every second.

The steam flow required to transfer 1.7×10^6 kJ/s

$$= 1.7 \times 10^6 / 2418.8 \text{ kg/s}$$

$$= \underline{703} \text{ kg/s.}$$

J. Irwin-Childs

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HEAT & THERMODYNAMICS

MODULE B.2

STEAM GENERATOR

Heat & Thermodynamics

MODULE B.2

STEAM GENERATOR

Course Objectives

1. You will be able to explain how the temperature difference between the steam generator and the PHT system changes during a "crash-cool" exercise.

2. You will be able to state how the PHT average temperature is affected by increasing the thermal resistance of the steam generator tubes.

3. You will be able to explain why the programmed steam generator level increases with power.

4. You will be able to explain one problem concerning high boiler level and three problems concerning low boiler level. You will be able to state the control action which is designed to overcome these problems.

5. You will be able to state the three elements used for boiler level control and explain why they cannot be used at low loads.

6. You will be able to explain the response of the station control system to a falling boiler pressure when control is in the 'normal' mode and the control of the speeder gear is in 'auto'.

7. You will be able to explain why the BPC program terminates at 170°C when in the 'cooldown' mode.

8. You will be able to explain how raising the pressure of the steam generator improves the efficiency of the steam/water cycle.

9. You will be able to explain the limitation on raising the steam generator pressure in the CANDU system.

We have examined the basic thermodynamic principles and must now apply these principles to the operation of the steam generator and finally the reactor.

The steam generator removes the heat from the reactor under normal conditions. The heat which is removed from the fuel in the reactor channel by the heat transport D_2O is rejected in the steam generator to the lower temperature light water system.

The steam generator heat transfer takes place at the tube bundles through which the primary heat transport fluid, flows and around which the feedwater flows.

By varying the rate of heat removal in the steam generator we can control the rate at which the heat transport temperature changes or we can ensure that it remains constant, depending upon the power manoeuvring at the time.

In addition to acting as the major heat sink for the reactor the steam generator produces high quality working fluid that may be used to produce mechanical power in the steam turbine.

The heat that is transferred from the PHT system to the steam generator depends upon the temperature difference which exists between the D_2O and the lightwater in the steam generator.

As the temperature difference increases, more heat is transferred. In a "crash-cool" exercise, this is exactly what happens. By rejecting steam from the steam generator to lower the pressure, the temperature falls as well and increases the temperature difference between the steam generator and the reactor. As a result, more heat is transferred and the cool-down rate of the reactor is increased.

The heat which is transferred also depends upon the thermal resistance of the tubes in the steam generator. If these tubes become coated with oxide or other material, the thermal resistance will increase which means that a higher temperature will be needed in the PHT system in order to transfer the same quantity of heat.

B.2.1

Explain how the temperature difference between the PHT system and the steam generator changes during a "crash-cool" exercise.

B.2.2

Explain how an increase in thermal resistance, across the steam generator tubes, affects the average PHT temperature.

* * * * *

Level Control

It is important that the mass of light water in the steam generator remains constant to provide an adequate heat sink capacity for the reactor.

We have already seen that the liquid in the steam generator will expand as the temperature rises. This expansion will cause an increase in the level of liquid in the steam generator.

Do this exercise and compare your answer with the notes at the end of the module.

B.2.3

Feedwater in the steam generator is heated until the temperature rises from 170°C to 250°C. Determine the percentage increase in volume that would occur due to this temperature rise.

* * * * *

In addition to this increase in level there is another effect which will occur. As boiling takes place steam bubbles will form within the liquid and if the mass of water stays constant this will cause the steam water mixture level to rise. As the rate of steaming in the steam generator increases the ratio of steam to liquid in the steam generator will increase and cause an even higher level although the mass of 'water' in the steam generator will not have changed.

This increase of steam generator level is programmed into the control system. The level setpoint in the steam generator increases linearly with steam flow until maximum steam generator level is achieved at 100% steam flow.

The effect of rapidly lowering the pressure of saturated liquid may be seen on a temperature/enthalpy diagram.

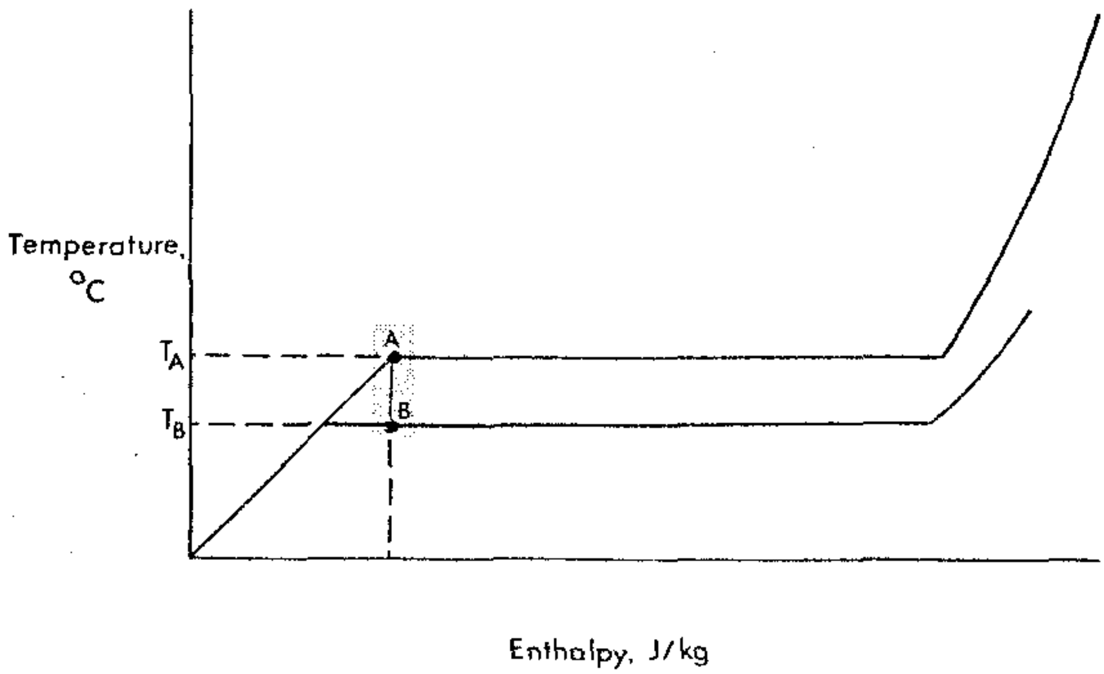

Fig. 2.1

The enthalpy remains constant and as the pressure rapidly falls, the liquid has more heat than is needed for saturation conditions and the excess heat produces vapour. What happens to the level in the steam generator? It rises! You can see this effect if a large steam reject valve or a condenser steam dump valve is open. The steam generator level rises momentarily. If there had been a high level in the steam generator then there would have been a danger of priming the steam lines with liquid from the steam generator. This effect of increased volume due to a sudden decrease in pressure or rise in temperature is called "swell".

The maximum swell effect in the steam generator would occur when there is a large demand in steam flow, eg, an increase in load from 50% to 100% power on a hot turbine. In this case the swell would not cause a problem because the programmed level would only be at the 50% power setpoint and so priming is less probable.

In the event that an abnormally high level occurs in the steam generator, a governor steam valve trip is initiated to prevent liquid being carried into the turbine where massive blade failure could occur.

Look at the following questions and compare your answers with those at the end of the module.

B.2.4

The mass of "water" is kept constant in the steam generator over a wide power range. As the steam flow increases the programmed level in the steam generator also increases. Explain why the programmed level has to increase with steam flow.

B.2.5

Explain why it is undesireable to have liquid enter the steam turbine and state how the probability of this event occurring is reduced.

* * * * *

The effect of swell is reversed when the pressure in the steam generator is suddenly increased. This may occur with a turbine trip when the steam flow is instantaneously reduced. Any vapour bubbles which exist within the liquid are collapsed and the liquid level falls. This causes the fluid in the steam generator to "shrink". If the steam generator is operating at a low level when the turbine trip occurs, then the resulting shrink may result in a very low steam generator level.

There are three potential problems with a very low steam generator level. First, the level may fall below the sensing point for level control, which is above the top of the tube bundle. This means that the level control program can no longer detect the level - it still operates at minimum level signal.

Secondly, as the water inventory in the steam generator falls the capacity as a heat sink for the reactor is also reduced and this is obviously an undesireable trend.

Thirdly, if the level in the steam generator falls any further the tube bundle will be uncovered and dry out will occur. The dissolved solids existing in the steam generator will "bake out" on the tube surfaces and impede future heat transfer.

The problem of low level is accommodated initially with an alarm which may allow operator action and finally with a reduction of reactor power, either by a setback or a trip depending upon the operating rationale at the station concerned. The effect of rapidly reducing reactor load ensures that the reactor thermal power is more closely matched to the reduced heat sink capacity of the steam generators.

Answer the following questions and compare your answer with the notes at the end of the module.

B.2.6

Explain why the level in the steam generator initially falls on sudden reduction of steam flow.

B.2.7

Explain three potential problems of low steam generator level and how the effect of these problems is reduced in practice.

* * * * *

There are three signals used for the level control program,

(a) steam flow,
(b) feed flow,
(c) actual level.

The steam flow signal is used to produce a programmed level setpoint for the steam generator which varies linearly from 0% to 100% steam flow.

Control circuits compare steam and feed flows for mismatching, they also compare actual and programmed steam generator levels.

At low flows of steam and feedwater, measurement of flow is unreliable. In addition to this problem any feedwater regulating valve operation has a dramatic effect on the system because the flowrates are so low. One minute there is virtually no flow at all, then a regulating valve cracks open and a great slug of water enters the system.

In this low power/flow condition steam generator level is essentially controlled by the level controller exclusively. Above ~20% flowrate, when the large feedwater regulating valves are in service the level control system can operate with all three elements.

Change of Steam Generator Programmed Level/Power

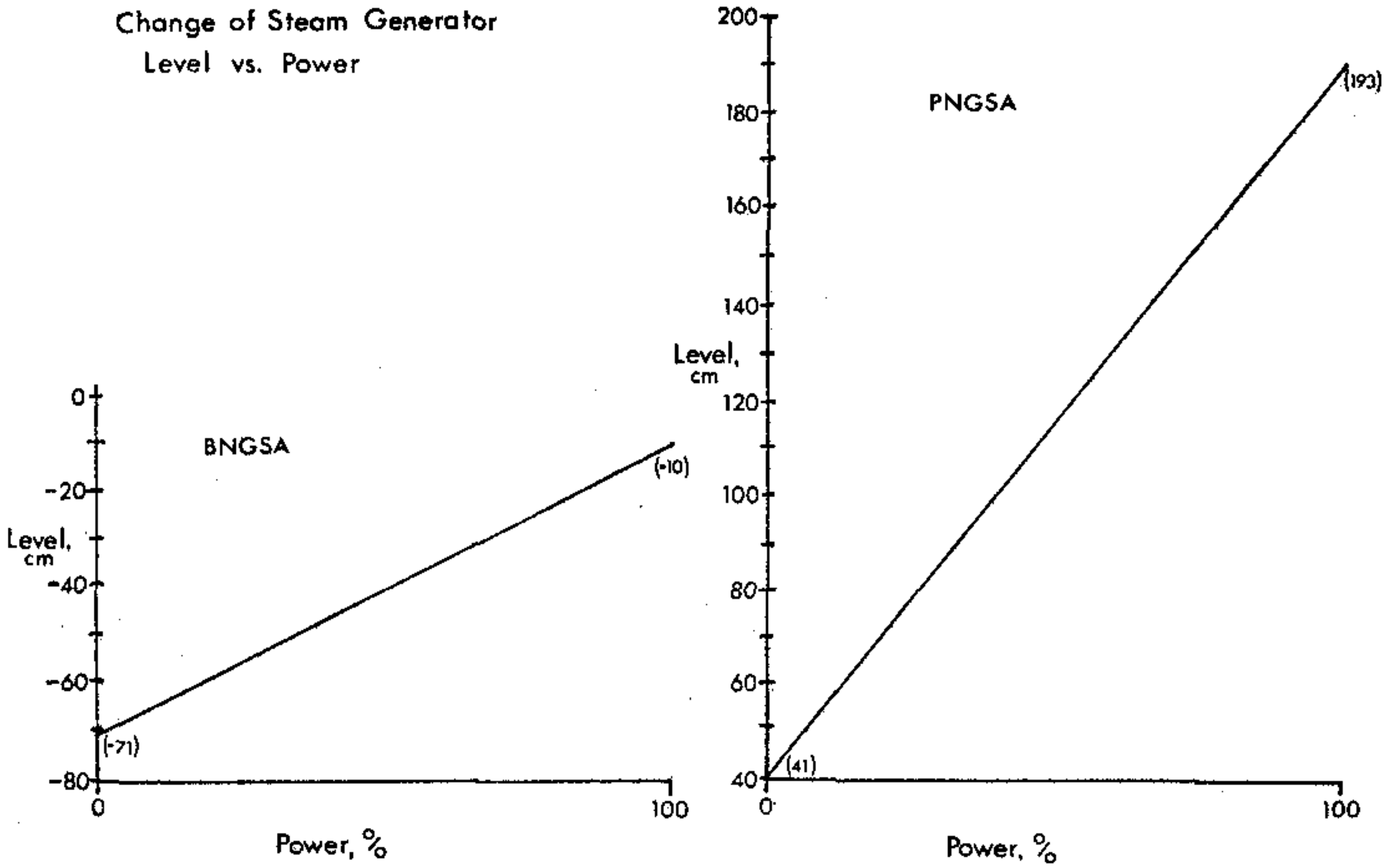

Fig. 2.2

By comparison you can see that the programmed level at Pickering NGS-A changes by 152 cms whilst the programmed level at Bruce NGS-A only changes by 61 cms.

B.2.8

Why do you think this difference exists? Compare your answer with the notes at the end of the module.

B.2.9

State the three elements which are used in a boiler level control program. Explain how level control is effected at low power levels.

B.2.10

The high level alarm has been received on a boiler. What actions can the operator take?

* * * * *

Boiler Pressure Control

Boiler pressure is used to control the mismatching which may occur between the thermal power produced by the reactor and the thermal power removed from the steam generator by the steam flow.

As we have already discussed, in a saturated steam system either temperature or pressure may be used to represent the same heat quantities. In the Candu system we use pressure because it is so sensitive to changes in the balance of thermal power.

The main heat sink for the reactor is the steam generator. In turn, the steam generator has its own heat sinks, some small, some large, some variable, some fixed.

Steam Turbine

This is the normal consumer of steam from the steam generator. At Pickering NGS-A it is capable of using all the reactor steam. At Bruce NGS-A the situation is complicated by the supply of reactor steam to the Heavy Water Plants.

At Bruce NGS-A the turbine cannot take all the reactor steam and consumes 88% of the total reactor steam if both the reactor and turbine are at full load.

Changes in turbine or reactor power may be made by the BPC program to meet the designed pressure setpoint.

Steam Reject/Discharge Valves

These valves are capable of discharging any steam flow necessary to restore system control. If the turbine is available there is usually an offset before these valves operate, to allow speeder gear operation to have an effect on the steam flow via the GSV.

If the turbine is not available, the offset is removed and these valves operate as soon as the pressure setpoint is exceeded. If the mismatching is large enough for the main reject/discharge valves to operate, then a reactor setback is initiated until the large valves close and equilibrium is restored.

Safety Valves

In the unlikely event that the turbine and/or the reject/discharge valve systems cannot control the pressure excursion, then the steam generator safety valves will allow the excess steam to be vented to atmosphere.

Auxiliaries (D/A, Gland Steam, Steam Air Ejectors)

These loads are relatively fixed and although they may account for up to 10% of the total steam flow, they do not appear as controllable heat sinks from a steam generator pressure viewpoint.

Boiler Blowdown

This is a variable heat sink and may affect the steam generator. However, the flowrate is only 1-2% and as a result has an insignificant effect on boiler pressure.

B.2.11

List the three major heat sinks for the steam generator and state when they are used.

* * * * *

Boiler Pressure Set Point "At-Power"

In all the BPC programs there is a pressure set-point at various power levels.

At Bruce NGS-A the pressure set point is constant at 4.3 MPa(a).

At Pickering NGS-A the pressure setpoint falls from 5.09 MPa(a) at 0% power to 4 MPa(a) at 100% power.

The rationale for these two situations will be discussed in further detail in Module B.1 "Reactors". At this point this is the set of conditions that have to be met by the steam pressure control programs at each station.

BPC Pressure Setpoint vs. Unit Power

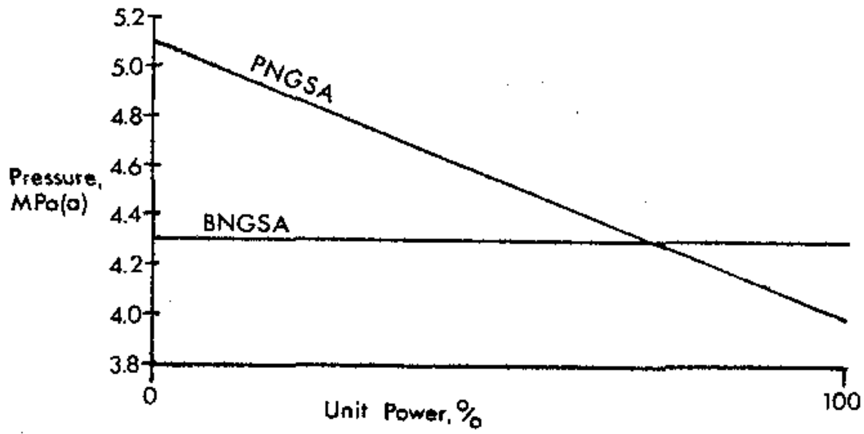

Fig. 2.3

We are examining the pressure of the steam generator. Suppose we want to raise the pressure in the steam generator, how could we do this? The reactor is rejecting heat to the steam generator and the steam generator is rejecting heat via the steam system.

If we wish to raise the pressure in the steam generator we have to produce an imbalance which results in more heat being supplied to the steam generator from the reactor than is being removed from the steam generator via the steam. There are two ways that we could to this:

(a) Raise reactor power.
(b) Decrease steam flow from the boiler.

In practice the method used would depend upon the mode of control.

On the other hand, if we wanted to lower the steam generator pressure, there are two actions that could be taken:

(a) Reduce reactor power.

(b) Increase steam flow from the steam generator.

Reactor Leading Mode

In this mode, the reactor power is kept constant and the steam flow from the steam generator is varied to meet the programmed BPC setpoint pressure for the reactor power. This mode is used at Pickering NGS-A as the 'normal' operating mode and is used at Bruce NGS-A for low power operation and for abnormal conditions.

Reactor Lagging Mode

In this mode, the generator load is kept constant and the reactor is controlled to maintain the boiler pressure setpoint. This is the 'normal' mode used at Bruce NGS-A.

Boiler Pressure Control - Reactor Leading

In this mode, the reactor power is changed to the new value and the BPC program makes sure that the rest of the system follows.

Suppose we want to raise unit power. Initially we can change demanded reactor power and produce more heat. There will now be more heat rejected to the steam generator than is being removed by the steam. As a result the pressure will rise in the steam generator. The BPC program sees the rise in pressure and opens the governor steam valves to allow more steam to flow out of the steam generator into the steam turbine, thereby reducing the steam generator pressure back to the programmed setpoint for that reactor power.

The turbine provides the primary heat sink for the steam generator. In the event that the turbine could not reduce the steam generator pressure, then the secondary heat sink would be used, ie, Steam Reject Valves (SRV's).

If the speeder gear is not under BPC control and the mismatch causes the steam pressure to rise above the pressure setpoint the small SRV's will open. If this does not reduce the steam pressure then two events will follow:

(a) the large SRV's will open to reduce the steam generator pressure.

(b) the reactor power will be reduced until the large SRV's shut, thereby quickly reducing the mismatch in power.

If the unit power is to be reduced, a reduced demanded reactor power is input. The steam pressure starts to fall as now more heat is being removed from the steam generator than is being supplied by the reactor.

The BPC program monitors the falling steam generator pressure and reduces the steam flow into the steam turbine via the GSV's to restore the setpoint pressure.

B.2.12

Describe how a rising boiler pressure signal would be handled with a "reactor leading" mode, at power, when the speeder gear is not controlled by the BPC program.

* * * * *

Boiler Pressure Control - Reactor Lagging

In this mode the generator power is kept constant and the reactor power setpoint is adjusted to maintain the pressure setpoint.

Suppose we wanted to raise unit power. Initially an increase in demanded power would result in an opening of the GSV's which would result in a lowering of the steam generator pressure because more heat is being removed with the steam than is being supplied by the reactor. The BPC program responds to the falling boiler pressure by raising the reactor power setpoint until the boiler pressure returns to the programmed value.

As already mentioned, this mode applied only at Bruce NGS-A. In extreme cases where the reactor manoeuvring cannot control the pressure, the BPC program reverts to reactor leading. In the high pressure situation atmospheric steam discharge valves relieve the excess pressure. If the boiler pressure error is too large because of low pressure, a slow speeder runback is initiated until boiler pressure is restored.

B.2.13

Describe how a falling boiler pressure signal would be handled with a "reactor lagging" mode at power.

* * * * *

Warm Up Mode

In this mode the Heat Transport system temperature may be raised by requesting a constant rate of change of boiler setpoint pressure.

The excess steam is vented to atmosphere via the steam reject valves at Pickering NGS-A or the atmospheric steam discharge valves at Bruce NGS-A.

By increasing the pressure in the steam generator the temperature is also increased. A common example is an automobile radiator. (Why increase the radiator pressure? If overheating was a problem raising the pressure may prevent boiling and would increase the heat removal rate from the radiator due to the higher coolant temperature resulting from the higher pressure.)

Cooldown Mode

In the cooldown mode heat has to be removed from the reactor until the reactor can be cooled with shutdown cooling.

If the turbine is available the turbine load can be reduced using the BPC program so that the electrical output reduces with the reduced steam flow available from the steam generator.

It should be noted that as the steam pressure falls, the quality of steam in the turbine is deteriorating and this increasing wetness in the turbine may be a very good reason for not allowing the BPC program to use the turbine all the way down. In this case switching the speeder control to "Manual" would bring the steam reject values into operation.

If the turbine is not available, as in a turbine trip, then steam is rejected either to atmosphere via steam reject valves at Pickering NGS or to the main condenser via condenser steam discharge valves at Bruce NGS-A. This process continues until the temperature of the PHT falls to around 170°C at which point the SRV's are full open and no longer capable of reducing the PHT temperature. It is at this point that the shutdown cooling takes over.

B.2.14

Explain why the BPC program terminates at 170°C when in the 'cooldown' mode.

Cycle Efficiency

As stated in Module B.3.1, we can get best use (ie, most efficiency) from steam when the temperature difference between the steam in the steam generator and the steam in the condenser is at maximum.

If we raise the steam pressure in the steam generator, how does this affect the steam temperature?

Since the water in the steam generator is at saturation conditions, if the pressure of the water is raised the water will boil at a higher temperature. Thus, the temperature of the steam produced will increase - this increases the temperature difference between the steam in the steam generator and that in the condenser. The efficiency of the cycle will increase as well.

There is a limitation on the pressure of the steam generator. As the pressure and temperature of the water/steam system are increased, the temperature difference across the steam generator tubes is decreased and less heat is transferred from the primary heat transport fluid. The temperature of the primary heat transport fluid in the tubes will increase. This will cause the temperature of the primary heat transport fluid in the reactor to increase. Less heat will be transferred through the fuel sheath and the fuel and fuel sheath temperatures will rise.

The limiting temperature of the primary heat transport fluid in the reactor is 290 to 300°C. At this limit, the temperature in the fuel reaches a maximum of 2300°C and the fuel sheath temperature is approximately 350 to 400°C. If the heat transport fluid temperature rises above 300°C, (with no boiling), the maximum fuel temperature approaches the melting point (about 2800°C).

If melting of fuel occurs, fission product gases normally held at the fuel grain boundaries are released, building up high pressures inside the fuel sheath. The fuel sheath temperature is increasing rapidly (and its mechanical strength is decreasing) as the heat transport fluid and fuel temperatures increase. The high pressures on the inside of the fuel sheath will contribute to failure of the sheath which will likely occur in the range of 800 to 1100°C. When sheath failure occurs there will be release of fission products into the primary heat transport system.

Answer the following questions and compare your answers with those at the end of the Module.

B.2.15

How does raising the pressure of the steam generator improve the efficiency of the steam/water cycle?

B.2.16

Explain the limitation (in the CANDU system) on raising the steam generator pressure.

* * * * *

We have covered the major points concerning the steam generator. You should turn to the objectives and read them carefully. If you feel that you can satisfy these requirements, ask the course/shift manager for the Criterion Test.

* * * * *

When you have completed the test, ask for the Self Evaluation Sheet and compare your answers.

When you are ready, ask the course/shift manager to review your work. If you identify areas that need further practice, return to the relevant section and then try the test again when you feel you are ready.

When you are both satisfied with your work, have the manager sign off the progress summary sheet and proceed to the final Module, B.1 "Reactor".

Answers

MODULE B.2

STEAM GENERATOR

B.2.1

In a "crash-cool" exercise, the steam is rejected from the steam generator fast enough that the pressure will fall. In this situation, the temperature in the steam generator falls with the pressure. The result of the falling temperature is to increase the temperature difference between the PHT system and the steam generator which increases the rate of heat removal from the reactor and reduces the time for reducing reactor temperature.

B.2.2

The effect of increased thermal resistance means that a higher temperature difference is required to transfer the same amount of heat. This is exactly the same as in the electrical analogy where the voltage applied to a higher resistance has to be increased to transfer the same amount of power through the circuit.

The higher temperature difference can only be produced by an increase in the PHT average temperature. So an increase in the thermal resistance of the steam generator tubes, due to corrosion products and other material contamination, will result in an increase of the average PHT temperature.

B.2.3

Using the steam table, we can compare the specific volume of liquid v_f at 170°C and 250°C using table I,

$$v_f \text{ at } 170°C = 1.1144 \ \ell/kg$$

$$v_f \text{ at } 250°C = 1.2513 \ \ell/kg.$$

$$\text{Change in volume} = 1.2513 - 1.1144$$

$$= 0.1369 \ \ell/kg.$$

$$\text{This percentage increase in volume} = (0.1369/1.1144) \times 100$$

$$= \underline{12.3\%}.$$

Obviously there is some increase in level solely due to this expansion effect.

B.2.4

Suppose the steam generator is at operating temperature but producing no steam. At this condition the boiler would be full of liquid containing no vapour bubbles. The level of the liquid would be that corresponding to the programmed level at 0% power.

If the heat input to the steam generator is increased boiling will now occur and vapour bubbles will be produced within the liquid. This will have the effect of "floating" the surface of the liquid to a higher level.

As the rate at which heat is being supplied to the boiler increases, to the maximum, so the generation of vapour bubbles reaches a maximum. At this full power steaming rate the steam generator level reaches its highest value.

Steam is leaving the boiler and the fluid is being replaced by feedwater entering the boiler to maintain a level, programmed to the rate of steaming, to keep the mass of water in the vessel sensibly constant.

At full load approximately 10% of the weight of fluid in the boiler is due to vapour bubbles. These vapour bubbles produce an increase in the total fluid volume of approximately 5 times, when steaming at full power.

B.2.5

Liquid has a high density in relation to vapour. It is also relatively incompressible. This means that when a change of direction is needed with liquid flows at high velocities and large flowrates very large forces can result. Water hammer is an illustration of this effect. The liquid will tend to move in a straight line. Can you imagine a slug of water passing through the high pressure turbine in a straight line? Slugs of water in a steam turbine produce the same type of problem as birds flying into aviation gas turbines.

The blading attempts to change the direction of the liquid flow into the turbine and it is even money at best as to whether the blade is strong enough to withstand the impact or the water breaks the blading and wholesale blade shedding results.

Needless to say the presence of water is to be avoided and this event is anticipated by a high level alarm on the steam generator which may allow some operator action before a high level trip operates the governor steam valves on the turbine to exclude the liquid.

B.2.6

One of the easiest ways of analyzing this effect is to return to the temperature/enthalpy diagram and plot the initial condition and raise the pressure keeping the enthalpy constant.

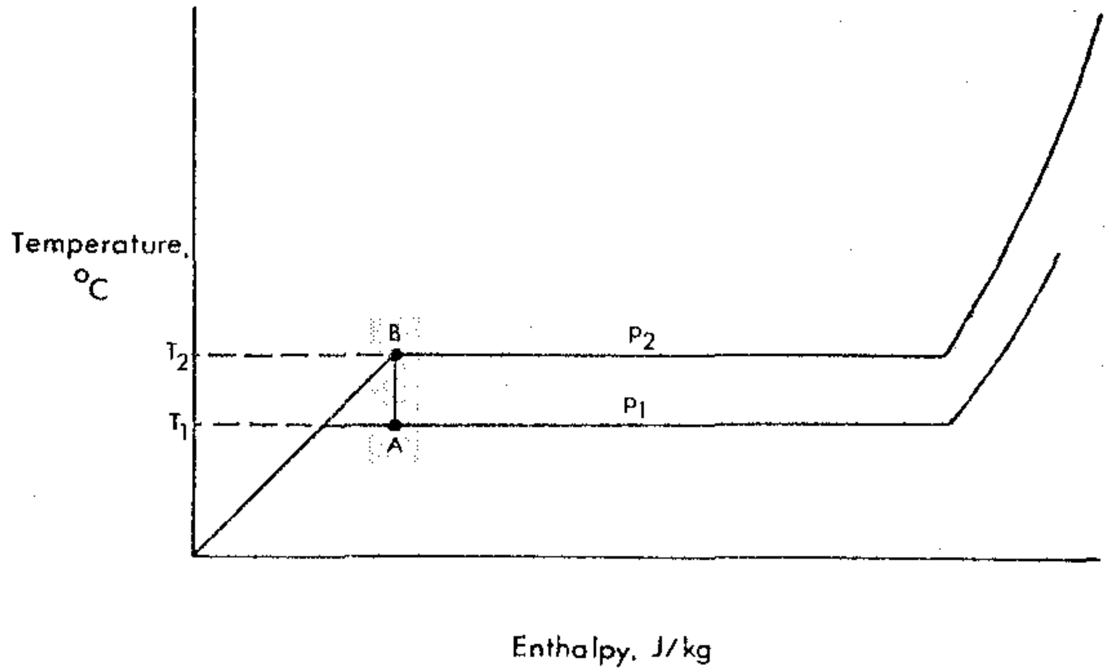

Fig. 2.4

Initially the steam generator has fluid as liquid/vapour mixture at pressure P_1 as shown at point A. When the pressure suddenly increased to P_2 the mixture is now below the saturation temperature corresponding to the higher pressure and the vapour bubbles condense as the latent heat of vapourization is used to raise the liquid to the new saturation temperature.

The condensation process causes the vapour to disappear and the volume shrinks resulting in a reduced steam generator level.

B.2.7

There are basically three problems that arise from a very low steam generator level.

First, as the water inventory in the steam generator is reduced there is less capacity as a heat sink for the reactor. This means that from a control point of view we are moving in a direction where we have more reactor thermal power than we can handle. Not a desireable situation!

Secondly, if the level falls below the low level tapping on the steam generator, the level control program will not recognize this event and actual level measurement will be lost.

Thirdly, if the steam generator level falls below the top of the tube bundle, dry out will occur and dissolved solids existing in the steam generator will "bake out" onto the external tube surfaces and impede future heat transfer.

The probabilities of the above events occurring are reduced by a low level alarm which may allow some operator action. If this is not successful, a significant reduction in reactor power occurs to restore the match of thermal power of the reactor to the reduced heat sink capacity of the steam generator. The reduction of reactor power may be a setback or trip depending upon operating rationale at the specific station.

B.2.8

The whole concept of changing the programmed level with steaming rates revolves around maintaining adequate heat sink for the reactor.

If you don't think about it, it would appear that the Bruce NGS-A reactor which is 60% larger than Pickering NGS-A doesn't require as large a heat sink. This obviously is not the case. There is a large design difference in the steam generators at Bruce NGS-A not the least of which is the common steam drum which is partly full of liquid and therefore presents a much larger capacity than at Pickering NGS-A. This is the primary reason for the smaller change in steam generator level with power, there is more capacity available for the same level change.

B.2.9

The three elements are:

(a) Steam flow,
(b) Feedwater flow,
(c) Actual level.

The steam flow is used to produce the programmed level.

The comparator circuits look at:

Steam/Feedwater flow
Actual/Programmed level.

At low power levels measurement of steam flow and feedwater flow is not very accurate and control of the feedwater flow via the feedwater regulating valves is insensitive. At this point the steam generator level is more easily handled by the level controller alone without the other two elements.

When the steam flow is in excess of 20% and the large feedwater regulating valve is being used, the three elements may be used to monitor steam generator level.

B.2.10

Every station is going to have different systems and constraints. As a result we can only examine the concepts and then see how the concepts are applied in the operating manuals.

The question does not state whether the boiler is associated with a bank of boilers, furthermore it does not state whether all the boilers have the same high level.

We must make some assumptions. We'll assume that the boiler is in a bank of boilers and is the only boiler with a high level.

At low loads it is common for different boilers to have different steaming rates due to physical positions within the system. It is important to identify the boiler which has the highest steaming rate and ensure that the feedwater trim/isolating valves are left in the full open position.

The high level in the boiler should be reduced by slightly opening the trim valves on the remaining boilers. The objective is to have all the boiler levels at sensibly the same value.

If after adjusting trim valves the levels overall remain high, then this situation may be corrected by reducing the setpoint of the feedwater control valve controller.

This situation is most likely either at low loads where small changes in actual flowrates are going to have a very significant effect, or when reactor power distribution to the boilers is changed by changes in reactor zonal power production.

If there is a danger of boiler high level tripping the turbine then the boiler blowdown valves may be opened to try and prevent this happening.

B.2.11

The three main heat sinks for the steam generator are:

(a) Steam Turbine
(b) Steam Rejection System
(c) Boiler Steam Safety Valves.

Steam Turbine

This is the normal heat sink and is used as a heat sink when the turbine steam flow is used to control the boiler steam pressure.

Steam Rejection System

This is used as the second heat sink and may reject steam to atmosphere or the condenser depending upon the station in question. This system is used if the turbine is not available to remove the excess steam. In this case the offset is removed and the SRV's operate as soon as the pressure setpoint is exceeded.

Boiler Safety Valves

In the unlikely event that neither the turbine nor the SRV's can restore the over pressure the boiler safety valves will lift to protect the steam generator from overpressure.

B.2.12

The "reactor-leading" mode is the 'normal' mode for Pickering NGS-A which means that the reactor power will stay constant whilst the steam flow is adjusted to maintain the pressure setpoint.

If the turbine speeder gear is not controlled by the BPC program then no change in steam flow to the turbine can occur and steam flow from the steam generators will be achieved by opening of the reject steam valves.

The offset which normally applies to the steam reject valves, when the turbine is available to the BPC program, is removed. As soon as the boiler pressure exceeds the setpoint pressure the steam reject valves will start to open.

If the over pressure is such that the large reject valves are needed, then a reactor setback will be initiated to reduce the time taken to restore control.

The reactor setback would stop when the large steam reject valves closed. If this did not happen the reactor would reduce power to 2% FLP.

B.2.13

In the 'reactor lagging' mode of operation the variable power is associated with the reactor. If the steam pressure started to fall below the setpoint pressure the demanded reactor power would be increased to restore the steam generator pressure.

In the event that the steam pressure continued to fall the unit control would change and initiate a slow speeder gear runback until the steam pressure was restored.

B.2.14

The BPC program relies upon being able to change the steam flow from the boiler to change the boiler pressure.

As the steam pressure in the boiler drops the volume of steam increases. For example at 250°C, 1 kg of dry steam has a volume of 50 liters. As the temperature and pressure fall, this volume increases. At 130°C the volume has now increased to 668 liters per kg which is an increase of more than 13 times.

The effect of this increasing steam volume causes the SRV's to open until they reach a point where they are fully open and can no longer reduce the pressure in the steam generator.

This happens at around 170°C. As a result, this is the termination point of cooldown using BPC. Further cooling of the PHT system will take place using the shutdown cooling circuits.

B.2.15

As the pressure in the steam generator is raised, the water boils at a higher temperature, ie, the steam temperature increases. This has the effect of increasing the temperature difference between the steam in the steam generator and that in the condenser. This increased temperature difference means there is more work available in the turbine, which increases the cycle efficiency.

B.2.16

The fuel limits the operating pressure and temperature of the steam generator. The fuel is a ceramic which has very poor heat transfer characteristics. With centre fuel temperature about 2300°C, the sheath temperature is only 350 to 400°C. Allowing for heat transfer from the fuel to the D_2O and heat transfer from the D_2O to the light water in the steam generator, the operating temperature in the steam generator is around 250°C.

If the centre fuel temperature reaches the melting point (at about 2800°C), release of fission product gases from the fuel may contribute to sheathing failure and escape of fission products into the primary heat transport system.

Thus the limiting fuel temperature is 2300°C (allowing a safety margin), which means the maximum pressure available in the steam generator is the saturation pressure corresponding to 250°C, ie, about 4 MPa(a).

J. Irwin-Childs

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HEAT & THERMODYNAMICS

MODULE B.1

REACTOR

Heat & Thermodynamics

MODULE B.1

REACTOR

Course Objectives

The student will be able to:

1. Briefly explain how reactor channel blockage can be detected and may be confirmed.

2. Briefly explain one major problem resulting from channel blockage.

3. Briefly explain why crash cooling is necessary for a leak which results in a very low rate of pressure decrease in the heat transport system.

4. Briefly explain how a loss of heat transport coolant may be detected.

5. Briefly explain how a small loss of coolant may eventually produce fuel failure similar to that expected in a major LOCA.

6. Briefly explain the immediate and longer term effects of losing feedwater supply to the steam generators.

7. Briefly explain how the temperature and quality of the PHT coolant change when bulk boiling occurs.

8. Explain how the PHT thermosyphon is established and how the ROH temperature is used as a datum for the control of the thermosyphon.

Enabling Objectives

The student will be able to:

1. Briefly explain four possible reasons for a high heat transport system pressure.

2. Briefly describe two major problems that could result from a low heat transport system pressure.

The reactor is the first step in our energy transfer process to produce electricity. The control of the reactor is extremely complex in that it is so sensitive to changes in dependant systems, eg, the moderator system, the heat transport system and the steam system. It is virtually impossible to discuss one system without referring to another.

As a heat source, the reactor system has three inputs:

a) Decay heat from fission products.
b) H.T. pump heat.
c) Fission heat.

When at power the fission heat is, by far, the largest of these three terms. At low power, the pump heat becomes significant.

The only ways that the heat produced within the reactor can be removed are by the heat transport system and to a much lesser degree, by the moderator system.

The main purpose of the heat transport system is to remove the heat from the three sources that we have already mentioned, ie, decay and fission heat in the fuel bundles and the pump heat. At power, this is done with a constant mass flow of D_2O.

The main method of removing heat from the heat transport system is via the steam generators. In the event that the steam generators are not available to act as a heat sink for the heat transport system, the reactor is tripped because there is no backup capable of removing the full load reactor power.

When the reactor is in the shutdown state with the heat transport temperature below about 170°C, the shutdown cooling system removes the heat produced by the decay of fission products. The heat from the decay of fission products is less than 6% FLP.

B.1.1

State the three sources of heat to the heat transport system and the two main heat exchanger processes which are used to remove this heat. Compare your answer with the notes at the end of the module.

Before we look at temperature and pressure effects in the heat transport system, let's have a look at a fuel channel and examine more closely some of the conditions which exist.

Going right back to design considerations for the ideal fuel for the reactor, three of the criteria which we would like to satisfy are:

a) The fuel should have a good thermal conductivity.
b) The fuel should not react chemically with the heat transport fluid.
c) The fuel should be dimensionally stable over its life cycle.

The choice that is to be made is between a metallic fuel and a ceramic fuel. If a metallic fuel is used, it reacts readily with hot D_2O in the event of a leak in the fuel sheathing. In addition to this problem, metallic fuel may experience severe mechanical distortion which results in premature sheathing failure.

If a ceramic fuel is used, we have very good dimensional stability but the heat transfer coefficient is significantly reduced in relative terms because a ceramic is a thermal insulator. A ceramic does have one benefit, however. It has a high melting point and the melting point of uranium dioxide is 2800°C.

The temperature profile of a fuel element may be seen from the diagram.

Calculate the total reactor power. Check the notes at the end of the module.

* * * * *

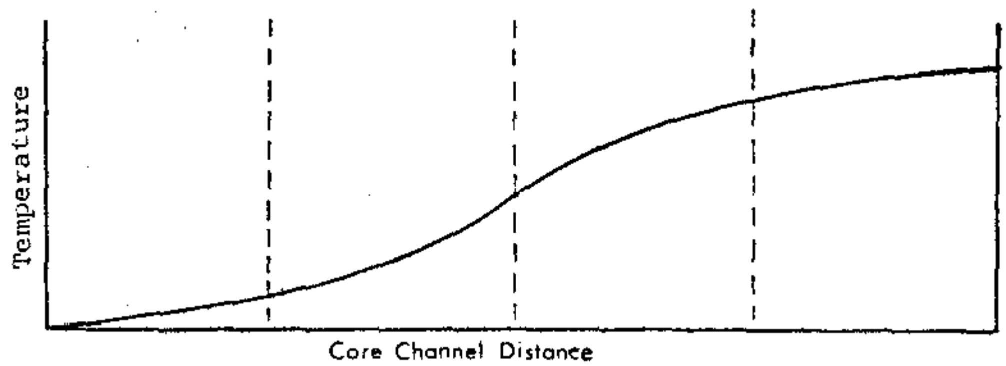
We calculated the total channel power using the mass flowrate and the temperature rise across the channel. In principle, this was relatively easy to accomplish.

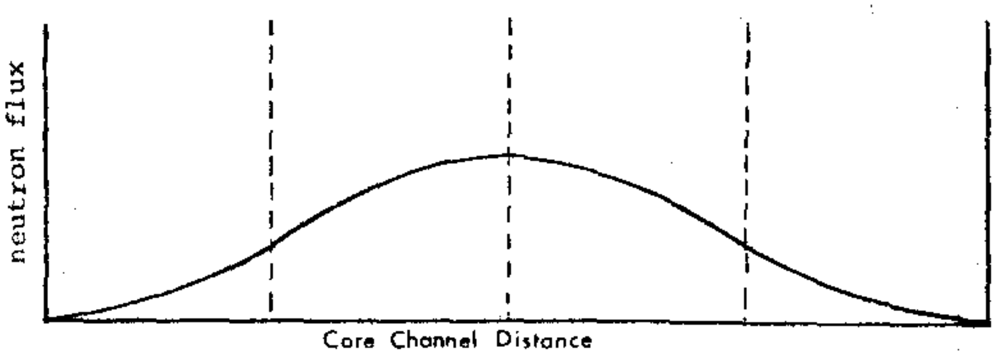
We know that the fuel element sheath has a temperature limit and that the rationale upon which this limit is based is the avoidance of excessive fuel temperatures leading to fuel sheath failure.

How do we know what is happening to the fuel bundles in a particular channel? How do we know if one bundle is being overpowered or being subjected to excessive temperatures? The short answer to both these questions is that we do not know directly what is happening with an individual bundle.

We have to look backwards from the channel coolant temperatures to the basics of fuel channel physics to find out about the individual bundle powers.

The neutron flux distribution along a fuel channel is a familiar shape. It represents the amount of power being produced at that point in the channel and we can see that at the outer sections of the channel, the neutron flux or power levels are lower than in the centre of the channel.





Our main concern is that the fuel bundles which occupy these central positions in the channel are not being subjected to conditions beyond the fuel operating limits.

The basic shape of the flux distribution remains fairly constant although some changes will occur in shape due to positions of control and reactivity mechanisms; direction of fuelling and position of the channel in the core.

In practice, the power distribution along the channel is also affected by the fuel burnup. The effect of the fuel burnup is to produce a power distribution curve which is not the same shape as the flux curve. The major effect of fuel burnup is ignored in this discussion.

By mathematically calculating the area under the flux distribution curve, the channel power may be determined and the power being produced by the fuel bundles in the highest flux region in the centre of the channel may also be determined.

We know the nominal operating bundle power limit; at PNGS-A, it is 636 kW and at BNGS-A, it is 827 kW. The maximum or licensed power limit is 705 kW/bundle at PNGS-A. If any single bundle in the reactor exceeds this value, we have a problem. The reactor is designed so that the operating bundle powers normally remain below this quoted value. However, due to the effects of reactivity mechanisms and fuel burnup on the power distribution, fuel bundles may approach the licensed power limit. In this case, the reactor must be derated to prevent the licensed power limit being exceeded.

In summary, using the flux shape and the maximum values for bundle power, a particular channel is designed to produce a maximum amount of power. Knowing the maximum amount of power and the mass flowrate of the coolant, we could find the temperature rise across the channel that represents this amount of power.

If this temperature rise is exceeded, it would suggest that the channel may be producing more power and in this event, the fuel bundles in centre channel would be operating outside design limits.

The increase in fuel channel temperature rise may not be due to an increase in power.

When we calculated the channel power earlier in the module, we used an equation:

Power = Mass Flowrate x Change in Enthalpy.

Let's expand this a little further:

Power = Mass Flowrate x (Enthalpy Out - Enthalpy In).

Keep the channel inlet temperature constant. Keep the channel power constant. The channel mass flowrate now reduces due to channel blockage.

Going back to the power equation, let's identify those quantities which are constant and see what this produces.

***Power** = Mass Flowrate$\downarrow$ x (Enthalpy$\uparrow$ Out - **Enthalpy In**).*

The Power will remain constant.
The Enthalpy of the coolant into the channel will remain constant.
The change that we now make is to reduce the coolant flow in the channel.

If the channel power remains constant, the only way that this can occur is for the reduced coolant flow to pick up the same amount of heat. In doing so, the enthalpy of the coolant out of the channel becomes greater, ie, the temperature rise across the fuel channel increases.

B.1.4

In the event that a channel blockage occurs, the enthalpy of the coolant leaving the channel rises with the channel power remaining sensibly constant.Explain why the enthalpy of the coolant leaving the channel rises and explain what indications would suggest a blocked fuel channel.

B.1.5

A fuel channel is operating normally with the following conditions:

Channel outlet temperature 296°C.

Channel outlet pressure 8.47 MPa(a).

$(t_s) = 299°C$.

The fuel channel becomes partially blocked and the channel power remains constant. *Explain the change in channel* outlet temperature that would occur as the channel outlet enthalpy rises.

* * * * *

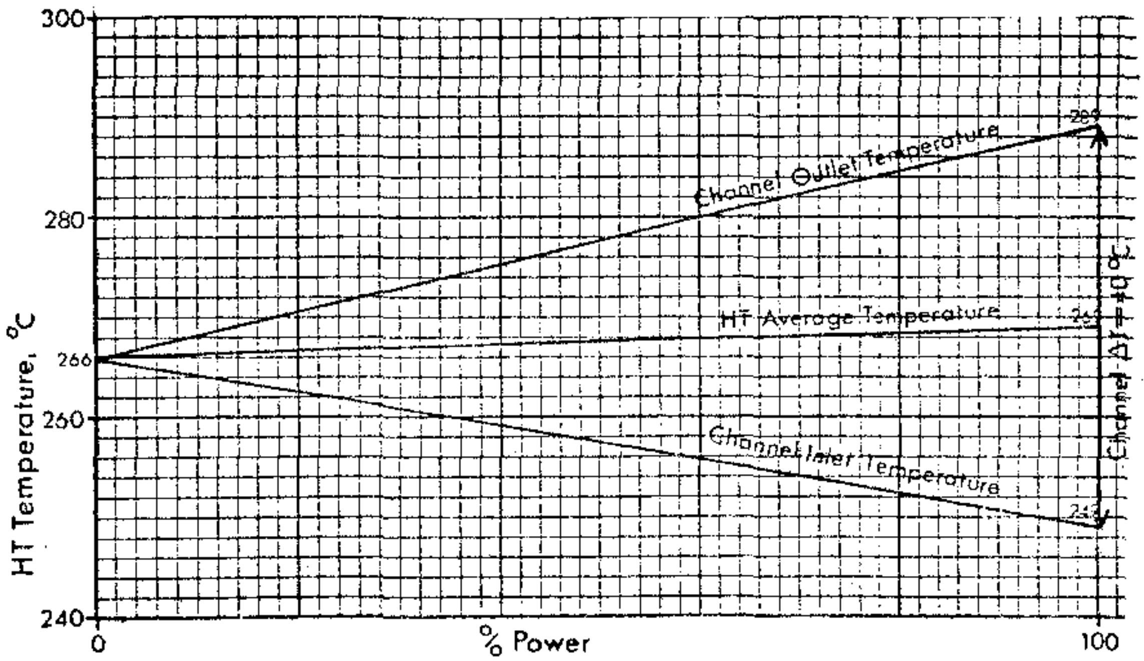
As we have already seen, the channel power with constant mass flowrate, is proportional to the channel ΔT, provided no boiling occurs in the channel.

If the outlet and inlet temperatures are equal, then there is no temperature difference and reactor power is essentially zero. As the power is increased, the channel ΔT increases to a maximum at full power.

At PNGS-A, the channel ΔT at full power is 40°C. At BNGS-A, the maximum ΔT occurs in the inner zone and is 53°C at full power.

There are some significant differences in the method used to obtain the ΔT across the fuel channel at PNGS-A and at BNGS-A.

At PNGS-A, the average primary heat transport temperature is kept sensibly constant, rising from an average value of 266°C at 0% power to an average value of 269°C at 100% power.



From the diagram, we can see that the channel inlet temperature falls as the channel outlet temperature rises and the average temperature stays sensibly constant.

B.1.6

The steam generator and heat transport systems are fully warmed up with the reactor at the zero power level. What pressure and temperature would you expect to find in the steam generator in the PNGS-A example shown above?

B.1.7

In order to transfer heat from the heat transport system to the steam generator, there has to be a temperature difference. How would you expect this temperature difference between the heat transport system and the steam generator to change with unit power increasing from 0 - 100% at PNGS-A?

Check your answers with the notes at the end of the module.

* * * * *

At BNGS-A, the situation between the heat transport system and the steam generator is reversed. The pressure in the steam generator is kept constant at 4.25 MPa(a) from 0 - 100% power.

B.1.8

From the information in the previous paragraph relating to BNGS-A, what is the heat transport average temperature when the unit is at zero power hot.

B.1.9

How would you expect the heat transport average temperature (inner zone) to change with power for the BNGS-A illustration. How would this be reflected in terms of the channel outlet and inlet temperatures? Assume that the channel ΔT at full power is 53°C for inner zone.

Heat Transport Pressure Control

The heat transport pressure is extremely sensitive to changing conditions within the system and has to be controlled within design limits for safe reactor operation.

There are basically two designs of PHT circuit. The 'solid' system has very little vapour space and the PHT system pressure is very sensitive to changes in fluid volume. This design uses a bleed cooler for controlling the pressure of the PHT system. condenser

The second design uses a pressurizer which contains a large volume of D_2O vapour that expands when the liquid volume in the PHT decreases and is compressed when liquid volume increases. This arrangement is very much less sensitive to the changes in PHT volume when controlling pressure.

In a 'solid' system, the change of pressure due to the change of volume, as a result of leakage or temperature, is immediate. In the pressurizer system the rate of change is very much smaller.

A high pressure in the heat transport system may cause over pressure of the heat transport circuit which will result in a reactor trip to safeguard the heat transport circuit.

At PNGS-A, this final high pressure trip occurs at 9.55 MPa(a) and at BNGS-A, the pressure is 9.66 MPa(a).

The heat transport high pressure may be caused by:

a) A loss of reactor power regulation as a result of which the nuclear power now exceeds the heat sink capabilities.

b) A loss of circulation of the heat transport fluid resulting in a loss of heat transport capacity.

c) A loss of heat transport pressure control.

d) A loss of feedwater to the steam generator rapidly reduces the rate at which heat is removed from the H.T. system.

e) Total unavailability of steam generator as a heat sink.

The immediate effect of losing the feedwater is to reduce the heat transfer by around 17% due to the loss of sensible heat required to raise the feedwater temperature from 175°C to 250°C. As a result, the PHT system temperature immediately starts to rise and the liquid volume expands.

As the steam generator tubes become uncovered, the steaming rate decreases because of reduced heat transfer surface area. This situation further accelerates the rise in the PHT system temperature.

In this situation, the primary heat sink for the reactor is lost and the reactor must be shut down quickly and placed on shutdown cooling if massive channel voiding is to be prevented.

This situation represents a large mismatch in thermal power. The PHT pressure will rise rapidly up to the saturation pressure and then more slowly as vapour is produced.

* * * * *

B.1.10

Explain the immediate and longer term effects of losing feedwater to the steam generators.

* * * * *

A low pressure in the heat transport system may be caused by one of two conditions:

a) Large mismatch in thermal power with the steam generator removing more heat than is being produced by the reactor. This causes the PHT fluid to reduce its volume due to the drop in temperature.

b) A loss of coolant from the PHT circuit.

In both cases, the rate of volume reduction may be greater than the make-up from the pressurizing circuit and the PHT system pressure will fall as a result.

A low pressure in the heat transport system may produce the following problems:

a) There is a minimum value of pressure for the heat transport pump suctions to avoid cavitation. If this pressure is reached, a reduction in coolant flow and pump damage will result.

b) As the pressure falls, the heat transport fluid has more heat than is needed to produce saturated liquid at the lower pressure. In this event, the excess heat is used as latent heat to produce vapour. If excessive vapour is produced, then the heat transfer from the fuel bundles drops dramatically and fuel sheath failure will occur due to the rapid rise in fuel temperature.

B.1.11

State the heat transport pressure which produces a reactor trip at your station.

B.1.12

Explain four significant causes that produce a high heat transport system pressure and two major problems that could result from a low heat transport system pressure.

The control of pressure in the heat transport system depends upon how the average heat transport system temperature is changing together with the effect of any additions or subtractions of coolant from the heat transport system. Needless to say, the systems at each station are different!

PNGS-A

At PNGS-A, the major benefit of having the heat transport average temperature sensibly constant is that there are no great changes in heat transport volume due to temperature effects. In addition, the reactor is designed to have no boiling occur in the fuel channels.

Under normal operation, the pressure variations are relatively small and are accommodated using a feed and bleed system.

Bleed flow is taken from the heat transport pump suction headers. This flow tends to reduce the heat transport pressure. Pressurizing pumps return the feed to the heat transport system, thus tending to raise the pressure. The shrink and swell effects of the heat transport system are accommodated by the D_2O storage tank, which also provides the suction for the heat transport pressurizing pumps. Under steady state conditions, there is a balance between the feed and bleed to provide constant pressure.

The pressure relief valves release heat transport D_2O into the bleed condenser. The first valve opens at 9.1 MPa(a) and the rest at 9.55 MPa(a).

In the event of a problem with the bleed condenser that results in high pressure, a relief valve is installed which operates at 8.7 MPa(a) and causes heat transport D_2O to be discharged to the boiler room.

BNGS-A

At BNGS-A, there is a considerable rise in the average heat transport temperature for the whole reactor, from 254°C to around 281°C. This temperature rise will result in an increase of heat transport D_2O volume of approximately 5%. This increase in volume amounts to approximately 17 m^3.

The changes of volume that occur in the heat transport system with power are much larger than at PNGS-A and the technique used to maintain heat transport system pressure control is different.

The pressure control is affected by a pressurizer which acts as a cushion on the heat transport system and absorbs pressure transients. It is similar to a conventional steam drum, having a steam space and a liquid level.

The pressurizer has sufficient capacity to keep the heat transport pressure within the predetermined limits for any normal reactor power manoeuvring.

The heat transport system pressure is determined by the vapour pressure that exists in the pressurizer. If the heat transport pressure rises, steam bleed valves open on the pressurizer to relieve the vapour pressure and thereby reduce the heat transport pressure. The steam from the pressurizer is fed into the bleed condenser.

In the event of a low heat transport pressure, there will be a correspondingly low vapour pressure in the pressurizer. In this case, there are electric heaters which heat the D_2O and produce steam in the pressurizer which increases the pressure in the pressurizer and heat transport system.

In the event of a high heat transport pressure, the liquid relief valves will open and discharge into the bleed condenser. The relief pressure is 9.55 MPa(a). The reactor high pressure trip is set at 9.66 MPa(a).

B.1.13

Briefly explain how the heat transport system volume changes, when hot, from 0% to 100% power level at PNGS-A and BNGS-A.

B.1.14

Briefly explain how the heat transport system pressure is controlled at power at PNGS-A and BNGS-A.

Check your answers with the notes at the end of the module.

* * * * *

A loss of pressure control of the heat transport system is undesirable for obvious reasons. One of the possible indications of high pressure is a rising level in the pressurizer at Bruce and the Bleed condenser at Pickering. This may be due to a reduction of steam flow from the steam generator which causes the PHT temperature to rise.

For whatever reasons, the heat transport fluid is expanding at a greater rate than the control system can handle. The solution to the problem is to reduce the average heat transport temperature so that the volume reduces. The control action on high level in the pressurizer or bleed condenser is a <u>reactor setback</u>. The <u>reactor setback</u> reduces thermal power and restores the match between the thermal power produced by the reactor and the thermal power removed from the steam generator. As the reactor power is reduced, the PHT temperature falls and the volume of the PHT system is reduced.

This problem is compounded at PNGS-A by the fact that the vapour space in bleed condenser is relatively small and will quickly be used up when the heat transport fluid expands. If the bleed condenser goes "solid", the pressure will rise rapidly. This creates a real risk of rupturing the bleed condenser and creating a major LOCA. This event is avoided by the use of pressure relief valves on the condenser.

B.1.15

Explain the significance of a high level in the pressurizer at BNGS-A or the Bleed condenser at PNGS-A and explain the result of the high level from the reactor control program.

B.1.16

A high level in the pressurizer at BNGS-A and a high level in the bleed condenser at PNGS-A is moving towards the setback value. Is there any action that the operator could take to try to control this condition before a programmed reactor setback or a high H.T. pressure trip occurs? Briefly discuss the major effect of any action you suggest.

* * * * *

Pressure Reduction in Heat Transport System

We have looked at the protection that is designed to accommodate high pressures in the heat transport system.

Low pressures in the heat transport system are indicative of three possible situations:

a) Large mismatch in thermal power between the reactor and the steam generator, eg, the inadvertent opening of a large steam reject/discharge valve.

b) A faulty control system which reduces the ability to control heat transport system pressure.

c) LOCA

Suppose the heat transport system was pressurized at 8.00 MPa(a) and the heat transport temperature at this pressure point was 270°C.

How would the condition be shown on a temperature/enthalpy diagram.

B.1.17

Sketch a temperature/enthalpy diagram to show heat transport fluid at 270°C and 8.00 MPa(a). What is the state of the heat transport fluid? (Use H_2O steam tables.)

Check your answer with the notes at the end of the module.

* * * * *

Suppose we start to reduce the heat transport pressure by bleeding off some liquid whilst the temperature remains at 270°C.

B.1.18

Explain what happens when the heat transport pressure reaches and then falls below 5.5 MPa(a) when the temperature of the D_2O is 270°C.

* * * * *

The effect of producing a large quantity vapour in the heat transport system such as occurs in a LOCA, produces several problems.

There is a significant rise in the volume of the heat transport fluid due to the much larger vapour volume produced from the relatively low liquid volume.

The vapour, being much less dense, does not absorb as many neutrons as the liquid and this produces the effect of increasing reactivity.

The most serious effect is on the heat transfer mechanism that exists at the fuel bundle. In the channel, the voiding or production of vapour starts where the temperature of the fluid is highest and the pressure is lowest. In principle, the lowest pressure occurs in the centre of the channel because that is where the flow is highest.

The highest temperatures exist at the fuel bundle sheathing as far as the heat transport fluid is concerned. The normal method of heat removal is by forced convection where the liquid swirls past the bundles and becomes heated.

Nucleate boiling <u>increases</u> heat transfer but in nucleate boiling, the liquid remains in contact with the fuel.

The effect of voiding prevents the liquid coming into contact with the fuel bundle due to the vapour being produced.

The only mechanism by which heat can be transferred at this state is by conduction through the vapour. Unfortunately, the thermal conductivity of vapour is extremely low.

The effect of this reduced heat transfer causes the temperature of the fuel elements to rise so that heat is now being transferred by conduction initially and thermal radiation through the vapour as the fuel sheath temperatures become higher.

The major problem is that in this situation, the fuel sheath temperature starts to rise from around 350 - 400°C towards the fuel temperature of around 2300°C. Zircalloy 4 has a melting point of around 1800°C which means that the fuel is quite capable of melting the sheathing.

Long before the melting point is reached, sheath failure will occur; probably in the range 800 - 1100°C, and release of fission products into the heat transport circuit will result.

The failure mechanism is accelerated by the release of fission product gases from the fuel grain boundaries at the higher temperatures which create a high pressure inside the fuel sheath.

B.1.19

Explain why uncontrolled coolant voiding is undesirable in the reactor.

* * * * *

Voiding of the fuel channel may also occur when the channel flow is reduced. If this only applies to a single channel as would occur due to channel blockage, then the low flow trip will not be effective. If the channel does not have flow monitoring, then there will be no direct indication of reduced flowrate. The only indication will be a channel outlet high temperature alarm.

If voiding of all the fuel channels has occurred due to overall low coolant flow, then the flow monitored channels will produce a reactor trip on low coolant flow.

A second possible cause for the voiding effect is a falling heat transport system pressure. A low pressure alarm alerts the control room operator so that remedial action may be taken.

The values of low pressure alarm are:

PNGS-A 8.5 MPa(a)
BNGS-A 8.92 MPa(a)

Bulk Boiling

Bulk boiling may be designed to occur in the final section of the fuel channel when at full power. In this situation, conditions will change at the channel outlet header as the reactor power is increased.

The channel ΔT will increase with power until the saturation temperature for the PHT pressure is reached. At this point, the D_2O will start to boil, initially at the outlet header, and the temperature will now stay constant at the channel outlet. As the channel produces further power, the temperature will not rise but more vapour will be produced progressing towards the channel inlet as the power is further increased. If 10% boiling was designed to occur, then the fluid leaving the channel would be a mixture of 10% vapour and 90% liquid by weight.

This ratio would be very different by volume, 63% vapour and 37% liquid. Once the temperature reaches the saturation value, the only change with power will be the % of vapour leaving the channel.

In this condition of bulk boiling, it is almost impossible to tell what the vapour fraction actually is and deciding whether a channel blockage exists is a whole new ball game.

One change in flow conditions that will occur with bulk boiling is the mass flowrate, as a rule-of-thumb this will decrease, for the same power, by the % increase in vapour, ie, 20% vapour $\rightarrow$ 80% original flowrate. This decrease is due to the increased enthalpy of the vapour liquid mixture.

* * * * *

B.1.20

Briefly explain how the PHT temperature and coolant quality change as increasing reactor power produces bulk boiling.

Loss of Coolant Accident (LOCA)

In this situation, the prime concern in that the reactor should be shutdown safely. This means the provision of cooling for the fuel at all times.

We could define a LOCA as a condition where the loss of coolant was at such a rate that the ability to maintain heat transport system pressure was lost.

At either end of the scale, the two extremes are:

A Massive rupture of heat transport circuit where the pressure is lost almost immediately, and

A Smaller loss rate where the heat transport system pressure is falling gradually.

Small LOCA

In this situation the pressurizing system should be able to maintain pressure in the PHT. If the pressurizing system is unable to maintain pressure, the pressure in the heat transport system will fall gradually until the saturation pressure is reached. At this point, bulk boiling in the channel occurs and rate of pressure decrease is reduced or even halted.

The problem is now that the pressure transient will stabilize and the fuel sheath will become damaged due to the loss of heat transfer resulting from the steam which blankets the bundle. This happens in a very short time; a few minutes from the commencement of bulk boiling.

The solution to this problem is to remove the heat from the reactor at a greater rate. This can be done in a "crash-cool" exercise by opening up the steam reject/discharge valves. This has the effect of cooling the heat transport fluid rapidly and minimizing the vapour formation.

The pressure and temperature in the heat transport system will fall rapidly to the lower pressure at which Emergency Injection can begin.

Major LOCA

In a loss of coolant condition where the breach in containment is massive, the drop in both temperature and pressure will be very rapid. Consequently, the system will have already been "crash-cooled" by the massive leak and Emergency Core Injection may begin.

Emergency Core Injection System

The emergency core injection system is designed to remove the fission product decay heat from the fuel following a LOCA. The reactor power drops from 100% to around 6% before the injection occurs. The 6% full reactor power represents the initial decay heat from the fission products.

At PNGS-A, the injection into the reactor core uses the moderator system and so injection can only occur when the heat transport system pressure has fallen below the moderator pump discharge pressure.

At BNGS-A, light water is used on a gravity feed circuit from a dousing tank housed in the top of the vacuum building. In this case, the heat transport pressure must fall below the static head of the dousing tank before injection can take place.

In both stations, the injected fluid discharges via the rupture to the vaults and boiler room sumps or the fuelling machine duct and is recovered and pumped back into the reactor. Obviously at BNGS-A, there is no highly tritiated moderator D_2O contaminating the station which is an advantage.

Indications of Loss of Coolant

At both PNGS-A and BNGS-A, the heat transport D_2O storage tank accommodates the changing volume of the heat transport fluid. A low level alarm alerts the operator to the fact that there may be a problem, even if the problem is merely due to not having changed the level set point when power manoeuvring.

A loss of heat transport system pressure may be a first indication of loss of coolant.

If the D_2O is leaking into the boiler room, a boiler room high pressure trip may result. Beetle alarms would confirm this leakage. (Note a steam leak would produce similar results.)

If the loss of coolant resulted in voiding in the fuel channel due to low pressure, then the resultant positive reactivity may produce Hi Linear Rate Trip, Hi Log Rate Trip, Hi Power Trip on the reactor.

B.1.21

Explain two conditions which would result in channel voiding.

B.1.22

Explain how a loss of heat transport coolant may be detected.

B.1.23

Explain the effect of a Loss of Coolant on the heat transport system that is large enough to cause a loss of heat transport pressure. Describe the basic steps leading to emergency core injection.

B.1.24

How does a massive rupture in the heat transport system affect the rationale explained in B.1.21?

B.1.25

Explain the basic emergency core injection system at PNGS-A and BNGS-A.

Heat Transport Thermosyphon

As fluids are heated they become less dense and equally, as they are cooled, they become heavier. By carefully selecting the elevations of the reactor and the steam generators, the thermosyphon may be established.

The hot D_2O leaves the outlet headers and is physically pumped up to the steam generator where it travels up one side and returns as cooler fluid, down the other side of the tube nest, back to the reactor via the PHT pump.

Under the correct conditions, the flow as described previously, will occur without the pumps due to the natural convection caused by the temperature differences within the D_2O.

The thermosyphon can only exist all the time that the steam generator is at a lower temperature than the PHT circuit and that there is no vapour or gas in the PHT circuit which would collect at the top of the tubes in the steam generator.

The temperature at reactor outlet is used to control the thermosyphon. If the PHT temperature is rising towards the saturation value, vapour may be produced which would prevent the thermosyphon continuing. More heat must be removed from the PHT system and this is achieved by lowering the temperature of the steam generator by removing more steam and thereby lowering the pressure. It maybe possible to raise the PHT system pressure to a value above the saturation value.

If non-condensible gases collect in the steam generator tubes, the thermosyphon will stop and reactor cooling will be lost and the reactor temperature will start to rise and other heat sinks must be used.

* * * * *

B.1.26

Briefly explain how the PHT thermosyphon is established and how ROH temperature is used as a datum for the control of the thermosyphon.

You have almost finished this program. Look at the objectives and if you feel you are ready for the criterion test, obtain the test from the Course/Shift Manager.

* * * * *

When you have completed the test, compare your answers with the self evaluation sheet.

* * * * *

After you have been signed off by the Course Manager, please take time to complete the course evaluation form and let us know what we can do to make this course more suited to your needs, in format and content.

Answers

MODULE B.1

REACTOR

B.1.1

The three sources of heat for the reactor are:

a) Fission heat from the fuel.
b) Heat from the decay of fission products.
c) Heat produced by the operation of the H.T. pump.

Under power operating conditions, the heat generated by fission within the fuel is by far, the largest of these heat sources. The heat removed by the flow of the heat transport fluid is exchanged in the steam generator.

In a shutdown condition, the quantities of heat produced are relatively small, (less than 6% of full load power) and are handled by the shutdown cooling system.

B.1.2

As explained in the notes, the heat output from the fuel channel may be expressed as $\overset{o}{Q} = hA\Delta T$

where $\overset{o}{Q}$ is the rate of heat transferred.
h is the heat transfer coefficient which does not alter significantly.
A is the area for heat transfer which is fixed.

The only variable on the right-hand side of the equation is ΔT which is the temperature difference between the hot surface and the coolant.

Thus, if $\overset{o}{Q}$ doubles, then ΔT must double.

We can see this on raising a reactor from 50% power to 100% power. If at 50% power, the channel ΔT is 20°C, doubling the reactor power to 100% will raise the channel ΔT to 40°C, provided no bulk boiling occurs.

For most changes in power, the temperature difference varies directly as the power.

B.1.3

The change in enthalpy across the channel is

$$h_{f_{300}} - h_{f_{250}}$$

$$= 1297 - 1051$$

$$= \underline{246} \text{ kJ/kg}$$

The channel mass flowrate is 24 kg/s.

Channel Power = Mass Flowrate x Change in Enthalpy

kJ/s = kW = kg/s x kJ/kg

$$= 24 \times 246$$

$$= \underline{5904} \text{ kW (thermal)}$$

Total power from 420 channels

$$= 420 \times 5904$$

$$= 2479680 \text{ kW}_{th}$$

Total reactor power = $\underline{2480}$ MW_{th}

This compares with total reactor power at PNGS-A of 1665 MW_{th} and at Bruce of 2392 MW_{th}.

B.1.4

From the text, we saw that channel power was determined by the flowrate and the change of enthalpy across the channel, ie, $\overset{o}{Q} = \overset{o}{m}$ x Change of Enthalpy

where $\overset{o}{Q}$ is the channel power, and

$\overset{o}{m}$ is the channel mass flowrate

The channel power remains constant and the channel flowrate decreases. In this event, the change in enthalpy must increase in direct proportion with the falling flowrate.

$$\mathring{Q} = \underset{\downarrow}{\mathring{m}} \times \overset{\uparrow}{\text{Change of Enthalpy}}$$

The change in enthalpy is the difference between channel outlet enthalpy and channel inlet enthalpy. However, the channel inlet enthalpy remains constant. Thus, the only way that the change of enthalpy across the channel can rise, is for the channel exit enthalpy to rise. In other words, the only variables were the flowrate which was decreasing, and the exit enthalpy which had to increase in direct proportion to maintain constant channel power.

One of the first indications of channel blockage would be a rise in the channel outlet temperature. This assumes that no channel voiding is going to occur.

It may be possible to monitor the pressure at either end of the fuel channel using the fuelling machines. The pressure drop is due to that of the fuel plus blockage. This may be compared with similar channels or previous readings.

B.1.5

As explained in the previous question, the temperature will start to rise until it reaches 299°C which is the saturation temperature corresponding to 8.47 MPa(a). At this point, a change of state occurs and the liquid is being turned into vapour within the channel and voiding of the channel is taking place but the temperature will not rise above 299°C.

Suppose the channel had been operating with a designed 10% boiling - how would you know if there was a channel blockage?!

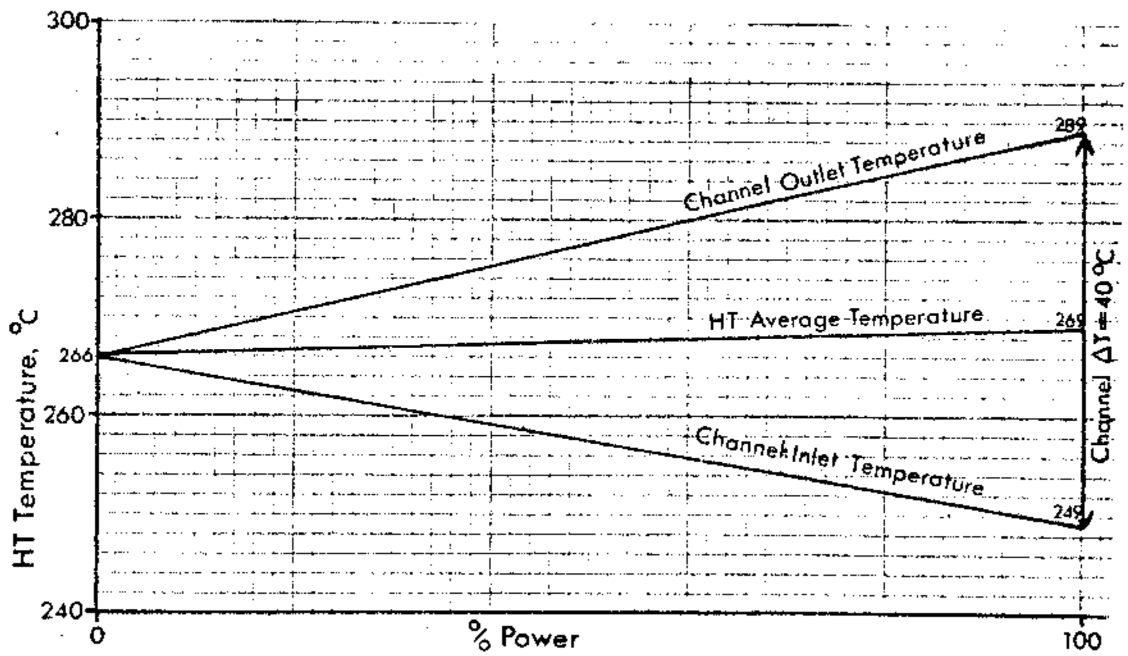
B.1.6

At zero power, the steam generator temperature, channel inlet and outlet temperatures, would all be equal at 266°C. The saturation pressure corresponding to 266°C is 5.17 MPa(a). This is the pressure which would exist in the steam generator at this temperature.

B.1.7

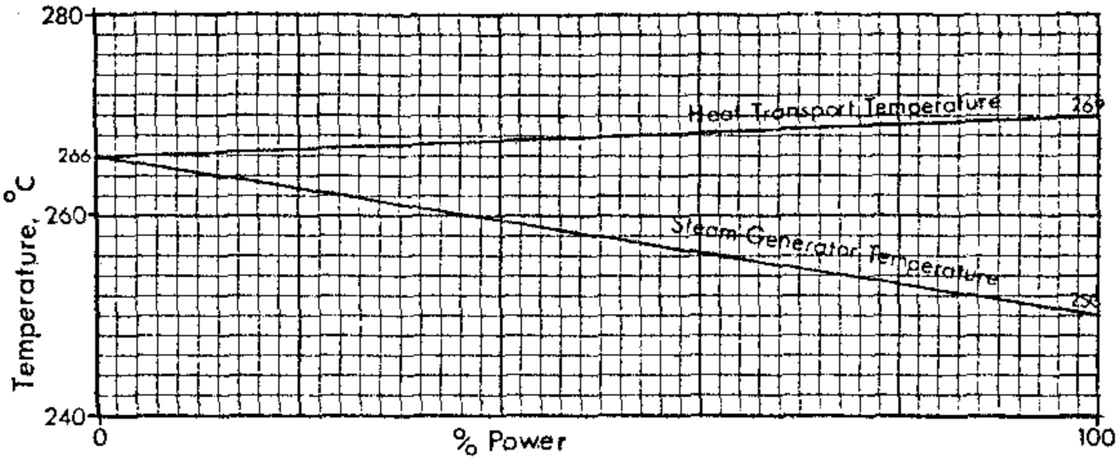
In this case, the heat transport average temperature is almost constant. At zero power but at operating conditions, the steam generator temperature will be equal to the average heat transport temperature.

To transfer thermal energy to the steam generator, a temperature difference must exist. The only way that this can happen is for the steam generator temperature to fall with increasing power. It cannot rise because the reactor is the heat source, not the steam generator. The temperature in the steam generator will always be less than the average heat transport temperature when at power.



The thermal reactor power is around 1665 MW at PNGS-A and this energy is transferred in the steam generator with a maximum temperature difference between boiler inlet and boiler outlet of 40°C - same as the channel ΔT because channel outlet = boiler inlet and boiler outlet = channel inlet.

As the temperature in the steam generator falls from 266°C to 250°C, the pressure falls from 5.17 MPa(a) to around 4 MPa(a). This falling pressure of steam flow is entered into the boiler pressure control program.

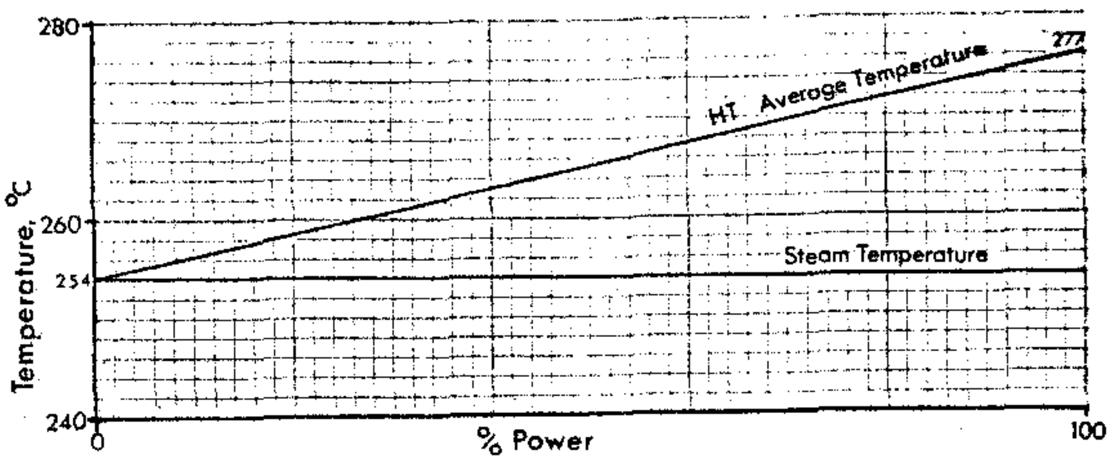


B.1.8

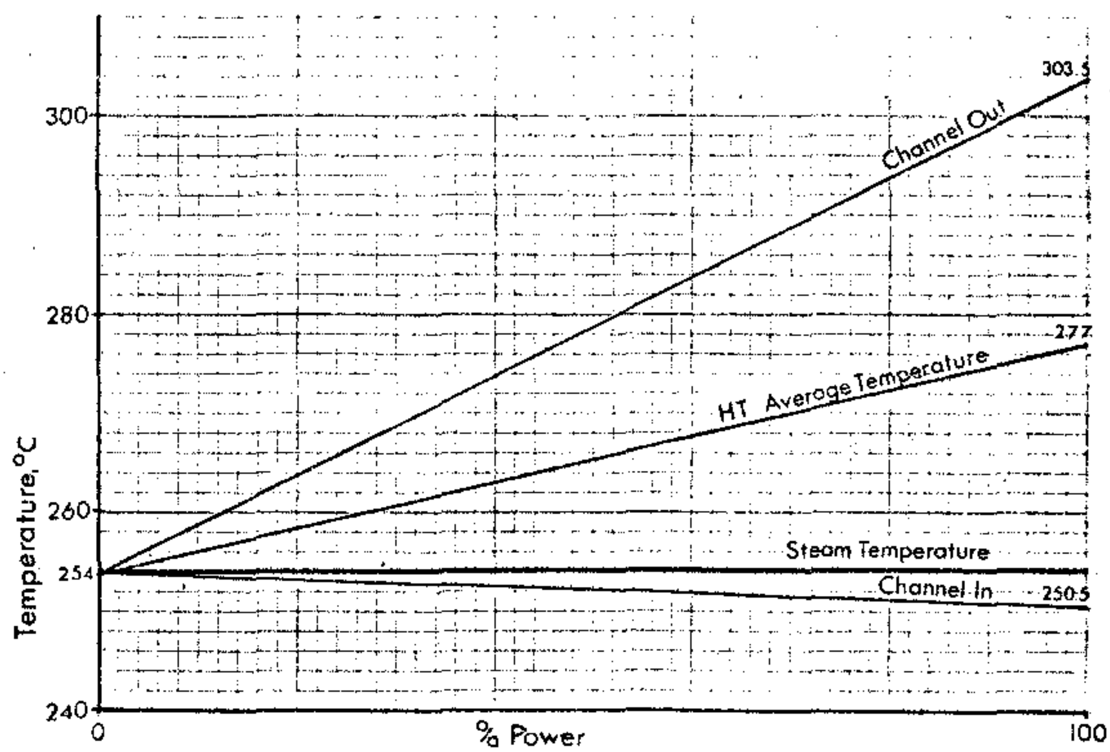
At zero power when the steam generator and reactor are at operating temperature, the average heat transport temperature and the steam generator temperature will be sensibly equal. If the steam generator pressure is 4.25 MPa(a), then the temperature is 254°C. At this condition, the heat transport average temperature is also at 254°C.

B.1.9

At BNGS-A, the steam generator temperature is going to remain constant between 0% and 100% full power. In order to transfer the heat to the steam generator, there must be a temperature difference between the heat transport fluid and the steam generator. In addition, the average temperature of the heat transport fluid must be higher than that of the steam generator. This is shown in the diagram where the average heat transport temperature leaves the steam temperature at 254°C and rises to a higher value around 277°C. The important point to note is that the average H.T. temperature rises - you couldn't determine that the H.T. temperature was 277°C. This is complicated by the arrangement of inner/outer zones with the heat transport precoolers.



At full power, the channel ΔT will be 53°C in which case the channel outlet temperature will be 26.5°C above the average value and the channel inlet temperature will be 26.5°C below the average value.



These figures have been simplified to show the trends. The design channel inlet temperature for the inner zone is 250.5°C and 265°C for the outer zone. At full power, the design channel outlet temperature is 304°C. These values have been modified to operate the reactor with no boiling in the channels.

B.1.10

Feedwater is heated in two stages in the steam generator. Initially, the temperature is raised from around 175°C to 250°C as sensible heat is being added. Secondly, the liquid is turned into vapour as the latent heat of vapourization is added.

The immediate effect of losing feedwater to the steam generator is a reduction of heat transfer capacity, around 17%, due to the sensible heat which is no longer being removed. At this point, thermal inequilibrium occurs and the PHT average temperature starts to rise.

As the level in the steam generator falls below the top of the tube bundle, heat transfer is further reduced due to the reduce heat transfer surface area available and the PHT system average temperature rises faster than before.

These conditions may both result in a massive thermal power mismatch as a result of having lost the major heat sink.

B.1.11

At PNGS-A, the high pressure trip on the heat transport system occurs at 9.55 MPa(a).

At BNGS-A, the heat transport high pressure trip occurs at 9.66 MPa(a).

B.1.12

A high pressure in the heat transport system will normally result from a high temperature. This condition will arise when there is an imbalance in the rate at which heat is being produced by the reactor and the rate at which heat is rejected in the steam generator. More specifically, if the temperature is rising in the heat transport system, it is because the steam generator is not removing heat from the heat transport system at the same rate. This situation may arise in the event of loss of feedwater to the steam generator when the rate of heat transfer will rapidly reduce and result in an increased H.T. temperature and pressure.

This may occur if the reactor power exceeds the heat capacity of the steam generator. Such a condition may arise due to a loss of reactor power regulation. In this case, the heat transport flowrate is unchanged but the total heat has increased beyond the capacity of the steam generator and results in an increase of heat transport temperature and pressure.

A loss of H.T. pressure control may also result in a high pressure in the H.T. system.

The steam generator is unable to act as an effective heat sink if the heat transport flowrate decreases. In this situation, the reactor power has to be removed by a reduced mass flow which means that the heat transport averages temperature and therefore, pressure rises.

The two major problems of a low heat transport pressure concern the effect that vapour production within the D_2O has on (a) Heat Transport Pumps, and (b) Fuel in the Channel.

To avoid cavitation in the heat transport pumps, there is a minimum suction pressure below which the heat transport pressure should not fall. This value of suction pressure depends upon the temperature of the heat transport D_2O. If cavitation does occur, pump damage may result. In addition to this effect, the flow through the pump will be reduced and this could result in an increase in heat transport temperature due to the reduction of flow through the reactor.

If the heat transport pressure drops to the saturation pressure corresponding to the heat transport temperature, vapour will be produced in the fuel channel. If large scale voiding occurs, this will drastically reduce the heat transfer from the fuel to the D_2O. The result will be a rapid increase in fuel and sheath temperatures which will produce fuel sheath failure and fuel damage if not prevented.

B.1.13

At PNGS-A, the reactor design was such that the volume of the primary heat transport system should remain sensibly constant over the whole reactor power range. The average heat transport temperature only changes by 3°C, from 266°C at 0% to 269°C at 100% power. This change in average temperature of 3°C means that the change in fluid volume is less than 1%. Boiling in the fuel channels is not a designed feature at PNGS-A.

At BNGS-A, there are two major differences when compared to PNGS-A:

a) the average heat transport temperature rises by some 27°C.

b) boiling was designed to occur in the fuel channels, but operating limitations have resulted in reactor operation with no channel boiling.

There is a significant increase in heat transport volume as the power is increased from 0% to 100%. The increase in volume amounts to 17 m^3.

B.1.14

As we have already seen, the volumetric expansion of the heat transport system at PNGS-A, when at power, is not very large.

Control of the heat transport system pressure is effected by feeding D_2O into the heat transport circuit using the pressurizing pumps and by bleeding D_2O from the circuit at the heat transport pump suction headers. The shrink and swell of the heat transport system is accommodated by the D_2O storage tank.

If low pressure exists in the heat transport circuit, the bleed valves will close and, conversely, if high pressure exists, the bleed valves will open to reduce the system pressure to the programmed value.

At BNGS-A, the change in heat transport volume with power is much larger than at PNGS-A and exceeds the rates of change which could be handled easily with a feed and bleed system alone.

The heat transport system is connected to a pressurizer which is partially full of D_2O liquid. The pressurizer acts as a receiver for the D_2O resulting from the heat transport swell and also acts as a pressure control device. The vapour space is compressible and acts as a cushion for any pressure fluctuations.

If the heat transport pressure is high, the steam bleed valves on the pressurizer opens to reduce the system pressure. If the system pressure is falling, electric heaters in the pressurizer raise the pressure in the vapour space and increase the heat transport pressure.

B.1.15

At both PNGS-A and BNGS-A, a high level in the vessel controlling reactor pressure is taken as an indication of loss of ability to control the heat transport pressure.

The heat transport system is expanding at a greater rate than can be handled by the pressure control circuit.

In the short term, the only way that the heat transport system volume can contract instead of expand is as a result of the temperature being reduced, either by increased steam flow or a reduction in reactor power.

At PNGS-A, a high level in the bleed condenser will initiate a reactor setback. A major problem with the bleed condenser is that as soon as the vapour space disappears, the condenser will go solid. At this point, the pressure will rise rapidly and there is a danger of rupturing the bleed condenser. Bleed condenser relief valves discharge into the boiler room to prevent the rupture of the condenser.

At BNGS-A, *the inability to control reactor heat transport* pressure as seen by a high level in the pressurizer, also results in a reactor setback.

B.1.16

As discussed in the previous question, the rise in level in the pressure controlling vessel is the result of an inequilibrium between the expansion rate of the heat transport fluid and the bleeding rate of the pressure control system.

We can restore this equilibrium by reducing the temperature of the heat transport system. This may be done by two methods:

a) *removing more heat from the heat transport fluid.*

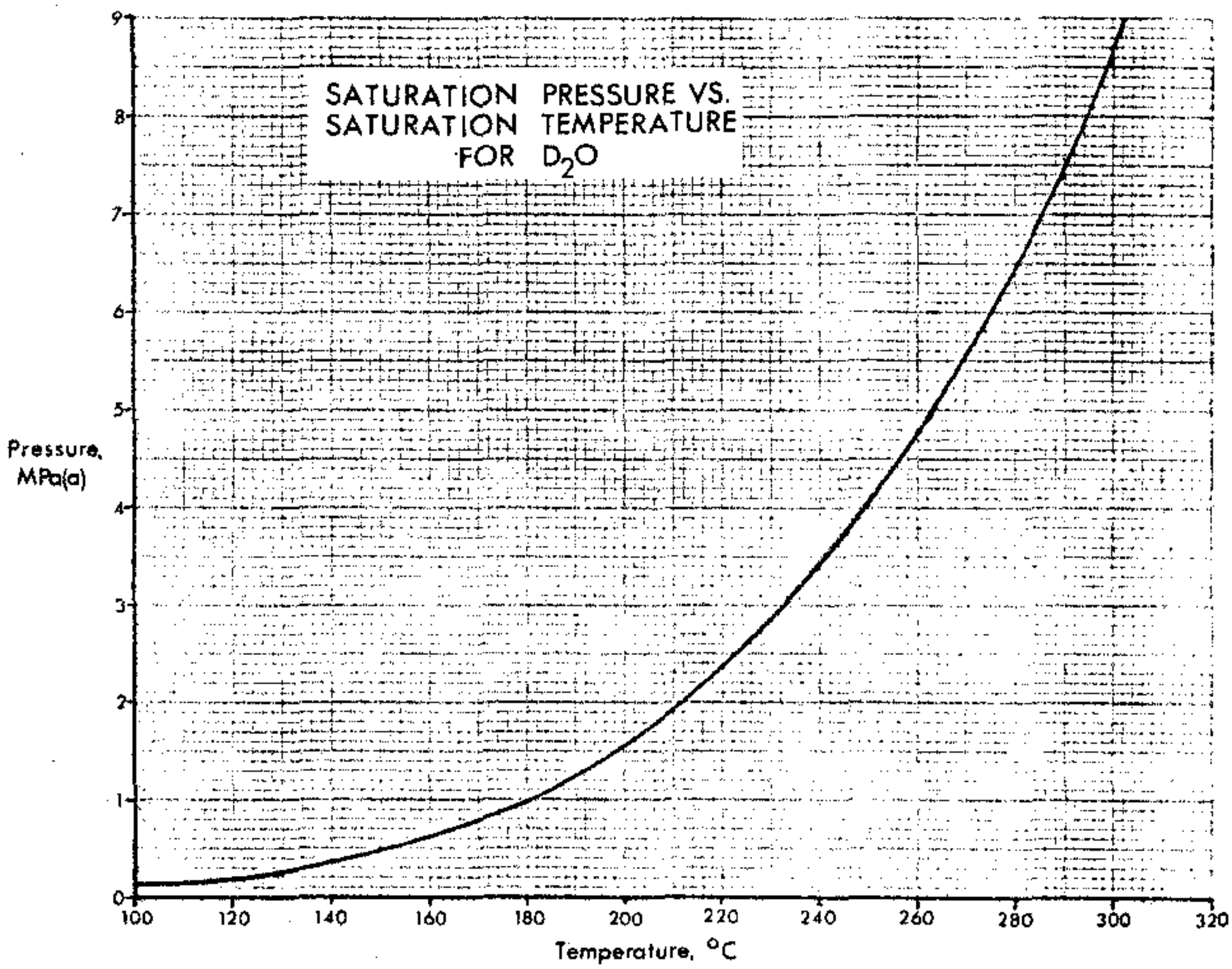
b) producing less heat in the reactor.

If the turbine is at full load, steam may be rejected from the system via the steam reject valves or the steam discharge valves. This action will produce a significant increase in the heat sink capacity to the reactor and quickly reduce heat transport temperature.

A reduction in reactor power will produce the same effect. The time taken will depend upon the setback rate that is input. This is the normal reaction.

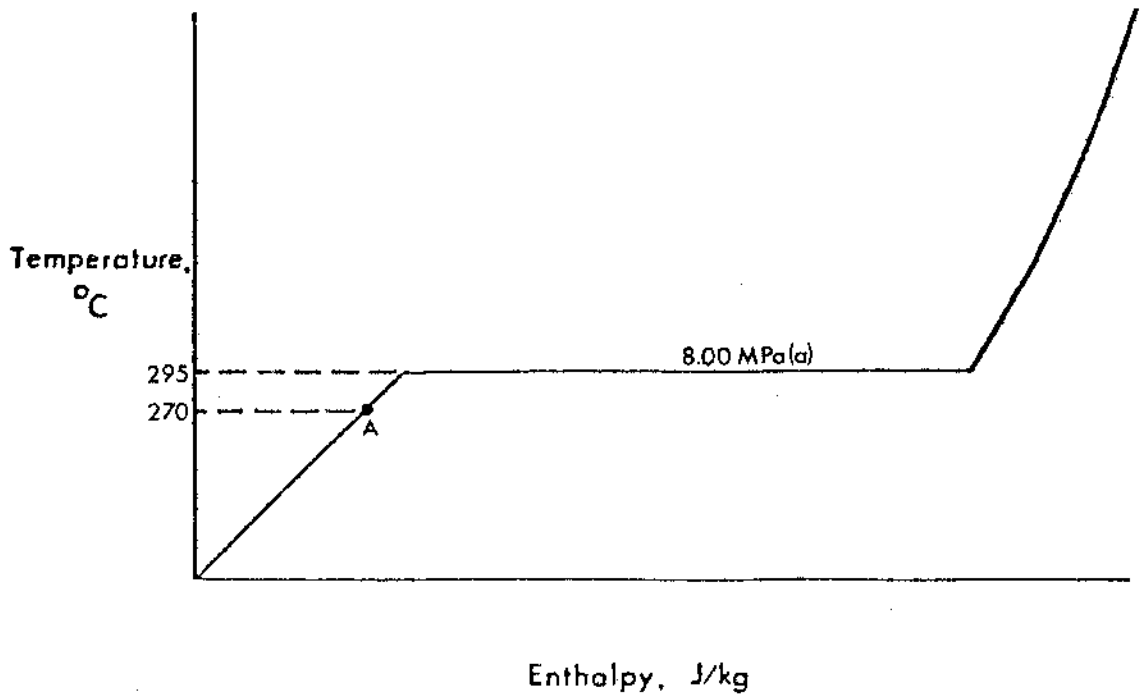
The effect of opening a large steam valve will cause the heat transport fluid to shrink at a greater rate than can be matched by the heat transport pressure control system and the temperature will fall. As soon as the pressure reaches the saturation value, the heat transport system will start to boil and cause voiding in the fuel channel.

The operator must closely watch that the heat transport pressure does not reach the saturation pressure if channel voiding is not to occur.



The graph of saturation pressure/temperature is useful to compare actual heat transport pressure with the saturation pressure corresponding to the H.T. temperature. The actual H.T. pressure should always be higher than the saturation pressure.

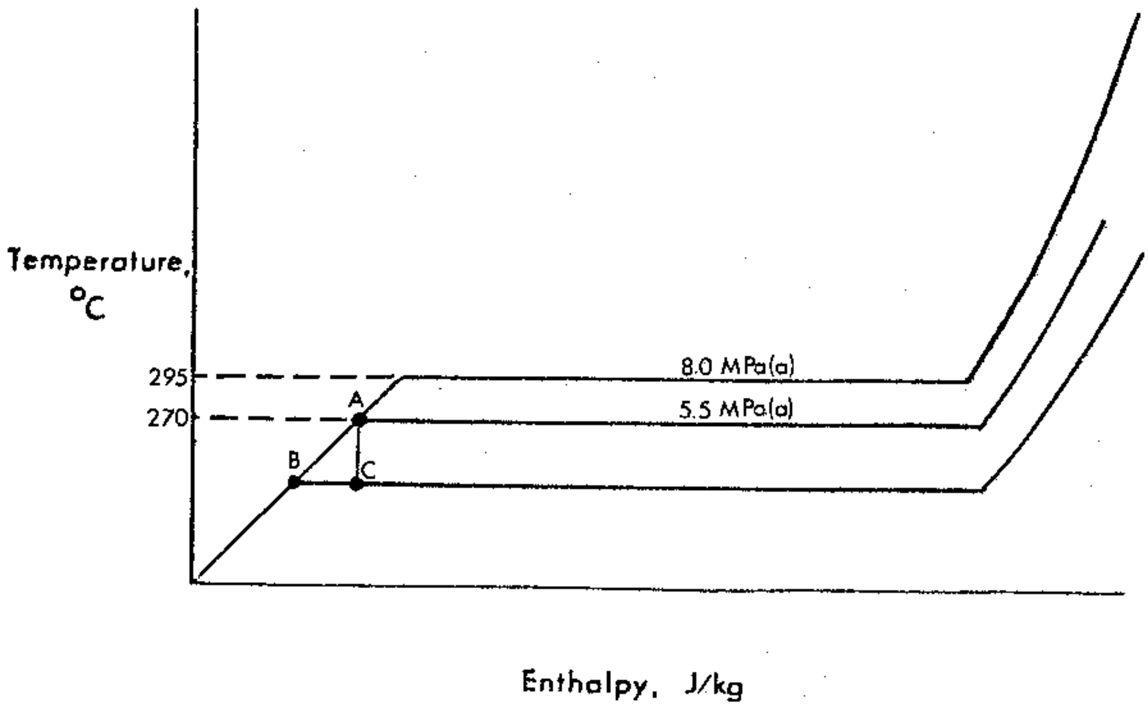
B.1.17



At 8.0 MPa(a) from steam tables, the saturation pressure is 295°C. The actual temperature of the heat transport liquid is 270°C which means that it is subcooled by 25°C.

B.1.18

When the pressure has fallen to 5.5 MPa(a), the corresponding saturation temperature is 270°C. This is also the actual temperature of the liquid. Any further reduction in pressure will result in bulk boiling as the enthalpy, which is in excess of that needed for saturated liquid, supplies the latent heat of vapourization for vapour production.



The enthalpy of the fluid does not change. At point A, there is saturated liquid at a pressure of 5.5 MPa(a). If the pressure was to fall to a lower value, there would be a two-phase fluid. These two phases would be:

1. saturated liquid at point B.

2. vapour generated with the enthalpy B-C. You can see that for saturated liquid, the enthalpy at B is less than that at A.

B.1.19

The main concern with channel voiding is the loss of heat transfer that occurs due to the poor heat transfer through the D_2O vapour compared with the heat transfer to the liquid.

Although zircalloy 4 has a melting point of around 1800°C, sheath failure is likely to occur between 800 - 1100°C.

Loss of fuel containment and the release of fission products are major considerations that depend upon the integrity of the fuel sheath.

The fuel temperature at the centre of the pencil is around 2300°C and the melting point is around 2800°C. A loss of cooling as occurs when the channel is voided, could result in a fuel meltdown if no action was taken.

B.1.20

When the liquid coolant has reached the saturation temperature and vapour is about to be produced, the temperature rise will stop. From this point on, we have little idea of what is actually happening in the channel with respect to boiling. There may be 8% or 80% vapour being produced.

As power is increased, more vapour is produced at constant temperature. The channel ΔT is no longer an indication of channel power.

B.1.21

The two basic conditions which will result in channel voiding are:

a) a reduction of coolant flow.

b) a loss of heat transport system pressure.

As the coolant flow is reduced, the temperature has to rise in proportion to the loss of flow so that the same quantity of heat is removed. As soon as the temperature of the coolant reaches the saturation temperature, vapour generation begins and channel voiding occurs. Once vapour production starts, the coolant temperature remains constant.

If the pressure falls to the saturation pressure corresponding to the temperature of the heat transport coolant, *vapour production will begin and again, channel voiding will* result. The production of large volumes of vapour has the effect of reducing or even arresting the rate of pressure reduction. This is a dangerous condition because once this has happened, the channel voiding is established and fuel overheating has commenced.

B.1.22

The loss of coolant may still be contained within the system, eg, the D_2O may be leaking into the boiler or the loss of coolant may be leaving the system due to leak in the circuit.

A low level in the D_2O storage tank may be an indication of loss of coolant from the heat transport system.

A loss of heat transport pressure may also be an indication.

If the leakage is external and large as in a LOCA as opposed to a leak, high boiler room pressure trip and Beetle alarm would indicate leakage of D_2O or steam.

B.1.23

If the leak is large enough that the heat transport system pressure starts to fall, then channel voiding will occur at the saturation pressure. At this point, the rate of pressure decrease will reduce and the rate may even be zero as vapour is produced in the channel.

Also, at this point channel, voiding is established and fuel heat transfer is dramatically reduced.

The objective is to re-establish fuel cooling as soon as possible which means that liquid must rewet the fuel bundles.

The reactor is crash cooled using the steam reject/discharge valves. This exercise reduces the heat transport system pressure and temperature in a few minutes.

As soon as heat transport pressure falls low enough, emergency injection can commence. This provides another source of coolant if there is not enough heat transport D_2O left in the circuit to maintain cooling.

B.1.24

The basic difference between a large leak and a massive loss of coolant is the time taken for the system pressure to fall. In a large leak situation with crash cooling, the time scale is in the order of minutes. With a massive loss of coolant, the crash cool exercise and loss of pressure have virtually occurred simultaneously. As a result, emergency core injection can begin immediately. This reduces the time between the loss of pressure when voiding of the channel occurred and the point when emergency core injection commenced. Whether the injection will keep the fuel cool enough to prevent sheath failure is an extremely complex problem depending on the physical position of the rupture, size of the system break, operating condition of the reactor prior to the loss of coolant, etc. It is difficult to state with any accuracy, the degrees of success that will result in a given set of circumstances.

What we can say is that whatever else may occur in any postulated reactor condition, the fuel will not become unsafe due to loss of coolant.

B.1.25

At PNGS-A, the emergency injection system uses moderator D_2O. Consequently, injection cannot occur until the heat transport pressure has fallen below the moderator pump discharge pressure.

At BNGS-A, the emergency injection is by gravity feed from a dousing tank in the top of the vacuum building. The injection cannot occur until the heat transport pressure drops below the static head of the tank.

A pressurized tank is currently being installed at BNGS-A to speed up the emergency core injection process.

B.1.26

The primary heat sink, which is the steam generator, is physically higher than the reactor. The less dense D_2O will rise up to the steam generator whilst the D_2O that is cooled in the steam generator, will become more dense and fall to the suction of the PHT pump.

This condition will prevail with no pumps running, provided that the thermosyphon is not lost. The thermosyphon may be lost if vapour or gases collect in the top of the tubes in the steam generator.

The ROH temperature is monitored to ensure that it does not reach the saturation value when vapour would be produced. ROH temperature is also used to ensure that sufficient temperature difference exists between the steam generator and the reactor. This condition can be ensured by lowering the steam generator pressure and hence the temperature.

J. Irwin-Childs

Self Evaluation

MODULE B.6

BASICS

1. Define the following terms:

   (a) Temperature - "A measure of the quality of heat that a body possesses" - "A measure of the degree of hotness a body possesses".

   Your definition should make certain that you are defining the quality of heat and not the quantity.

   (b) Heat - "A quantity of energy that a substance possesses due to its temperature, specific heat and mass."

2. In explaining the meaning of the following terms you should cover the points detailed:

   (a) Saturation temperature - is the temperature at which the change of state from liquid to vapour occurs and it depends upon the pressure of the fluid.

   (b) Sensible Heat - is the heat which is needed to raise the liquid temperature from 0°C to the saturation temperature. You could also describe sensible heat as the heat which when added to the liquid will cause a temperature rise.

   (c) Latent Heat of Vapourization - is the energy which is required to change the state of the fluid from liquid to vapour. Whilst this heat is being added the fluid temperature remains constant.

   (d) Subcooled Liquid - describes any liquid which exists below the saturation temperature for the pressure of the liquid. It is liquid which has not received all its sensible heat.

   (e) Saturated Liquid - describes a specific condition, ie, when the liquid has received all its sensible heat and has therefore reached the saturation temperature. Any further addition of heat will cause a change of state in which the liquid is changed into vapour.

(f) Wet Steam - describes the region between the two extremes of saturation. At one end with minimal enthalpy is the saturated liquid. As the enthalpy is increased vapour is generated. As the enthalpy of the fluid is further increased the ratio of vapour/liquid increases as more liquid is used to generate steam until finally there is no liquid remaining and there is 100% steam still at the saturation temperature. Wet steam describes the condition anywhere between these two limits.

(g) Saturated Steam - is steam which has received all its latent heat and is still at the saturation temperature. It contains no liquid and is sometimes referred to as 'dry steam'.

(h) Superheated Steam - This steam is now behaving more like a gas and exists at a temperature above the saturation temperature and therefore cannot possibly have any moisture content.

3. Your graph should look similar to this one:

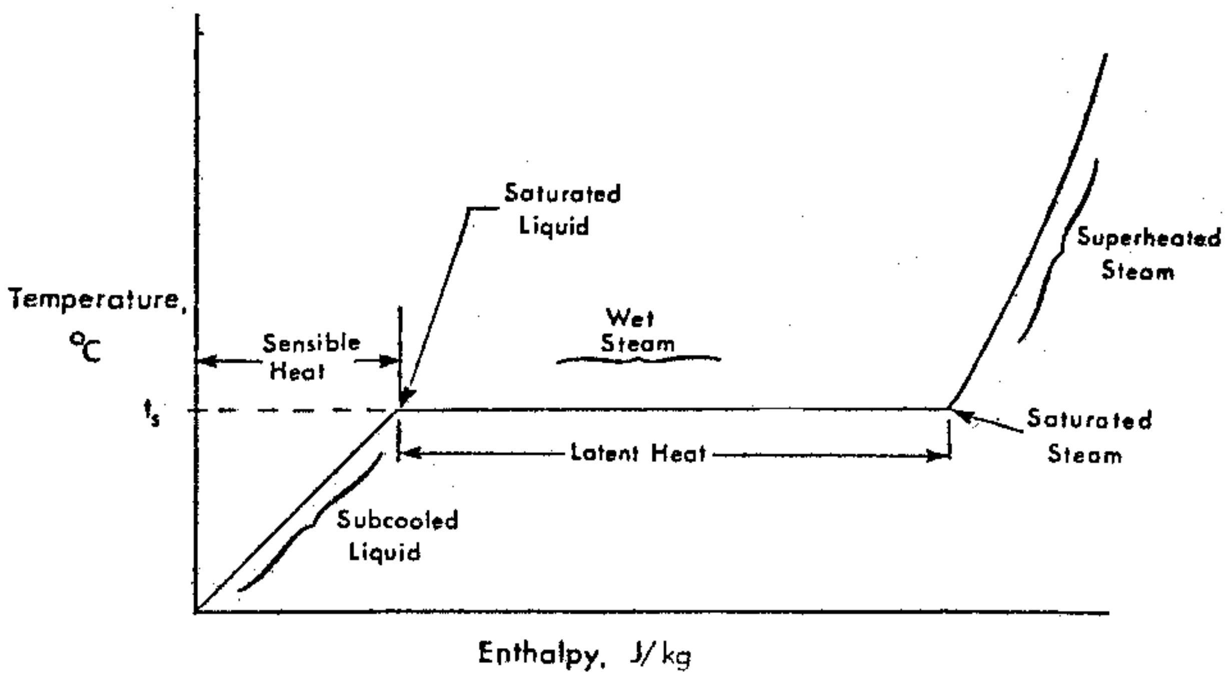


Fig. 6.3

4. (a) Conduction - heat transfer from molecule to molecule in a substance, with no transfer of mass involved. An example is the heat transfer through the tubes of a feedheater from the extraction steam side to the feedwater side.

   (b) Natural Convection - heat transfer due to fluid movement, when the fluid movement is because of density differences that occur in the fluid as heat is transferred. An example is the circulation of cooling oil in a transformer.

   (c) Forced Convection - heat transfer due to fluid movement, when the fluid movement is due to pressure difference created by pumps, fans, etc. An example is the primary heat transport D_2O flowing past the fuel in the reactor, picking up heat and carrying it to the boiler.

   (d) Radiation - heat transfer from a high temperature substance by emission of radiant energy. An example is the heat emitted by a quartz element radiant heater.

5. The compression process is a rapid event and produces extreme turbulence of the gas which results in the increase in temperature. The volume of the gas increases due to the higher temperature. The volume of the gas is reduced using an aftercooler so that either more gas may be stored in the receiver or a smaller receiver may be used for the same mass of gas.

6. Raising the temperature of a closed volume of gas raises its pressure. In the cover gas system, the pressure is kept constant at some value just above atmospheric pressure to prevent air in leakage. If the moderator temperature rises, the cover gas temperature will rise causing the pressure to rise above the set-point. The increase above the set point will result in the operation of the bleed valves to restore setpoint pressure.

7. Gas cylinders may become contaminated with oxygen and moisture from the air if allowed to completely empty. This occurs due to reverse flow or "suck-back". The contamination may also result in an explosive mixture when dealing with flammable gases.

   The contents of a compressed gas cylinder are checked by reading the pressure gauge.

   The contents of a liquified gas cylinder are checked by weighing the cylinder.

8. Gas is a compressible fluid and requires high levels of energy to raise its pressure. Most of this energy is recoverable and if recovered in a very short time, eg, if the system ruptures, the result will be an explosion.

   An incompressible fluid, ie, liquid should be used for pressure testing because liquids only use very small amounts of energy to raise their pressure.

* * * * *

When you have compared your test with the self evaluation sheet, take both the test and self evaluation sheet to the Course/Shift Manager and let him discuss your test. If you are both satisfied with the results, the Manager should sign the progress summary sheet. If there are some areas that need further reinforcement that have been identified, work on these and then take the test again when you are confident.

When you have completed this module proceed to Module B.5 - "Steam Tables."

J. Irwin-Childs
D. Taylor

Self Evaluation

MODULE B.5

STEAM TABLES

1. a) Check if the saturation temperature at 0.05 bar agrees with the stated temperature. The t_s at 0.05 bar is 32.9°C. The fluid is existing at a temperature above the saturation temperature, so the fluid is superheated steam.

   b) Check that 3.317 bar is the saturation pressure at 137°C. It is! So the fluid is at the saturation conditions and we have to check the enthalpy. The quoted value of 2279.2 kJ/kg is more than h_f at 576.2 but less than h_g at 2729.2 so the fluid is wet steam.

   c) Check that t_s at 4.0 bar is 133.5°C. At 4.0 bar t_s = 143.6°C. The fluid is existing below the saturation temperature and is therefore subcooled liquid.

2. If the steam is 14% wet it is also 86% dry and q = 0.86.

   The steam is at the saturation temperature of 64°C. If the condensate is subcooled by 12°C the temperature of the condensate is 64 - 12 = 52°C.

   Looking at the temperature enthalpy diagram, we can see the initial and final conditions.

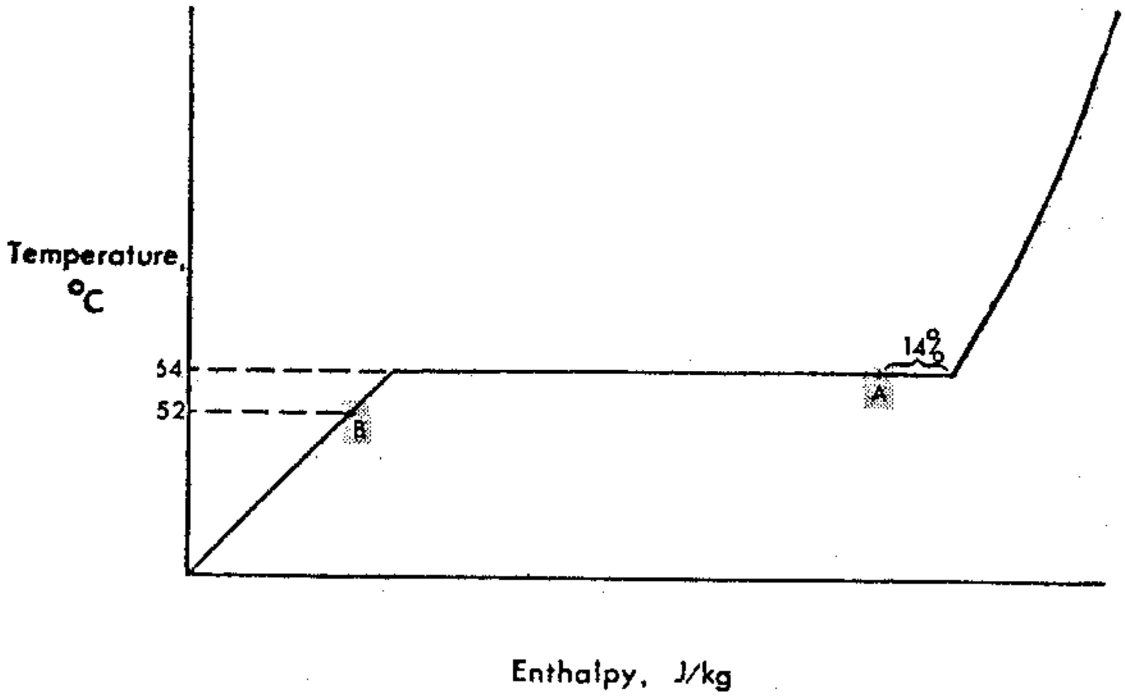


Fig. 5.15

At the point A, the enthalpy is found using $h = h_f + qh_{fg}$ when $t_s = 64°C$.

Using Table 1,

h_f at 64°C = 267.8 kJ/kg

h_{fg} at 64°C = 2348.8 kJ/kg.

So $h_A = 267.8 + 0.86 \times 2348.8$

$= 2287.8$ kJ/kg.

The enthalpy at the final condition of point B is h_f at 52°C which from Table 1 = 217.6 kJ/kg.

So the heat removed in the condenser is the difference between the initial and final conditions, ie, $h_A - h_B$

$= 2287.8 - 217.6$

$= 2070.2$ kJ/kg.

3. Using the temperature enthalpy diagram we can plot the initial and final conditions.

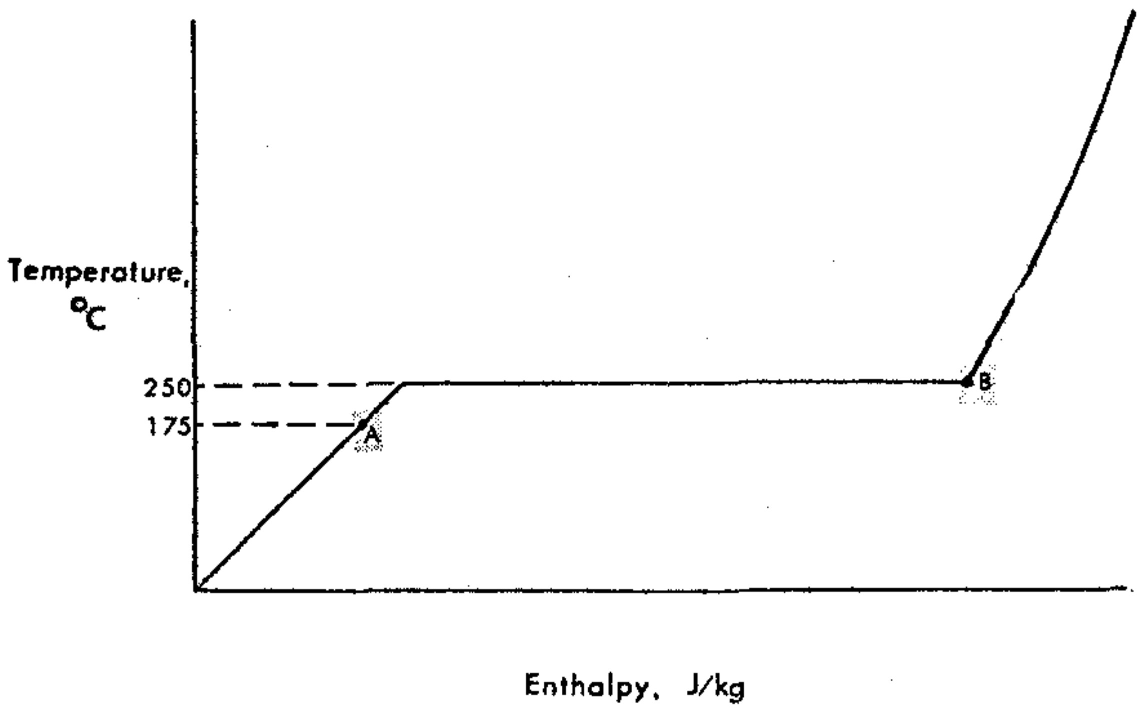


Fig. 5.16

Initial Condition A

The enthalpy at point A is h_f at 175°C which from Table 1 is 741.1 kJ/kg.

The specific volume at the initial condition is v_f at 175°C which is 1.1209 ℓ/kg.

Final Condition B

The steam is saturated at 250°C and the enthalpy may be found from Table 1 where h_g = 2800.4 kJ/kg.

The specific volume of the saturated steam at 250°C is v_g and is 50.037 ℓ/kg.

The heat added in the steam generator is the difference between the final and initial enthalpies, ie, $h_B - h_A$

= 2800.4 - 741.1

= 2059.3 kJ/kg.

The change in volume between the initial and final condition is $v_B - v_A$ = 50.037 - 1.1209, which is sensibly 49 ℓ/kg.

4. Steam hammer occurs with pressurized liquids when the line pressure falls to the saturation value. Continuous vapour production and condensation result in violent oscillations of the liquid in the pipe and can produce severe damage.

   It may be avoided by keeping the line pressure above saturation conditions whilst there is still liquid present. Valve operation should be extremely cautious. If steam hammer commences, the line flow should be reduced to raise the line pressure above the saturation valve.

5. As the system cools from 200°C to 100°C, the liquid water will contract. The volume of liquid will thus <u>decrease</u>.

   The decrease in liquid volume means that there will be a space created in the system. This space will be filled by vapour, which is produced using some of the heat lost by the liquid as it cools from 200°C to 100°C. So the volume of vapour <u>increases</u>.

   Due to the contraction of the water as its temperature decreases, the pressure of the system <u>decreases</u>.

* * * * *

When you have compared your test with the self evaluation sheet, take both the test and the self evaluation sheet to the Course/Shift Manager and let him discuss your test. If you are both satisfied with the results, the Manager should sign the test off in the top right hand corner.

If there are some areas that need further reinforcement that have been identified, work on these and then take the test again when you are confident.

When you have completed this module, progress to Module B.4.2 or B.3.2.

Self Evaluation

MODULE B.4.2

ENTROPY, THROTTLING & MOLLIER DIAGRAM

1. Using Table 1, S_g at 186°C = 6.5346 kJ/kg°C.

   At 42°C S_f = 0.5987 kJ/kg°C

   and S_{fg} = 7.6222 kJ/kg°C.

   The entropy before the expansion is equal to the entropy after the expansion.

$$S_{g186} = S_{f42} + qS_{fg42}$$

$$6.5346 = 0.5987 + q \times 7.6222$$

$$5.9359 = q \times 7.6222$$

$$q = \frac{5.9359}{7.6222}$$

$$= \underline{77.9\%}.$$

2. a) Let's make two assumptions to help clarify the answer:

   i) the steam has moisture content 10%
   ii) the steam temperature is 150°C.

   From Table 1 h_f at 150°C is 632.1 kJ/kg; h_g at 150°C is 2745.4 kJ/kg.

   1 kg of the wet steam is composed of a mixture of 0.9 kg of saturated steam and 0.1 kg of saturated liquid. The enthalpy of the wet steam is:

   0.9 x (2745.4) + 0.1 x (632.1) = 2534.1 kJ/kg.

   After moisture separation, the steam is saturated at 150°C. Its enthalpy is 2745.4 kJ/kg.

   The enthalpy (which is <u>per kg</u> of fluid) has increased from 2534.1 kJ/kg to 2745.4 kJ/kg. However, for every kg of wet steam entering the moisture separator, 0.9 kg of saturated steam exits, ie, even though each kg of steam contains more heat after the moisture separator, there is 10% <u>less</u> steam flowing.

b) In the reheater, main steam from the balance header is used to heat the process steam. The temperature and enthalpy of the process steam is increased by this addition of heat. Temperature of process steam typically increases from around 175°C to 235°C.

3. Remember this is a constant enthalpy process. We can determine the enthalpy of the superheated steam. Using Table 3, at 1.5 bar and 150°C, the enthalpy is 2773 kJ/kg.

Before throttling, the steam is at 194°C. Using Table 1 h_f at 194°C = 825.4 kJ/kg

and h_{fg} = 1961.7 kJ/kg.

Using $h = h_f + qh_{fg}$

$$2773 = 825.4 + q \times 1961.7 \text{ kJ/kg}$$

$$1947.6 = q \times 1961.7$$

$$q = \frac{1947.6}{1961.7}$$

$$= 99.3\%.$$

4.

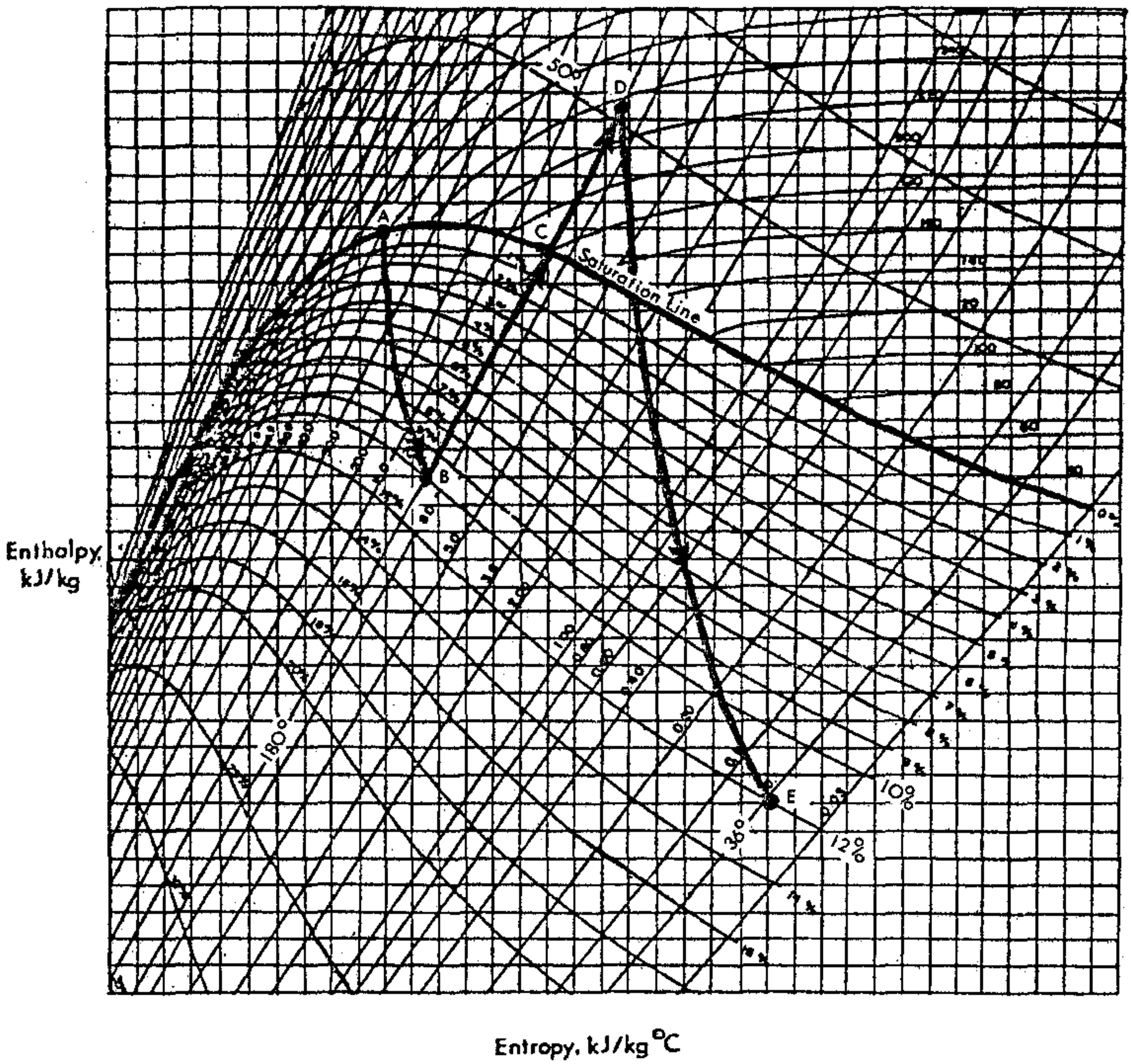


Fig. 4.2.20

A - B	hp turbine
B - C	moisture separator
C - D	reheater
D - E	lp turbine

5.

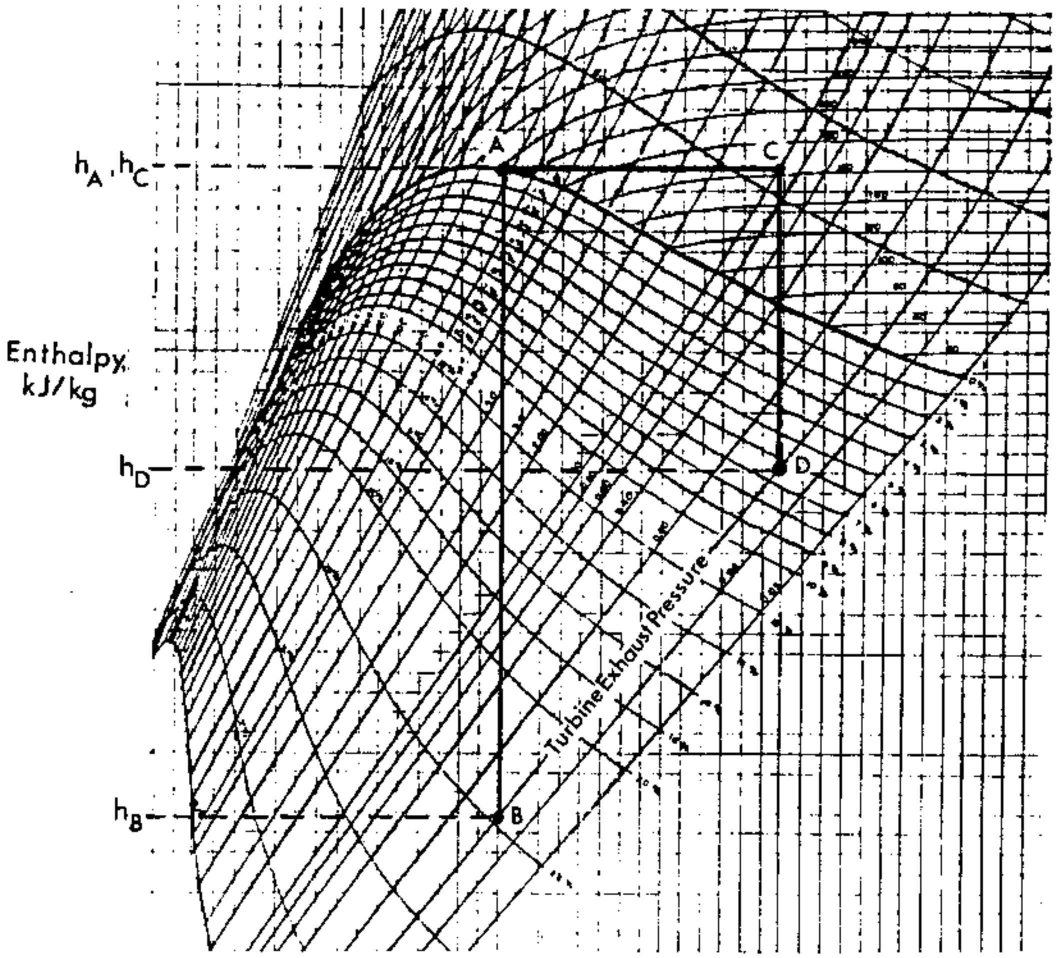


Fig. 4.2.22

Peak loading turbines operate at varying power levels, while base loading turbines generally operate at 100% power for long periods of time.

Let's assume that we have a peak loading turbine that will be operating at 50% power and that the unit has four governor steam valves. If the unit is nozzle governed, in principle, two governor valves will be wide open and two will be fully closed. No throttling will occur and the enthalpy drop available at the turbine is $h_A - h_B$. If the unit is throttle governed, all four governor valves will be partly open. Each valve will be throttling steam; the unit process is shown from A to C (throttling) then from C to D (turbine expansion). The enthalpy drop available at the turbine is $h_C - h_D$.

The enthalpy that is available in the nozzle governing system is greater than that available in the throttle governing system. This is true for all power levels up to 100%, so a peak loading turbine capable of operating at varying power levels will be nozzle governed.

In base load turbines that operate 100% power for the majority of operation, all the governor steam valves in both nozzle and throttle governing systems will be wide open and no throttling will occur. The enthalpy used by the turbine will be the same in either system, ie, $(h_A - h_B)$. The choice between systems is one of economics. Since throttle governing is less costly, due to simple turbine casing, governor valve sequencing and less complicated hydraulics, it is used for base load turbines.

* * * * *

When you and the Course/Shift Manager are satisfied with your performance, have the progress summary sheet signed and proceed to Module B.4.1.

Self Evaluation

MODULE B.4.1

TURBINE WITH REHEAT

1. Both the moisture separation and reheat processes occur at constant pressure. On a Mollier diagram the moisture separation is shown as a line running from the intersection of the constant pressure line at 1.5 MPa and the 12% moisture line, up to the saturation line. The reheat process is shown as a continuation along the constant pressure line into the superheat region.

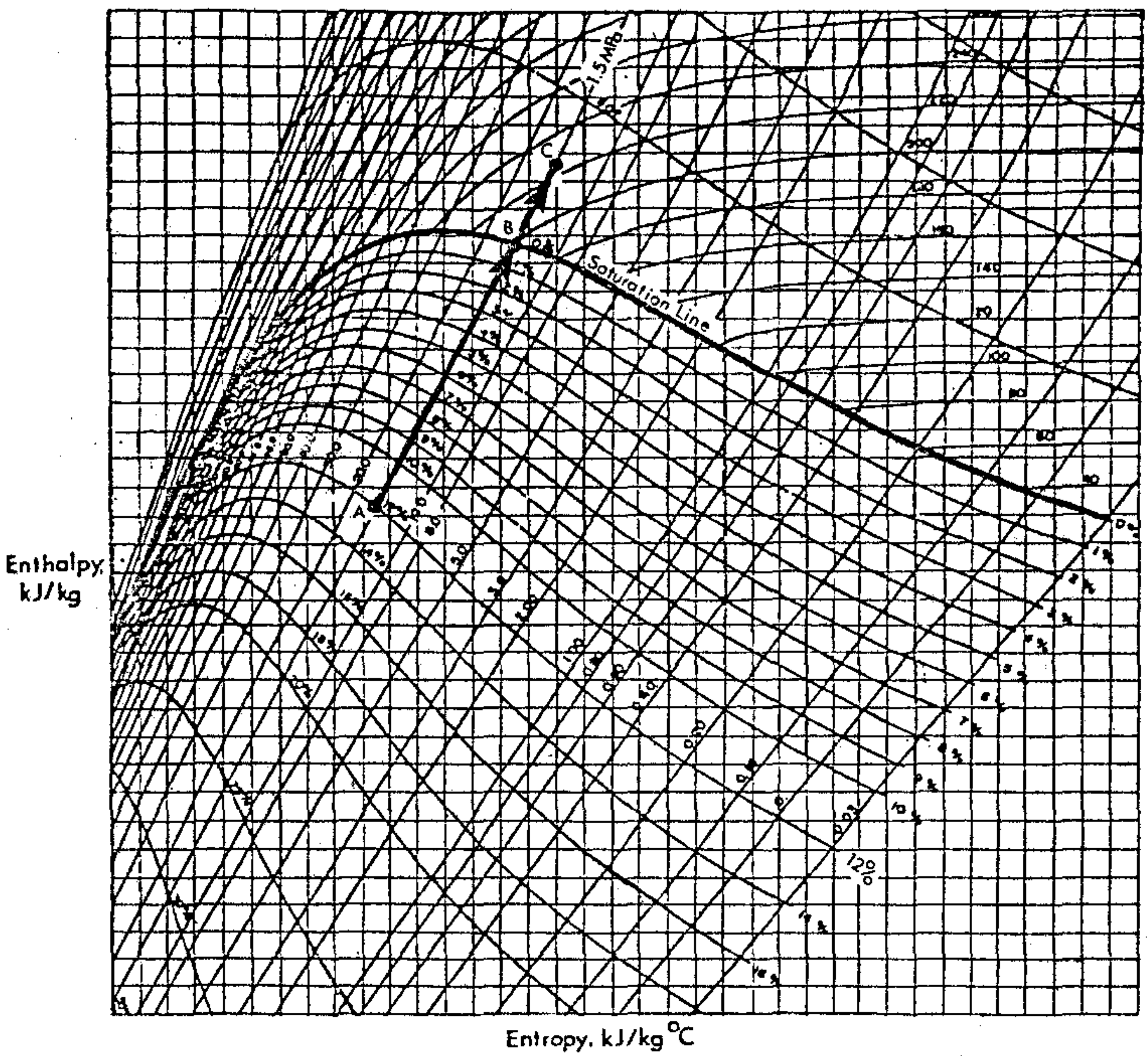


Fig.4.1.13

Step AB represents the moisture separation.
Step BC represents the reheat process.

Point	Flowrate	Pressure	Moisture Content
A	1100 kg/s	1.5 MPa	12%
B	968 kg/s	1.5 MPa	0%
C	968 kg/s	1.5 MPa	0%

Flowrate

This is reduced as the moisture is removed in the separator. Reduced flowrate out of the separator is 1100 x 0.88 = 968 kg/s.

Pressure

Ignoring the pressure drops through the system, there is no change in pressure.

Moisture Content

Reduced to zero in the moisture separator as saturated steam is produced and remains zero as the saturated steam is superheated in the reheater.

The next step to determine the temperature of the process steam leaving the reheater is based upon equating the heat lost by the heating steam in the reheater to the heat gained by the process steam in the reheater.

Heat Lost by the Heating Steam

The steam to the reheater is saturated at a pressure of 3.8 MPa. There is no subcooling of the condensate. This means that the heat removed from the heating steam is the latent heat h_{fg}. From tables h_{fg} = 1728.4 kJ/kg.

Total heat lost by the heating steam is the product of the mass flowrate, 36 kg/s and the enthalpy change, 1728.4 kJ/kg.

Heat lost per second = 39 x 1728.4 kJ

= 67408 kJ.

The heat lost by the heating steam is gained by the process steam. The heat gained per kg of process steam will be $\frac{1}{968}$ of 67408 kJ = $\frac{67408}{968}$ = 69.6 kJ/kg.

The enthalpy of the superheated process steam at 1.5 MPa is the sum of the enthalpy at saturation plus 69.6 kJ/kg.

From tables h_g at 1.5 MPa = 2790 kJ/kg.

Enthalpy of steam leaving the reheater,
2790 + 69.6 = <u>2859.6</u> kJ/kg.

Using superheated steam tables, we can find the temperature of the steam.

At 1.5 MPa and 200°C h = 2795 kJ/kg.
At 1.5 MPa and 250°C h = 2924 kJ/kg.

For a change of 50°C the difference in enthalpy is 129 kJ/kg. The enthalpy of the process steam is 2859.6 kJ/kg which is 2859.6 - 2795 = 64.6 kJ/kg due to superheating.

This is exactly half the difference between the enthalpy value at 200°C and that at 250°C, so the final temperature corresponding to the enthalpy will be 225°C.

2. In this question the solution is found by using the entropy of the initial condition and equating it to the final condition to determine the moisture content.

From superheated steam tables at 1.5 MPa, the entropy of steam at 225°C is the mean value of the entropy of 200°C, 6.451 kJ/kg°C and the value of entropy at 250°C, 6.710 kJ/kg°C.

Entropy at 225 = (6.710 + 6.451) 0.5

= <u>6.5805</u> kJ/kg°C.

Entropy remains constant throughout the turbine expansion because it is isentropic. We can equate the value of entropy of the superheated steam to the expression for the entropy of the wet steam at the turbine exhaust at a pressure of 15 kPa(a).

At 15 kPa(a) s_f = 0.7549 kJ/kg°C
s_{fg} = 7.2544 kJ/kg°C.

Equating the entropies:

$6.5805 = 0.7549 + q\ (7.2544)$

$5.8256 = q\ (7.2544)$

$q = \underline{80.3\%}$.

The moisture content is therefore <u>19.7%</u>.

3. The steam entering the hp turbine is saturated, which means that the temperature and pressure are dependent on each other. If the pressure falls, then the temperature falls and vice versa.

   At how loads and low steam flows significant throttling occurs past the GSV's which results in low pressure and temperature of steam entering the high pressure turbine. As the load increases the GSV's open further and reduce the throttling causing pressures and temperatures to increase throughout the turbine unit.

   It is interesting to note that the temperature of the steam leaving the reheater actually decreases with increasing steam flow due to primarily to the shorter time available for heat transfer to the process steam in the reheater.

* * * * *

Discuss your test with the Course/Shift Manager and have your progress summary sheet signed off when you are both satisfied with the results.

When you are ready to progress, move to Module B.3.2 or B.2.

Self Evaluation

MODULE B.3.2

FEEDHEATER OPERATION

1. Perhaps the least confusing way to present this information is to use some form of a table and fill in the "Givens" and then work through the rest.

	Feedwater	Steam
Flowrate	Increase(G)	Increase
Inlet Temp 1	Constant(G)	Reduce
Outlet Temp 2	Reduce	N/A
Feedwater $\Delta T(2-1)$	Reduce	N/A
Pressure	N/A	Reduce

(G) Information Given

As the feedwater flowrate increases, heat is being removed from the heater at a greater rate than is being supplied and the temperature in the heater starts to fall. As the temperature starts to fall, the pressure in the shell side of the heater also falls. The falling heater pressure increases the pressure difference which exists between the turbine and the feedheater and more extraction steam flows to the heater.

Although more heat is being transferred to the feedwater, the outlet temperature will have dropped because of the lower temperature existing in the heater shell and so the feedwater temperature rise across the heater will also fall.

2. The approach to this problem is to equate the heat gained by the feedwater to the heat lost by the extraction steam. The enthalpy rise of the feedwater is

$$h_{f_{162}} - h_{f_{134}} = 684.2 - 563.4 \text{ kJ/kg}$$

$$= \underline{120.8} \text{ kJ/kg.}$$

The total heat gained by the feedwater in one second is the product of the mass flow (740 kg/s) and the enthalpy change (120.8 kJ/kg).

Total heat gained = 740 x 120.8 kJ/s

= 89392 kJ/s.

Using the temperature/enthalpy diagram, we can see how much heat is lost by the extraction steam.

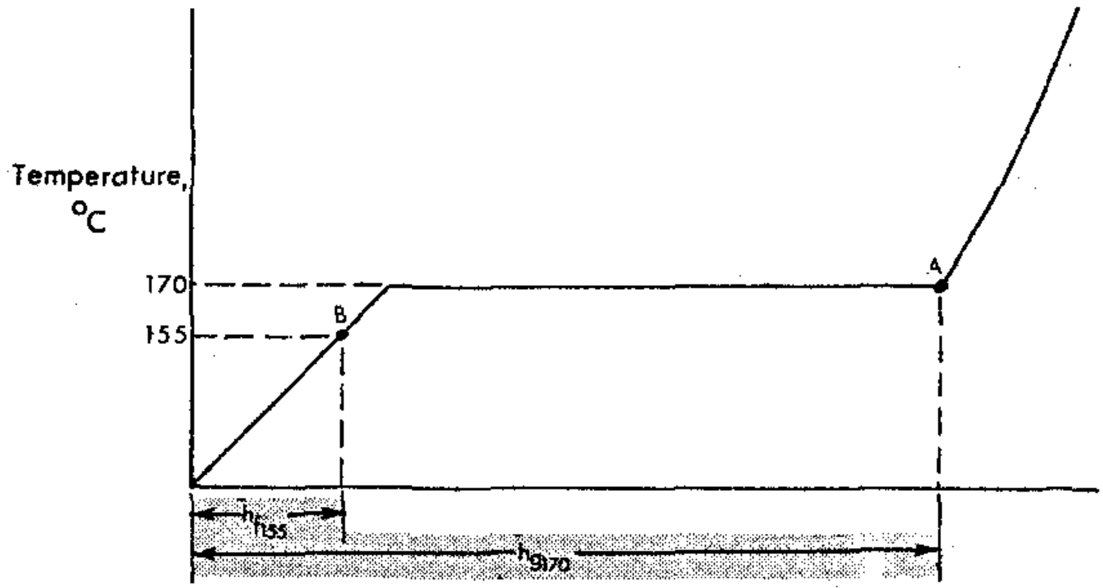


Fig. 3.2.9

The change in enthalpy is found by subtracting the enthalpy of the liquid at 155°C ($h_{f_{155}}$) from the enthalpy of the saturated steam at 170°C ($h_{g_{170}}$)

$h_{f_{155}}$ = 653.8 kJ/kg

$h_{g_{170}}$ = 2767.1 kJ/kg.

enthalpy change = 2767.1 - 653.8

= <u>2113.3</u> kJ/kg.

If $\overset{o}{m}$ is the mass of steam flowing per second, then $\overset{o}{m}$ x 2113.3 is the heat lost per second by the steam and gained by the feedwater.

Thus, 89392 = $\overset{o}{m}$ x 2113.3 kJ

and $\overset{o}{m}$ = 89392/2113.3 kg/s

= <u>42.3</u> kg/s.

3. In practice, the steam leaves the turbine with around 80% of its thermal energy unused. The majority of this energy will be rejected to the CCW system whilst the remainder will return to the feedwater system.

There are two reasons for feedheating. The first is to use heat which would otherwise be rejected out of the system. The second is to increase the cycle efficiency by raising the feedwater temperature as close as possible to the saturation temperature in the steam generator.

In the first case, low temperature steam shows high benefits for heating as the value for doing work in the turbine is small. As the steam temperature rises, the penalty of lost work in the turbine becomes greater if the steam is used for feedheating and there is an economic limit which on the Candu cycle leaves the feedwater inlet temperature to the preheater at around 175°C.

Even if the first conditions were not applicable, there is a thermodynamic limit based on time and temperature difference, as to how close you can heat the feedwater to 250°C with steam at the same temperature.

4. In this exercise, we must consider the two cases of a turbine with and without feedheating. Before we go any further, some thought should be given to the conditions that we are going to use in the problem and make some statements as to the assumptions we have made.

Assumptions

a) You cannot compare the potential value of the steam in the turbine if the exhaust pressure/temperature is unknown.

Assumption A Exhaust temperature is 35°C

b) The exhaust steam is going to be wet and you could assume an ideal expansion, ie, isentropic expansion but this is academic and for the purposes of illustration, we should choose a practical value of moisture.

Assumption B Exhaust moisture is 10%

c) The heat recovered from the condensate will be affected by any subcooling which occurs in the condenser although this is an undesirable condition.

Assumption C   Condensate in the hotwell is not subcooled.

d) We have to take a proportion of the turbine steam flow and use it for heating steam. In reality, the overall percentage is around 25% turbine steam flow extracted for feedheating. This figure is academic and if you average this percentage across five heaters, each heater would use roughly 5% of the total extraction steam flow. Use an easy figure for the purpose of demonstration.

Assumption D   Extraction steamflow is 10%.

Now we are ready to consider the case of the turbine without feedheating.

A sketch of the temperature/enthalpy diagram is useful to identify the recoverable heat.

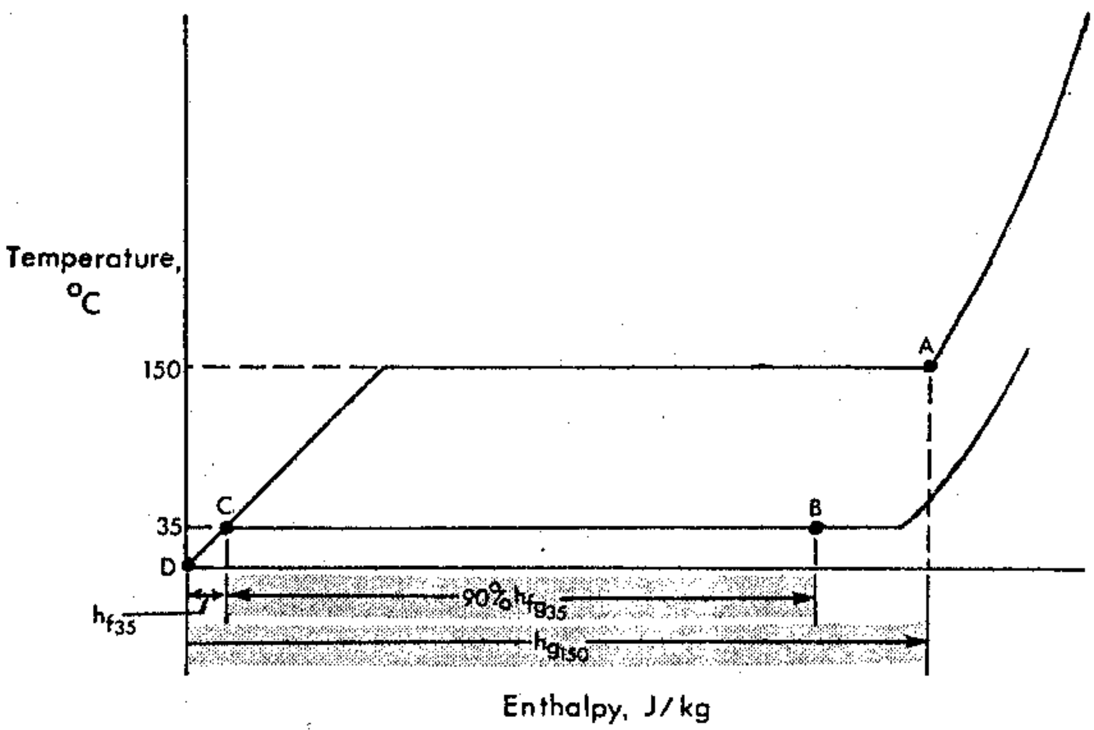


Fig. 3.2.10

A-B This represents the change in enthalpy from saturated steam at 150°C to steam having 10% moisture at a temperature of 35°C. This change in enthalpy represents the work done in the steam turbine.

B-C This is the heat rejected to the CCW in the condenser and is energy lost from the system.

C-D Represents the heat left in the condensate in the hotwell which is recovered when the condensate is returned to the feedheating system.

We can see that the only heat lost is the remaining latent heat. Thus, the recoverable heat per kilogram of steam entering the steam turbine is $h_{g_{150}} - h_{fg_{35}}$

$$h_{g_{150}} = 2745.4 \text{ kJ/kg}$$

$$h_{fg_{35}} = 2418.8 \text{ kJ/kg.}$$

The recoverable heat = 2745.4 - 0.9 (2418.8). (Remember the steam has already lost 10% of the latent heat because it is 10% wet.)

= 2745.4 - 2176.9

= 568.5 kJ/kg of steam at 150°C.

Turbine with Feedheating

If 10% of the steam is to be extracted for feedheating, then less work will be available and less condensate - in fact 10% less recoverable heat from the turbine.

Recoverable heat from the turbine with 10% steam extracted for feedheating is 90% of the recoverable heat from the turbine without feedheating = 0.9 x 568.5

= 511.7 kJ/kg of steam at 150°C.

Now we must consider the extraction steam and again a temperature/enthalpy diagram is useful.

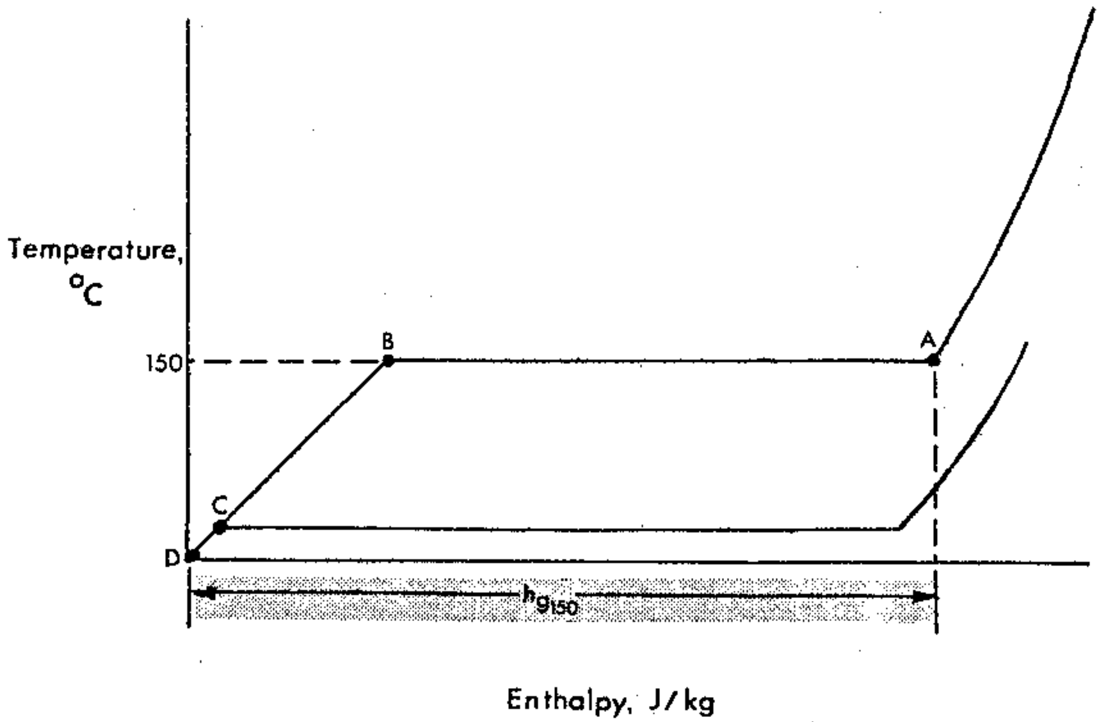


Fig. 3.2.11

A-B is the latent heat which is removed by the feedwater and causes condensation in the feedheater.

B-C This is the heating lost as the feedwater subcools the drains.

C-D is the heat left in the heater drains which remain in the system.

Consequently, no heat is lost from the system. All the heat from the extraction steam is recovered.

Recovered heat per kg = h_{g150}

$$h_{g150} = 2745.4 \text{ kJ/kg}$$

thus 0.1 kg has 274.5 kJ of heat.

Total recoverable heat using feedheating is 511.7 kJ from the turbine plus 274.5 kJ from the feedheater making a total of 786.2 kJ per kg of 150°C steam compared with 568.5 kJ/kg of 150°C steam in the turbine without feedheating.

* * * * *

When you have compared your test with the self evaluation sheet, take both the test and self evaluation sheet to the Course/Shift Manager and let him discuss your test. If you are both satisfied with the results, ask the Manager to sign the personal progress summary sheet and proceed to Module B.3.1 "Condenser Performance".

If further reinforcement is necessary in some areas, work on these and take the test again when you are confident.

Self Evaluation

MODULE B.3.1

CONDENSER PERFORMANCE

1. Avoid using the cycle efficiency first because the whole aspect of efficiency depends upon being able to reject steam at a saturation temperature below that of 100°C which can only be done AFTER we have decided to use a condenser.

There are four basic points to cover:

a) If steam was not recovered from the system, the costs would be enormous. The water treatment plant would have to be capable of treating water at a rate exceeding the combined station unit full load mass flowrate, ie, in excess of 4000 kg/s. That would be some water treatment plant! The reserve feedwater capacity would have to be significantly increased.

   This point concerns the practicality of size of water treatment and storage plus costs.

b) If all the steam was rejected to atmosphere, there would be no recovered heat in the system from the condensate. Low pressure feedheating using steam at sub-atmospheric pressures would not be possible.

c) If we agree that it is to the systems advantage to return the working fluid to the system, we have to ask how it may be done. If we have to pump the vapour, we need an axial compressor at least as large as the turbine and would be unlikely to produce any net power.

   By reducing the volume of steam by a factor of around 30000/1, we can pump the liquid with a relatively small pump.

d) Having decided to use a condenser, we can ask about the operating conditions that will increase the unit thermal efficiency. In principle, the lower we make the condenser temperature, the more efficient the unit cycle will become. In practice, this minimum temperature is governed by the cooling water supply and results in designed condenser temperature around 36°C.

The lower temperature means higher cycle efficiency, greater turbine efficiency because of more work extracted per kilogram of steam, extraction steam available at sub-atmospheric pressures for feedheating.

In summary, your responses should follow:

- What are the problems of not returning the working fluid?

- What are the problems of returning the working fluid without condensation?

- Having decided on condensation, what other benefits arise?

2. Assume that we have steady state conditions in the condenser, ie, the heat lost by the steam is equal to the heat gained by the cooling water.

   If the CCW inlet temperature falls the average CCW temperature will fall which will increase the temperature difference between the steam space and the CCW. As a result, more heat will be transferred from the steam space which will lower the temperature in the condenser.

   The pressure will decrease with the condenser temperature which will result in an increased steam flow through the turbine to the condenser.

	Steam	CCW
Flowrate	Increase	Same
Inlet Temp	X	Decrease
Outlet Temp	X	Decrease
Ave Temp	Decrease	Decrease
Pressure	Decrease	X

3. The best plan to adopt is to examine the possibilities in the most likely sequence. We should look at all the possible causes because there may well be more than one reason for the increase in condenser pressure.

   a) Check the CCW inlet temperature. If this has increased, the average CCW temperature will have increased and caused a corresponding increase in the steam space. If the inlet temperature is the same, then this option is out.

b) Has the steam flow to the condenser changed because of changes in power or extraction steam flow?

If the steam flow to the condenser has increased for whatever reason, this will cause a rise in temperature in the steam space so that the extra heat may be transferred to the CCW. If there is no obvious change, then this is an unlikely option.

c) Has the CCW flowrate decreased due to tube blockage or CCW pump trip? This condition would be indicated if all temperatures had increased with the exception of the CCW inlet temperature. Make sure that the condensate temperature has also increased.

The reduced CCW flowrate would result in a higher CCW outlet temperature which would raise the CCW average temperature and result in an increase in the steam temperature to transfer the same amount of heat.

d) If air is getting into the condenser, this will act as an insulator around the heat transfer surfaces and this could result in a reduced heat transfer with a lower CCW outlet temperature. The condensate temperature would be below the condenser exhaust temperature and the whole situation would be confirmed by a significant rise in dissolved oxygen in the feedwater.

e) If the heat transfer surfaces had become flooded, the condensate would show a marked degree of subcooling. The temperature would rise in the condenser because the CCW is not only trying to remove the latent heat but is removing some of the sensible heat as well in subcooling the condensate.

f) Tube fouling, as opposed to tube blockage which restricts CCW flow, reduces the efficiency of heat transfer. This situation does not usually occur rapidly and is more associated with scale or oxide formation but could result from oil contamination on either of the two heat transfer surfaces of the condenser tube.

This condition would result in no significant change on the CCW circuit but a higher temperature in the steam space to overcome the increased resistance to heat transfer.

By analyzing the conditions of the steam system and the CCW, it is reasonably easy to decide which system caused the change.

4. Operation above design pressure

a) The first option is fairly obvious and is basically an economic consideration. If the condenser is operating above design pressure, the steam flow will be reduced and if the GSVs are in the 100% power position, turbine power will be reduced and the output and efficiency of the unit will suffer.

b) If the low pressure blades, which travel around 800 mph at the tips, are allowed to heat up in the higher density steam, permanent elongation may occur and close the radial clearances. This problem is overcome by the use of a vacuum unloader which reduces the turbine load as the pressure rises. A vacuum trip shuts the turbine down in the event that the vacuum unloader cannot control condenser pressure.

Operation below design pressure

Both problems are blade related problems. As the condenser pressure is lower, more work may be extracted from the steam. The extra work results in an increased moisture level which results in accelerated erosion of the turbine blades.

As the condenser pressure is reduced, the steam flow through the turbine increases and this also results in a higher turbine power level.

The overpowering of the turbine results in higher blade stresses which result in a reduced blade lifetime and an increased possibility of blade failure due to fatigue.

5. Using heat by the steam is equal to heat gained by the CCW, we can determine the unknown quantity - CCW flowrate.

Heat lost by steam

A temperature enthalpy sketch may help.

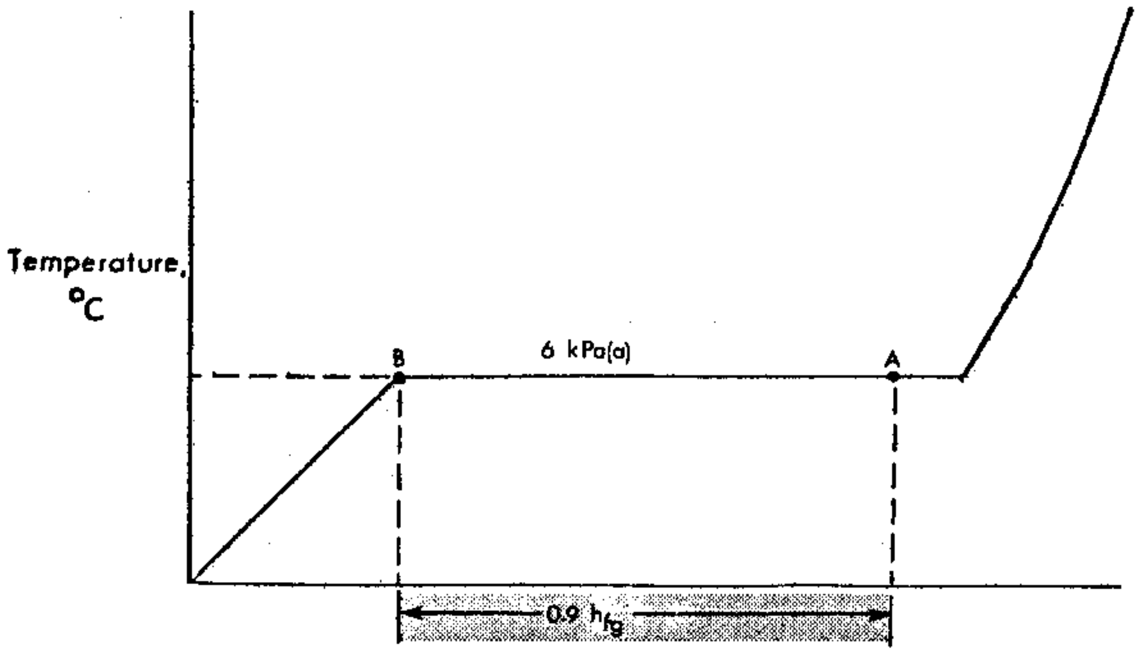


Fig. 3.1.8

The steam enters the condenser at point A where it has already lost 10% of its latent heat. The condensate leaves the condenser at point B where it is saturated liquid. The change in enthalpy is the remaining latent heat, ie, 0.9 h_{fg} at 6 kPa(a).

$$h_{fg} \text{ at } 6 \text{ kPa(a)} = \underline{2416} \text{ kJ/kg}$$

$$0.9 \times 2416 = \underline{2174.4} \text{ kJ/kg.}$$

Total heat lost by the steam per second is the enthalpy difference (2174.4 kJ/kg) multiplied by the mass flowrate (700 kg/s).

$$\text{Total heat lost by the steam} = 2174.4 \times 700$$

$$= \underline{1522 \times 10^3} \text{ kJ/s.}$$

This heat is gained by the CCW system every second.

Heat gained by CCW

Inlet temperature 5°C.

Outlet temperature 14°C.

Heat gained per kilogram of CCW

$= h_{f_{14}} - h_{f_5}$

= 58.75 - 21.01

= 37.74 kJ/kg.

The CCW removes 37.74 kJ for every kilogram of cooling water until 1522×10^3 kJ are removed every second.

Thus, the CCW flowrate is

$1522 \times 10^3/37.74$

= 40330 kg/s.

Self Evaluation

MODULE B.2

STEAM GENERATOR

1. At power it is a design requirement that the mass of light water in the steam generator remains constant. This produces two advantages:

   (a) The heat sink for the reactor remains sensibly constant.

   (b) The effects of sudden changes of steam flow on boiler level are reduced.

   Suppose the boiler is full of liquid at the saturation temperature and we increase unit power. As more heat is rejected to the steam generator from the primary heat transport system steam is going to be produced in the steam generator. The steam is produced as vapour bubbles within the liquid which has the effect of "floating" the surface in the boiler to a higher level although the mass of "water" in the boiler remains constant.

   As the steam flow increases, to the full load value, the ratio of steam bubbles to liquid in the boiler continues to increase. The increased volume of vapour "floats" the level to its highest normal value.

   If the boiler level had not been at a relatively low value before the steaming rate was increased, the level would have reached the top of the boiler before full load was achieved and liquid would have entered the steam lines.

   This increased vapour production is the reason for having a programmed boiler level with steam flow, where the programmed level is low at low steaming rates and is high at the high steaming rates.

2. (a) The major problem of a very high boiler level is that a small change in operating conditions could result in liquid being pushed out of the boiler into the steam turbine.

In this event several effects may result. As the liquid enters the turbine quenching of the rotor will occur as the liquid meets the center. This may severely distort the hp rotor. The liquid then has to pass through the blading which it does with difficulty and the chances of blade failure at this point are very real. All told, this is an event to be avoided!

(b) In a similar manner a relatively small operating change could cause a drop in boiler level which would produce problems if the boiler level was already low to start with.

The first problem is that the level of the boiler may fall below the lowest level sensing point for level control. As a result the actual level is no longer the indicated level because the indicator is already operating at the minimum signal. How do you know where the boiler level has gone? You don't!

Secondly, as the 'water' inventory in the steam generator is reduced so the heat sink capacity for the reactor is reduced which is an undesireable trend.

Thirdly, if the level in the boiler falls so that the tube bundle becomes uncovered then dryout will occur and dissolved solids existing in the boiler will 'bake out' on the outer tube surfaces, thereby impeding future heat transfer. This problem is clearly not of the same priority as the previous two.

In both cases of extreme level, an alarm is initiated which may allow the operator to take some appropriate action. If the boiler level continues to rise after the alarm then a GSV trip is initiated to prevent water entering the turbine from the steam generator.

If the boiler level continues to fall after the alarm a reduction of reactor power is initiated to ensure that the reactor thermal power is more closely matched to the reduced thermal capacity of the reactor heat sink, ie, the boilers.

This reduction in reactor power may be as a setback or a trip depending upon the operating rationale at the station concerned.

3. The three basic elements which are used for boiler level control are:

   (a) Steam flow,
   (b) Feedwater flow,
   (c) Actual level,

   The steam flow measurement is used to derive the programmed boiler level.

   Comparator circuits check for mismatching between Steam/Feedwater flowrates and actual/programmed boiler levels.

   At low power levels the measurement of low flowrates is not very accurate and the control of feedwater flow via the feedwater regulating valves is rather insensitive. Consequently, the inputs of steam flow and feedwater flow at low values are effectively ignored and level control is achieved using the level controller alone.

   As the flowrates rise above 20% and the large feedwater regulating valves are in service, then the three element measurement is used to advantage.

4. You will have noticed that the question does not state "reactor leading" or "reactor lagging". You should know whether the 'normal' mode at your station is "reactor leading" or "reactor lagging".

   The fact that the speeder gear is on 'auto' implies that the offset for the steam reject valves is in effect.

Reactor Leading (Pickering NGS-A)

In this mode the reactor power remains constant and the BPC program varies the steam flow from the steam generator to control the boiler pressure to the pressure setpoint.

As the steam pressure rises above the setpoint the BPC program initiates a signal which opens the GSV's on the turbine and allows more steam to flow through the turbine.

If this action does not restore the boiler pressure to the setpoint value by the time the SRV offset is reached, the small SRV's open to allow excess steam to be vented to atmosphere. In the event that the mismatch is such that the large SRV's open, then a reactor setback is initiated and only stopped when the large SRV's close or 2% reactor power is reached.

Reactor Lagging (Bruce NGS-A)

In this mode of operation the turbine load remains constant and the reactor power is changed to correct the boiler pressure error.

If the reduction of demanded reactor power does not return the boiler pressure to the setpoint and the boiler pressure reaches the offset value for the small steam reject valves, the unit control changes to reactor leading.

In this case the small reject valves operate and if the large reject valves are required to operate a reactor setback is initiated to reduce the power mismatch. The setback stops when the large reject valves close or 2% reactor power is reached.

5. The BPC program relies upon being able to vary the steam flow from the steam generator to control the boiler pressure.

   In the "cooldown" mode of operation the volume of steam increases dramatically as the pressure falls. At 130°C the steam volume has increased by more than 13 times.

   Two problems arise from this lowering of the steam pressure. Even though the steam mass flowrate is much reduced the volumetric flowrate increases due to the larger specific volume and the pipe sizing for the SRV's becomes inadequate and the SRV's become full open and can no longer reduce the steam generator pressure.

   One problem of using the turbine "all the way down" is that as the pressure in the boiler falls, so the levels of moisture in the turbine become higher. The exercise then becomes one of economics of a small amount of generation plus low feedwater loss against the blade damage on the turbine due to accelerated erosion.

   The main reason for terminating the 'cooldown' mode of the BPC program at 170°C is that this effectively represents the point where the SRV's are no longer capable of regulating boiler pressure because they are full open. At this point the PHT system temperature is further reduced using shutdown cooling.

6. The objective of a "crash-cool" exercise is to reduce the reactor temperature in a short period of time. The action which is taken to "crash-cool" is to reject steam from the steam generator at a rate which lowers the pressure. The effect of lowering the pressure is to reduce the temperature in the steam generator which means

that there is now a larger temperature difference between the PHT system and the steam generator. As a result of the larger temperature difference, the rate at which heat is removed from the reactor increases and the rate of cooling increases.

7. An increase in the thermal resistance of the steam generator tubes means that a larger temperature difference is required to transfer the same amount of heat from the PHT circuit. The only way that this can occur is for the PHT D_2O average temperature to rise to a value where the same amount of heat is being transferred through the higher resistance of the steam generator tubes.

8. (a) The efficiency of the steam/water cycle is proportional to the temperature difference between the steam in the steam generator and the steam in the condenser. When the steam generator pressure is raised, the steam temperature in the steam generator will increase (ie, the water will boil at a higher temperature). This increase in steam temperature increases the temperature difference between the steam generator and the condenser, which will increase the work done and the cycle efficiency.

   (b) The limit on raising the steam generator pressure is due to the temperature of the fuel. Since the fuel is a ceramic, it has very poor heat transfer characteristics. Thus, when the centre fuel maximum temperature is 2300°C, the temperature of the fuel sheath is about 350 to 400°C and, after heat transfer occurs from the fuel to the primary heat transport fluid and from the primary heat transport fluid to the light water in the steam generator, the temperature of the light water in the steam generator is about 250°C.

   If the centre fuel temperature is designed higher than 2300°C, the temperature and pressure of the light water in the steam generator can be increased.

   At centre fuel temperatures approaching 2800°C, the fuel will melt, releasing fission product gases which contribute to fuel sheath failure. Thus the maximum fuel temperature is limited to 2300°C (which gives a safety margin), and the maximum light water pressure in the steam generator is the saturation pressure for the resulting 250°C operating temperature, or about 4 MPa(a).

* * * * *

When you have compared your answers ask the course manager to review your test.

Self Evaluation

MODULE B.1

REACTOR

1. The major reason that channel blockage presents a serious problem in the reactor is that the rate of flow of coolant to the fuel is decreased.

   If we briefly explain the equation for power in the channel, we can see the effect of changing mass flow.

   $\dot{Q}$ = mass flowrate x (Enthalpy In - Enthalpy Out).

   In this expression, the channel power will remain sensibly constant so $\dot{Q}$ will not alter. The channel inlet enthalpy will remain constant. If the mass flowrate now decreases, the exit enthalpy must increase to compensate, keeping $\dot{Q}$ constant.

   The increased enthalpy is seen by a rise in Channel outlet temperature. This is the first indication of possible channel blockage, provided it does not appear in other adjacent fuel channels.

   The rise in temperature of the heat transport D_2O will cause an increase in the fuel sheath temperatures which will not be a problem provided that voiding does not occur. A channel high temperature trip is the expected result from this event.

   The danger lies in the situation where channel voiding occurs and the heat transport pressure is low enough that voiding occurs at a temperature below the high temperature trip setting on the channel.

   The channel blockage may be confirmed by monitoring the channel pressure drop using the fuelling machines.

2. The two problems that may result from a low heat transport system pressure are both related to the production of vapour.

   The two problems concern the fuel bundles and the heat transport pumps.

   If the system pressure falls to the saturation pressure, large scale vapour production will occur in the channel and voiding will result. The major concern in now of loss of heat transfer from the fuel. Instead of forced convection with liquid, the heat transfer is taking place with vapour which has a far inferior ability to transfer heat.

Under normal conditions, the centre temperature of the fuel is around 2300°C when the melting point is around 2800°C. As the fuel temperature rises, the possibility of fuel sheath failure increases and is likely to occur.

When the fuel sheath temperature has risen from around 350°C and has reached a range of 800 - 1100°C, sheath failure is accelerated by the release of fission product gases from the fuel grain boundaries at high temperatures, causing high pressure between the fuel and the sheath.

If the system pressure falls below the value to establish the required positive suction head for the heat transport pumps, then cavitation will result. The effect of cavitation will be pump damage and loss of coolant flow.

3. If the heat transport system pressure control program cannot maintain the pressure because of loss of coolant, this is a serious condition.

   As soon as the system pressure reaches the saturation value, large scale vapour production will begin and it may appear as though the problem was over because the system pressure has stabilized. In fact, from the moment the saturation pressure was reached and channel voiding commenced, the fuel was beginning to overheat.

   The object of the exercise is to reduce the fuel overheating to a minimum and re-establish fuel cooling as soon as possible. This cooling can only be achieved when liquid is again in contact with the fuel bundles.

   By crash cooling, the heat transport circuit is cooled and depressurized rapidly in a few minutes to a point where the heat transport fluid can restore cooling. If there is not enough heat transport D_2O left in the circuit, emergency core injection may commence as soon as the heat transport pressure has fallen below the maximum possible injection pressure.

The main difference between a small loss of coolant and a major LOCA is that in a small loss of coolant situation, it may not be obvious to the operator that channel voiding has occurred. The large quantities of vapour generated stabilize the system pressure and may disguise the real problem. In a major LOCA, the operator is left in no doubt as to what has happened!

4. A loss of coolant from the heat transport system may not appear in the immediate environment and may not necessarily result in a high boiler room pressure trip or a Beetle alarm.

   The D_2O could leak into the steam generator, for example. In this situation, we would have to look elsewhere for pointers indicating a loss of coolant.

   A reducing level in the D_2O storage vessel, ie, the D_2O storage tank may be some indication.

   A loss of heat transport system pressure may be a further indication of loss of D_2O.

   If the D_2O was leaking into the boiler room, then a high boiler room pressure trip and Beetle alarms would confirm this event. A steam leak could produce the same effect!

   If the loss of coolant created voiding, the resultant positive reactivity would produce the Linear Rate Trip, Hi Log Rate Trip, Hi Power Trip.

5. The immediate effect of losing the feedwater supply is to lose around 17% of the heat sink because no heat is being removed from the PHT to increase the sensible heat of the feedwater. There is now a mismatch of thermal power and the PHT temperature starts to rise.

   As the level in the steam generator falls below the tubes, heat transfer is further lost due to the reduction of heat transfer area and the rate of temperature rise of the PHT increases.

6. The onset of bulk boiling occurs at constant temperature which means that channel ΔT can no longer be used as an indication of channel power.

   The production of vapour increases the "steam quality" along the remaining section of the fuel channel but gives no external indication of whether 10% or 80% of the liquid has become vapour.

7. The reactor is at a lower elevation than the steam generator. This arrangement permits the less dense hot D_2O to rise up to the steam generator by convection and equally causes the cooler D_2O to return to the reactor. This mechanism establishes flow round the PHT circuit, with no pump running, by thermosyphon.

   The thermosyphon can only be maintained provided no vapour or gases collect in the tubes in the steam generator.

   ROH temperature is monitored to ensure that no vapour is produced in the PHT circuit and that sufficient temperature difference exists between the steam generator and the PHT system for adequate heat transfer. This ΔT may be controlled by the steam generator pressure.

* * * * *

When you have compared these notes with your own answers, have the Course Manager review them. When you are both satisfied with your answers, have the Manager sign off the test sheet.

* * * * *

Before you finish, please complete the course evaluation form and let us know what we can do to make this course more suited to your needs, in format <u>and</u> content.

* * * * *

Well Done!

Criterion Test

MODULE B.1

REACTOR

1. Give a major reason why reactor channel blockage is a serious condition and explain how this condition can be detected and may be confirmed.

2. Briefly explain how two major problems may result from low heat transport system pressure.

3. Briefly explain why crash cooling is necessary for a loss of coolant from the heat transport system that only results in a low rate of heat transport pressure decrease. Briefly explain how this condition may produce similar results to those found in a major LOCA.

4. Briefly explain how a loss of heat transport coolant may be detected.

5. Briefly explain the immediate and longer term effects of losing feedwater supply to the steam generators.

6. Briefly explain how the temperature and quality of the PHT coolant change when bulk boiling occurs.

7. Explain how the PHT thermosyphon is established and how the ROH temperature is used as a datum for the control of the thermosyphon.

Criterion Test

MODULE B.2

STEAM GENERATOR

1. Explain why it is necessary for the programmed steam generator level to increase with unit power.

2. (a) Explain a major problem with having a very high boiler level when the unit is at power.

   (b) Explain three problems that could result from a very low boiler level.

   (c) Describe the control actions that are designed to avoid these problems of extreme boiler level.

3. State the three elements which are used for boiler level control and explain why they cannot be used ~~as~~ at low power levels.

4. Explain how your station system responds to a rising boiler pressure when unit control is in the "normal" mode and the speeder gear is in 'auto'.

5. Explain why the BPC program is completed at 170°C when in the "cooldown" mode.

6. Explain how the temperature difference, between the steam generator and the PHT system, changes during a "crash-cool" exercise.

7. State how the average PHT temperature is affected by an increase in thermal resistance of the steam generator tubes.

Criterion Test

MODULE B.3.1

CONDENSER PERFORMANCE

You will need (a) a calculator
(b) a set of S.I. steam tables.

1. List and explain four advantages of using a condenser instead of rejecting steam to atmosphere from a steam turbine.

2. Explain the effect of a reduced CCW inlet temperature on condenser temperatures, pressure and flowrates. Summarize your answer in table form.

3. The pressure in a condenser is slowly rising. Describe the steps that you would follow to quickly determine some of the possible causes for the increase in condenser pressure. Explain why you are considering each parameter.

4. Explain two undesirable consequences for each of the following turbine condenser conditions:

   a) operating the condenser above design pressure
   b) operating the condenser below design pressure.

5. A condenser operates at a pressure of 6 kPa(a). CCW inlet temperature is 5°C and outlet temperature is 14°C. Steam enters the condenser at 700 kg/s and 10% moisture. Determine the CCW flowrate if there is no subcooling of the condensate.

Criterion Test

MODULE B.3.2

FEEDHEATER OPERATION

You will need (a) set of S.I. Steam Tables
(b) calculator.

1. Explain how conditions of pressure, temperature and flowrate change in a feedheater when the feedwater flowrate is increased. The feedwater inlet temperature remains constant and there is no change in turbine power.

2. A feedheater is supplied with extraction steam from a turbine. The steam is saturated at 170°C. The drains from the heater are at 155°C. The feedwater inlet and outlet temperatures are 134°C and 162°C. The feedwater flowrate is 740 kg/s. Determine the steam flow to the feedheater. Use a temperature/enthalpy diagram in explaining your logic.

3. Explain why steam is extracted from the turbine for feedheating and why there is a practical limit to the final feedwater temperature before entering the steam generator.

4. Saturated steam is supplied to a feedheater at 150°C. Demonstrate the benefit of feedheating by calculating the recoverable heat in the following turbine situations:

   a) turbine without feedheating
   b) turbine with feedheating.

   Use a temperature/enthalpy diagram to explain your reasoning and **state all your major assumptions.**

CRITERION TEST

MODULE B4.1

TURBINE WITH REHEAT

You will need a) a calculator
b) a set of S.I. steam tables.

1. The exhaust steam from a high pressure turbine flows at 1100 kg/s at a pressure of 1.5 MPa and with a moisture content of 12%. The steam flows to a moisture separator where the process steam becomes saturated and then passes through a reheater. Ignore the pressure drops through the separator and reheater.

   The reheater is heated with saturated steam at 3.8 MPa at a flowrate of 39 kg/s. The condensate is saturated.

   a) Sketch the process on a Mollier diagram.

   b) List the values of flowrate, pressure and moisture content at each step of the process.

   c) Determine the temperature of the process steam leaving the reheater.

2. In the previous question the steam from the reheater enters a low pressure turbine where it is expanded isentropically to a pressure of 15 kPa(a). Calculate the moisture in the exhaust steam from the turbine.

   NOTE: In both questions shown clearly how you proceed from one step to the next.

3. Explain how pressure and temperature change through the turbine unit as the load is increased from 25% to 100% full power.

CRITERION TEST

MODULE B4.2

ENTROPY, THROTTLING & MOLLIER DIAGRAM

You will need a) a calculator
b) a set of S.I. steam tables.

1. Steam which is saturated at 180°C is expanded, at constant entropy to 42°C. Determine the dryness fraction of the final steam condition.

2. Initially wet steam at 194°C is throttled to a pressure of 1.5 bar when the temperature is measured to be 150°C. Determine the dryness fraction of the wet steam.

3. Sketch your own Mollier diagram to illustrate the following series of processes: A high pressure turbine uses saturated steam at 250°C and exhausts steam at 180°C with 10% moisture to a moisture separator. The separator produces saturated steam and is followed by a reheater which raises the temperature of the steam to 235°C. The superheated steam expands in the low pressure turbine to 36°C and 12% moisture.

CRITERION TEST

MODULE B5

STEAM TABLES

You will need a) a calculator
b) a set of S.I. steam tables

1. Identify the state of water in the following cases, as being subcooled water, saturated water, wet steam, saturated steam, superheated steam.

	Enthalpy	Temperature	Pressure
a)	2575.3 kJ/kg	40°C	0.05 bar
b)	2279.2 kJ/kg	137°C	3.317 bar
c)	561.4 kJ/kg	133.5°C	4.0 bar

2. 14% wet steam at 64°C is condensed to liquid which is subcooled by 12°C. Determine how much heat is removed in the condenser.

3. A steam generator produces saturated steam at 250°C from feedwater at 175°C. Determine:

   a) the heat added per kg in the steam generator

   b) the change in volume which occurs per kg of water from liquid to saturated vapour.

4. Briefly describe the process of "steam hammer" and explain why it is a problem and how it may be avoided.

CRITERION TEST

B6

BASICS

1. Define the following terms from memory:

   (a) Temperature.
   (b) Heat.

2. Explain the meaning of the following terms in your own words, from memory, when applied to the various states of water:

   (a) Saturation temperature.
   (b) Sensible heat.
   (c) Latent heat of vapourization.
   (d) Subcooled liquid.
   (e) Saturated liquid.
   (f) Wet steam.
   (g) Saturated steam.
   (h) Superheated steam.

3. Draw a graph of temperature plotted against the enthalpy of water, when heated at constant pressure. The graph should be fully labelled by making the following:

   (a) The axes.
   (b) *Sensible heat region.*
   (c) Latent heat region.
   (d) Saturation temperature.
   (e) Subcooled region.
   (f) Saturated liquid.
   (g) Saturated steam.
   (h) Superheated region.
   (i) Wet steam range.

4. Explain the following heat transfer mechanisms, in your own words and give an example of each mechanism:

   (a) Conduction.
   (b) Natural Convection.
   (c) Forced Convection.
   (d) Radiation.

5. Explain why the temperature of a gas rises during compression and why an aftercooler is used.

6. Explain how the pressure of a closed volume of gas changes when heated and illustrate your answer with an example from the station that uses a "feed and bleed" system.

7. Explain why gas cylinders should never be completely emptied and state how you would check the contents of a compressed gas and a liquified gas cylinder.

8. Explain why compressed gas should never be used for pressure testing.