NUCLEAR TRAINING COURSE

COURSE 225

FOR NUCLEAR OPERATORS ONLY

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NUCLEAR TRAINING COURSE

COURSE 225

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

FOR NUCLEAR OPERATORS ONLY

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COURSE 225

HEAT & THERMODYNAMICS

MODULE 1

BASICS

Revised	Verified	Verified
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	Date 88-05-30	Date 88-07-29

Heat and Thermodynamics

MODULE 1

BASICS

Course Objectives

1. You will be able to define the following and state the units:
    - (a) Temperature.
    - (b) Heat.
2. You will be able to explain, in your own words, the following terms 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, in your own words, the following heat transfer mechanisms, and give an example of each mechanism:
    - (a) Conduction.
    - (b) Natural convection.
    - (c) Forced convection.
    - (d) Radiation.
4. You will be able to explain, in your own words, the following terms:
    - (a) Nucleate boiling.
    - (b) Partial film boiling.
    - (c) Dry out.
    - (d) Critical heat flux.
5. You will be able to state that a compressor will raise both the pressure and temperature of a gas and explain that an after cooler is used to reduce the volume of the receiver.
6. 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.
7. 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.

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

Enabling Objectives

1. You will be able to explain, in your own words, the following terms 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:

   (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.

   Note: In this and all following modules, enabling objectives are not tested directly.

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 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, ie, its internal energy. 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 or 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 quantity of energy that a body possesses due to its temperature and depending upon the material, its state and mass.

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.

The units are Joules per kilogram per degree Celsius. (J/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 required 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:

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

$$J = kg \times J/kg°C \times °C$$

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

kg x kJ/kg°C x °C

$= 14 \times 4.18 \quad \times 34$

$= 1989.7$ kJ

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

Q1.1 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

Enthalpy is the total heat value of fluid measured above a reference point. 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 Joules/kilogram. (J/kg)

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 reread 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 and it is not surprising that we should pay a lot of attention to the behaviour of water when it is heated and 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. Of course, 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.

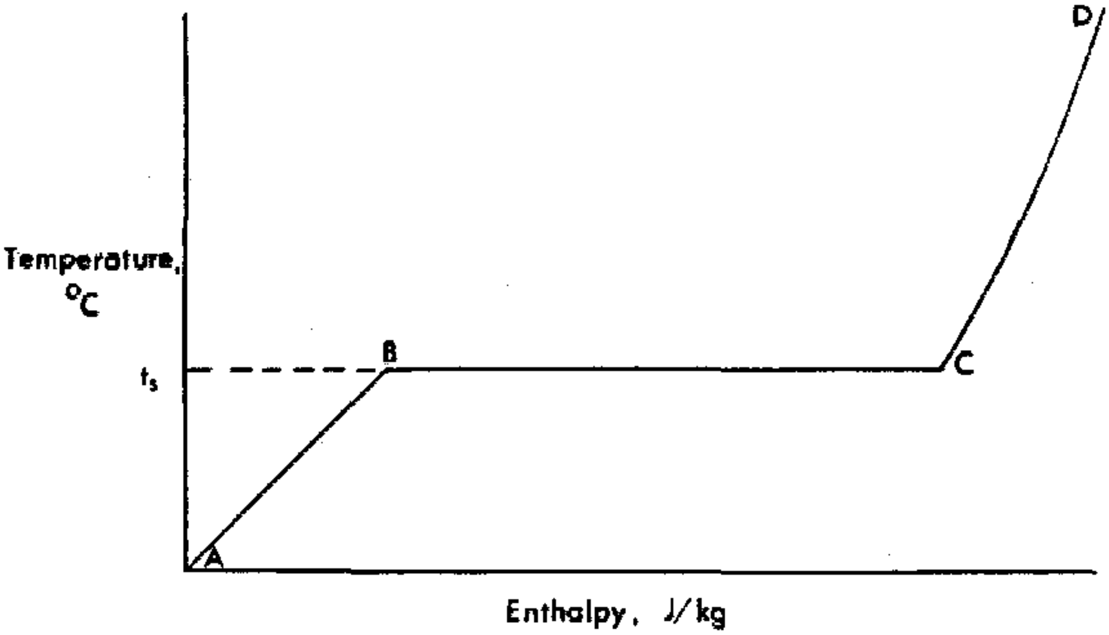

Fig. 1.1

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.

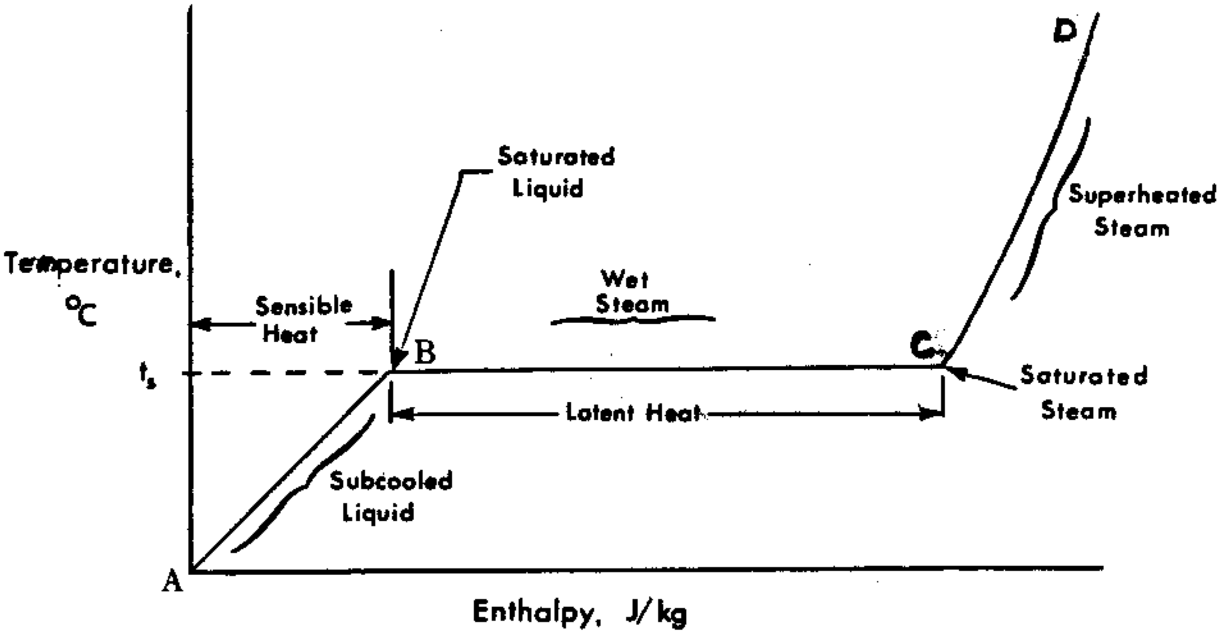

Fig. 1.2

Sensible Heat - Points A and 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 has 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.

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.

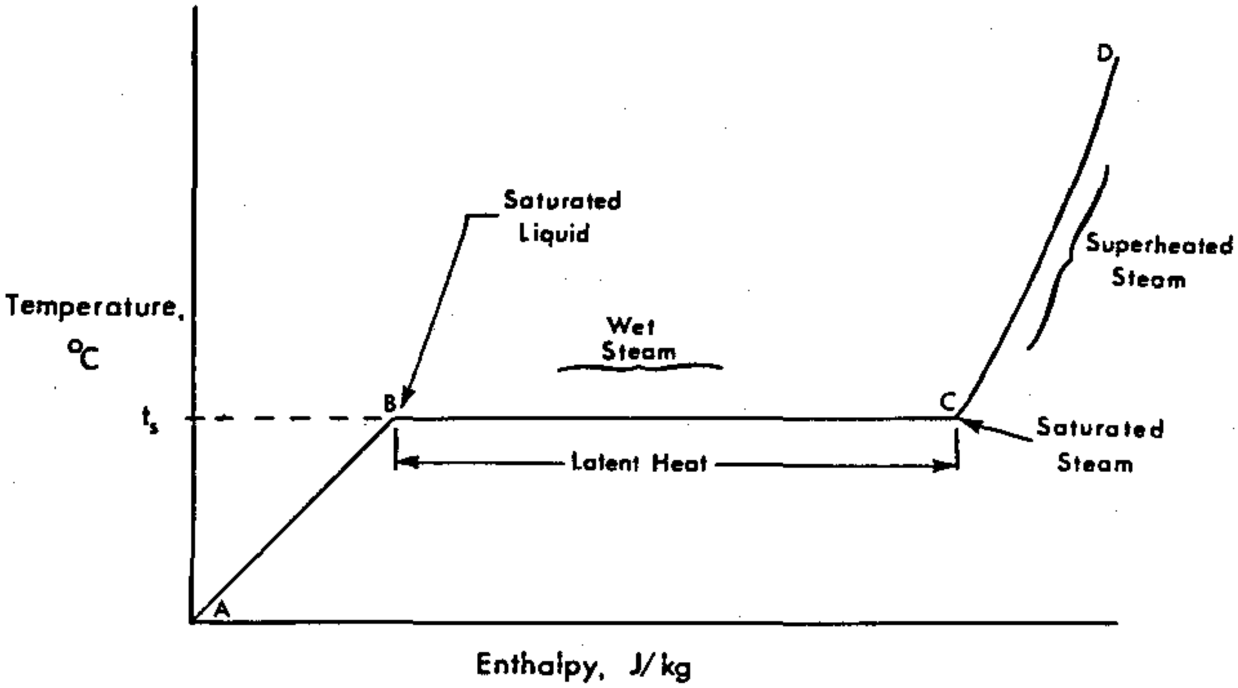

Fig. 1.3

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 us 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.

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.

Q1.2 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.

Q1.3 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.

* * * * *

Heat Transfer and Cooling of the Fuel

Many of the heat transfer processes associated with our CANDU power plants occur in a liquid medium and one of the most crucial, with respect to reactor operation, is removal of heat from the fuel. In this section we will examine this process in more detail.

Different heat transfer mechanisms are involved in cooling the fuel elements. Heat generated in the fuel pellets is transferred to the outer surface of the sheath by conduction. Assuming that no excessive boiling is occurring, removal of this heat by the coolant, ie, heat transport D_2O, is through

(a) forced convection when the heat transport fluid is circulated by pump, eg, HT, SDC, ECI, or

(b) natural convection (thermosyphoning) when no pumps are available to circulate the heat transport fluid.

Let us look more carefully at the convective heat transfer process focusing on the occurrence of boiling in the coolant and the consequent effects on heat transfer and reactor operation.

Boiling is a process of evaporation associated with vapour bubbles in a liquid. Figure 1.4 illustrates natural convection boiling in a pool of liquid (at atmospheric pressure and saturation temperature) heated by a flat plate at higher temperature. Heat flux (Q/A) which is the rate of heat transferred per unit surface area, is plotted *against the difference in temperature between the heated plate or* wall (T_w) and the saturation temperature (T_{sat}). The slope of the resulting curve represents the heat transfer coefficient. General characteristics of this type of boiling can be applied to forced convection boiling at various flow velocities and to other pressure and temperature conditions.

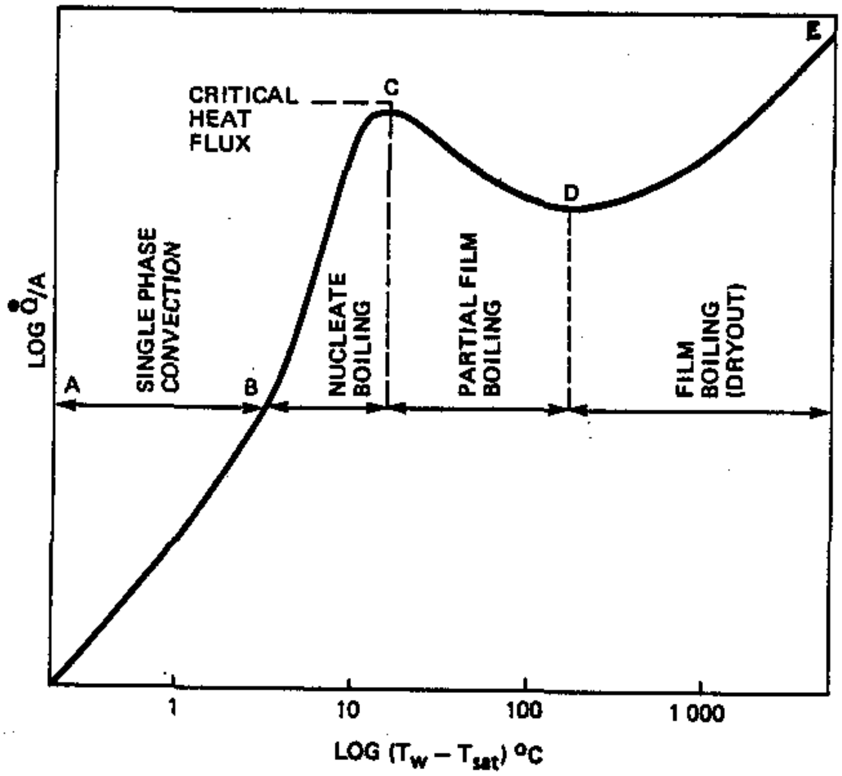

Figure 1.4 Boiling Regimes (Note log scales are used)

The process curve can be divided into four regions based on the mechanism of heat transfer. In the region A-B, single phase liquid convection is the mode of heat transfer. The temperature of the heating plate or wall is only slightly higher than the liquid saturation temperature and there is no boiling or bubble formation.

As the temperature difference (T_w-T_{sat}) increases (region B-C), nucleate boiling is initiated. It is characterized by the formation of bubbles at specific nucleation sites on the heating surface. The vigorous mixing caused by the formation and rising of vapour bubbles results in a greater heat transfer coefficient in this region than in region A-B (evidenced by the increased slope of the boiling curve). The peak nucleate boiling heat flux, called "critical heat flux," is reached when so many nucleation sites become active and the bubbles so dense, that a vapour film forms over the heating surface preventing the flow of liquid to the surface.

When the "critical heat flux" is reached convective heat transfer decreases and eventually conduction and radiation predominate. The consequence is that in region C-D, despite the increased temperature differential, the heat flux decreases. The vapour film established is unstable in this region. It spreads over a part of the heating surface, breaks down, is replaced by violent nucleate boiling, and is reestablished. This characterizes partial film boiling.

At even higher values of (T_w-T_{sat}), the heat transfer mechanism becomes more stable and the heat transfer coefficient begins to rise again but more slowly than in the nucleate boiling region, B-C. In region D-E, film boiling is stabilized and the heating surface is entirely covered by a thin layer of vapour. This condition is known as "dry out" and must be avoided. It is dangerous because in trying to attain the same high heat fluxes established under nucleate boiling, the heating surface temperature may become so excessive that it is above the melting point of the material.

If nuclear fuel is used as the heat source, operating at or near the critical heat flux region will impose thermal stresses on the fuel and fuel sheath due to the rapid changes in the heat transfer mechanism. This is further complicated by the varying nature of the neutron flux.

Using Figure 1.4 we have just described the process of natural convection boiling at atmospheric pressure and saturation temperature. The actual process in a fuel channel deviates from this simple model in many ways such as

(a) the process is by forced convection
(b) pressures are much higher

(c) coolant enters the channel subcooled
(d) the shape of the heat transfer surface is more complex, and
(e) heat flux within the fuel channel is not uniform.

All these factors complicate the conditions present during boiling and impair our ability to predict critical heat flux and dry out more than in the case of pool boiling.

The practical conclusions that can be drawn from the above discussion are

(a) limited nucleate boiling (at a heat flux well below the critical heat flux) improves heat transfer due to the vigorous mixing of the fluid by the vapour bubbles. This is why most CANDU reactors have been designed for this mode of boiling occurring in some fuel channels at high power, and

(b) excessive nucleate boiling (at a heat flux too close to the critical heat flux) jeopardizes fuel safety since even a small increase in heat load can easily convert such boiling to film boiling and eventually dry out with overheating of fuel and fuel failures.

Q1.4 Explain in your own words the following:

(a) Nucleate boiling.
(b) Partial film boiling.
(c) Dry out.
(d) Critical heat flux.

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 supplying the energy for the compression work done. The mechanical energy used in the compressor raises the gas pressure and increases the average kinetic energy of the molecules and hence the gas temperature. In addition, a smaller amount of frictional heat is generated by the turbulence of the compression process further increasing molecular motion and hence temperature. The net effect of this heat (seen as increased gas temperature) during compression is to decrease the compressive effect, ie, reduce or offset the decrease in volume caused by compression.

It is important to reduce the gas volume 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 "after cooler" 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.

Q1.5 Explain why gas increases in temperature when compressed and why an after cooler is necessary.

Q1.6 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 liquefied 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.

Q1.7 Explain why compressed gas should not be used for pressure testing.

Q1.8 Explain why gas cylinders should not be allowed to empty completely.

Q1.9 State how you would determine the contents of a compressed air and a liquefied gas cylinder.

* * * * *

MODULE 1 - ANSWERS

Q1.1

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,

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

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

$$\Delta T = 11\text{°C}$$

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

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

Q1.2

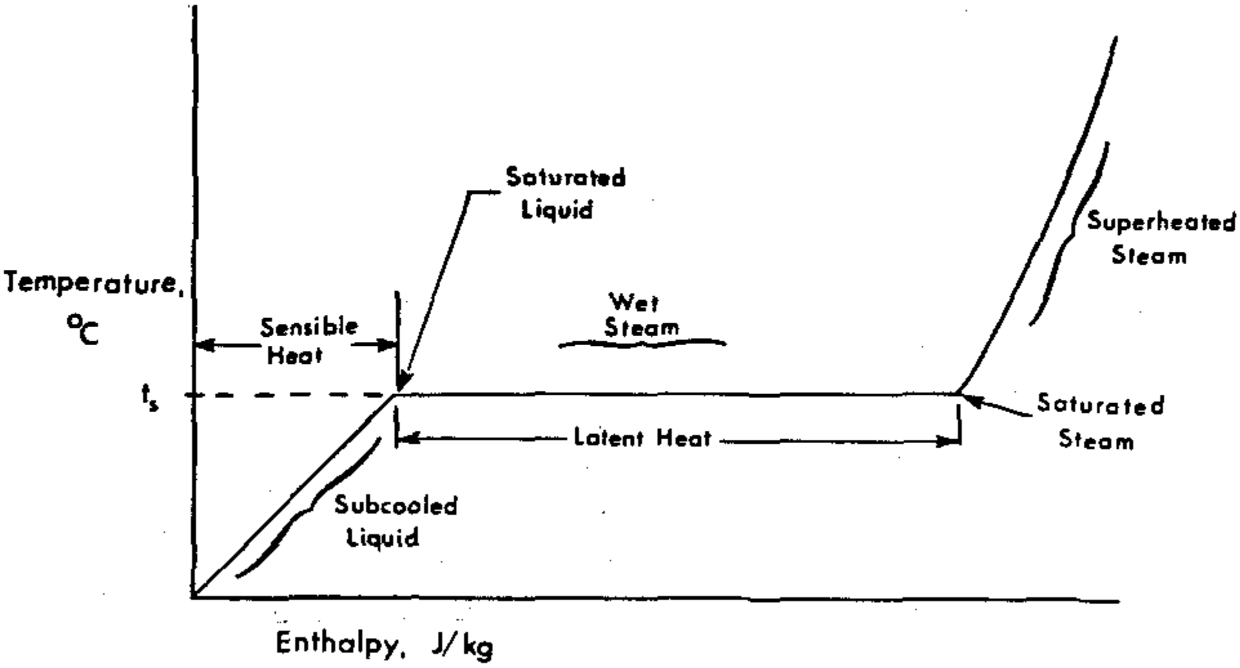

Fig. 1.5

Q1.3

(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 thermosyphoning of the PHT system when the PHT pumps are shutdown:

(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.

Q1.4

(a) Nucleate boiling is characterized by the formation of bubbles at specific nucleation sites on the heating surface. As the vapour bubbles rise from the heating surface they cause mixing in the liquid and subsequently increase the heat transfer coefficient.

(b) Partial film boiling is characterized by the formation, breakdown and re-establishment of a vapour film on the heating surface. There are so many active nucleation sites on the heating surface that the vapour bubbles coalesce to form an unstable film on the heating surface. The heat transfer coefficient decreases.

(c) Dry out is the term used to describe the formation of a stable film of vapour on the heating surface. It is dangerous to establish this condition because the heating surface temperature must be very high (even approaching the melting point) in order to attain high heat fluxes.

(d) Critical heat flux is the peak heat flux reached under nucleate boiling conditions. It represents the point where so many nucleation sites become active and the vapour bubbles so dense that a vapour film tends to form on the heating surface.

01.5

The increase in molecular kinetic energy during compression causes the gas temperature to rise which tends to increase the volume of the compressed gas partially offsetting the compression effect. The volume is reduced using an after cooler, after the compressor and before the receiver, to reduce the size of the receiver.

01.6

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.

01.7

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.

01.8

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.

01.9

A compressed gas cylinder may be checked for contents by <u>pressure</u>.

A liquified gas cylinder may only be checked for contents by <u>weight</u>.

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COURSE 225

HEAT & THERMODYNAMICS

MODULE 2

STEAM TABLES

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	Date 88-05-30	Date 88-07-29

Heat and Thermodynamics

MODULE 2

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.

Enabling Objectives

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

225 - 2

STEAM TABLES

The steam tables provide us with a very effective means of quantifying operating conditions and while we know that you don't use them on a regular basis as part of your job they provide a useful aid to investigating operating conditions.

You should have a copy of steam tables as part of the module. The units for the tables are mainly S.I. which may be a new experience for some of us. 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 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
03.5	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
[illegible]	1.013	419.4	2256.9	2676.0	1.3069	6.0485	7.3554	1.0437	1672.0	1673.0	100.0
[illegible]	1.031	421.2	2255.6	2676.8	1.3125	6.0369	7.3494	1.0441	1644.3	1645.3	100.5
[illegible]	1.050	423.3	2254.3	2677.6	1.3182	6.0252	7.3434	1.0445	1617.2	1618.2	101.0
[illegible]	1.069	425.4	2252.9	2678.3	1.3238	6.0136	7.3374	1.0449	1590.6	1591.6	101.5
[illegible]	1.088	427.5	2251.6	2679.1	1.3294	6.0020	7.3315	1.0453	1564.5	1565.5	102.0
[illegible]	1.107	429.6	2250.3	2679.9	1.3350	5.9905	7.3255	1.0457	1538.9	1540.0	102.5
[illegible]	1.127	431.7	2248.9	2680.7	1.3406	5.9790	7.3196	1.0461	1513.8	1514.9	103.0
[illegible]	1.147	433.8	2247.6	2681.4	1.3462	5.9675	7.3137	1.0465	1489.2	1490.3	103.5
[illegible]	1.167	435.9	2246.3	2682.2	1.3518	5.9560	7.3078	1.0469	1465.1	1466.2	104.0
[illegible]	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 = 4×10^3 kPa = $\frac{4 \times 1000}{100}$ bar = 40 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 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
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	16.548	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 P_s column until we get to 10.027 bar. The value of t_s is 180.0°C.

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

<u>Q2.1</u> Water is heated to produce saturated steam at 135°C. Determine the pressure of the steam.

<u>Q2.2</u> 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.

<u>Q2.3</u> 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?

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Sensible Heat

You will recall from module 1 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 a 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 $h_f = \underline{741.1}$ kJ/kg.

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume m³/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:

Q2.4 Condensate leaves the condensate extraction pump at 36°C. Determine the enthalpy of the condensate.

Q2.5 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.

Q2.6 A steam generator operates at 4.11 MPa(a). The feedwater entering the steam generator is subcooled by 65°C, ie, 65°C *below* t_s. *Determine the enthalpy of the feedwater.*

Q2.7 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.

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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 <u>constant temperature</u>. The symbol is h_{fg} and the units are again kJ/kg. The suffix 'fg' denotes transition from a fluid to a gas; that happens to be the way the symbol is written.

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.

<u>Q2.8</u> 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. (Remember that 5 MPa(a) is equal to 50 bars.)

<u>Q2.9</u> 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.

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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.

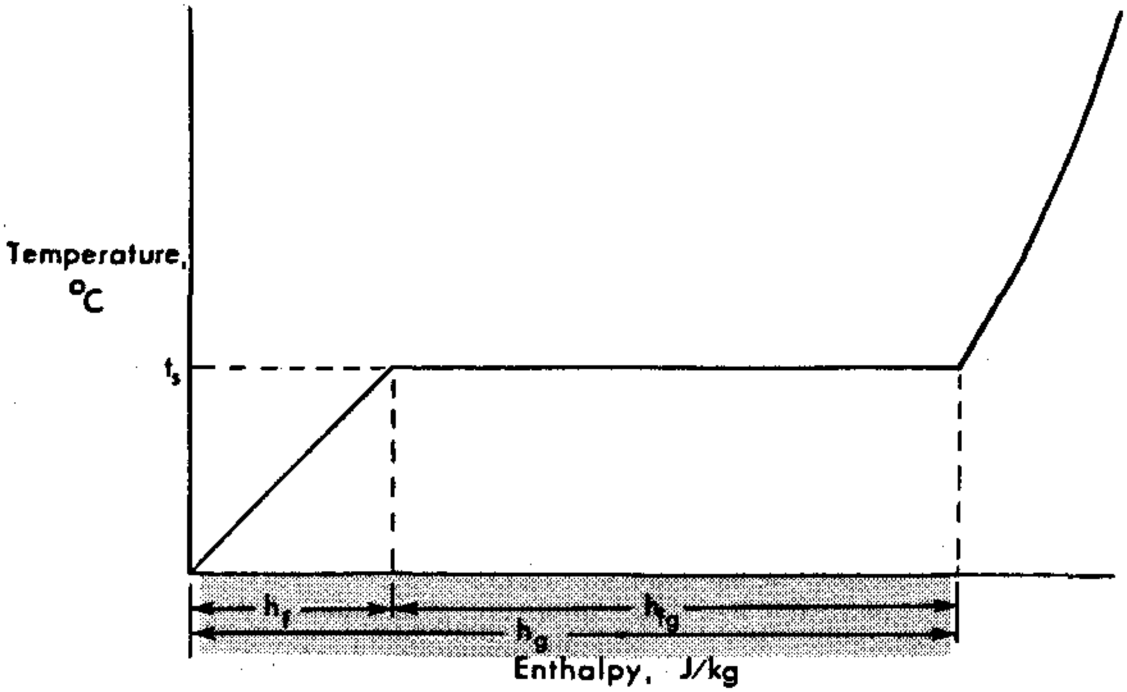

Fig. 2.1

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.

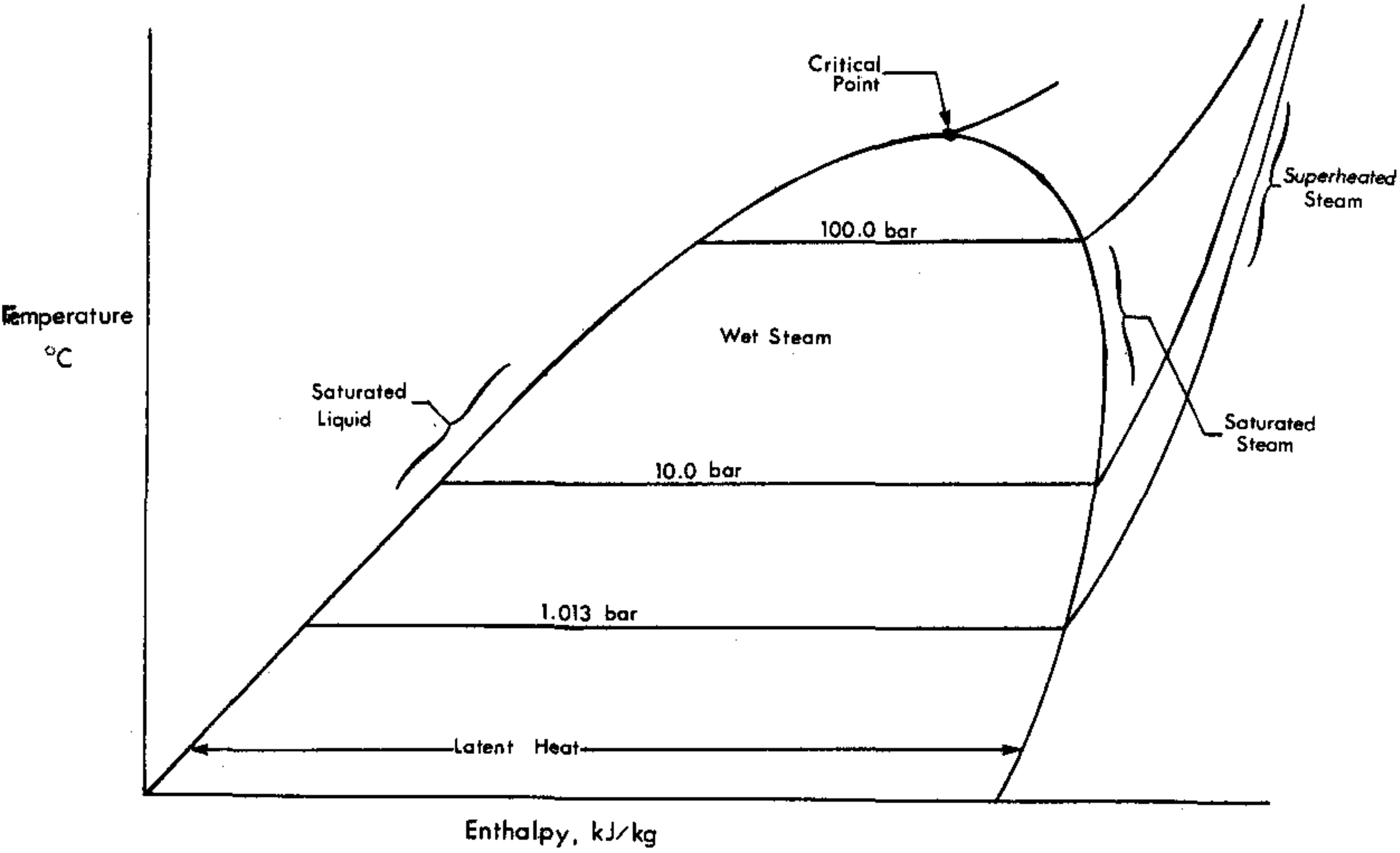

Fig. 2.2

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:

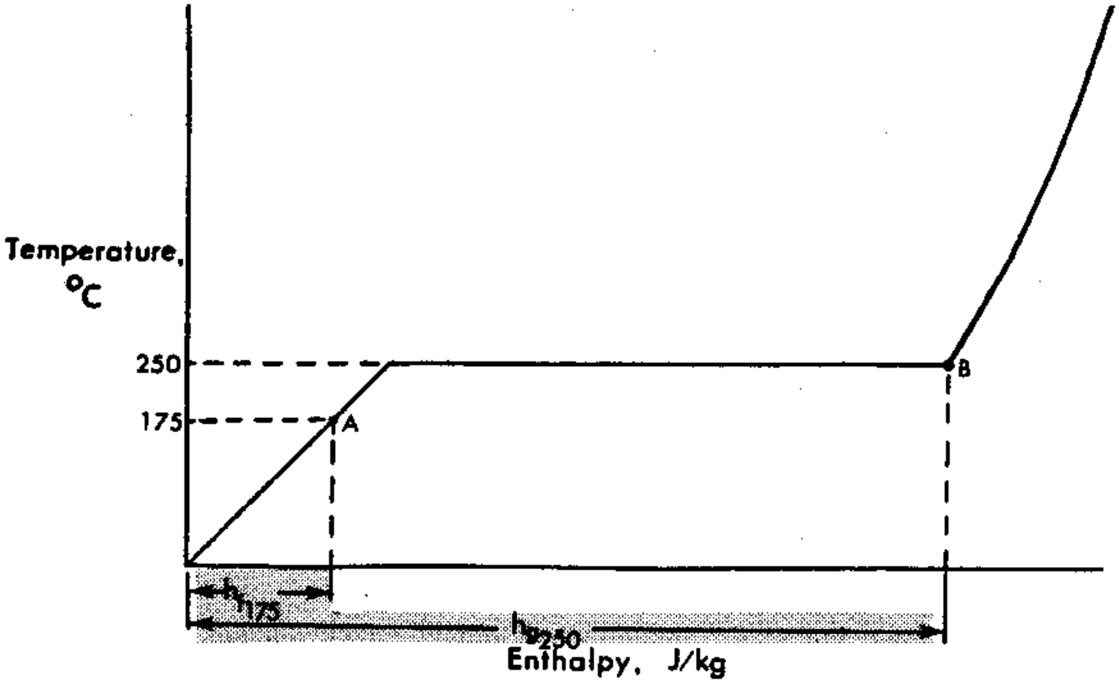

Fig. 2.3

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 = 2840.4 - 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 at Table 1, except that they use even steps of pressure as the base instead of temperature. Which one do you choose? The answer is simple. Whichever one suits you! 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.

Q2.10 Saturated water at 30 bar is cooled to a temperature that is 108°C below the saturation temperature. How much heat has been removed?

Q2.11 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?

Q2.12 An oil cooler has cooling water entering at 17°C and leaving at 41°C. Determine the increase in the enthalpy of the water.

Q2.13 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.

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Enthalpy of Wet Steam

You may recall from the 'Basics' Module 1 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.

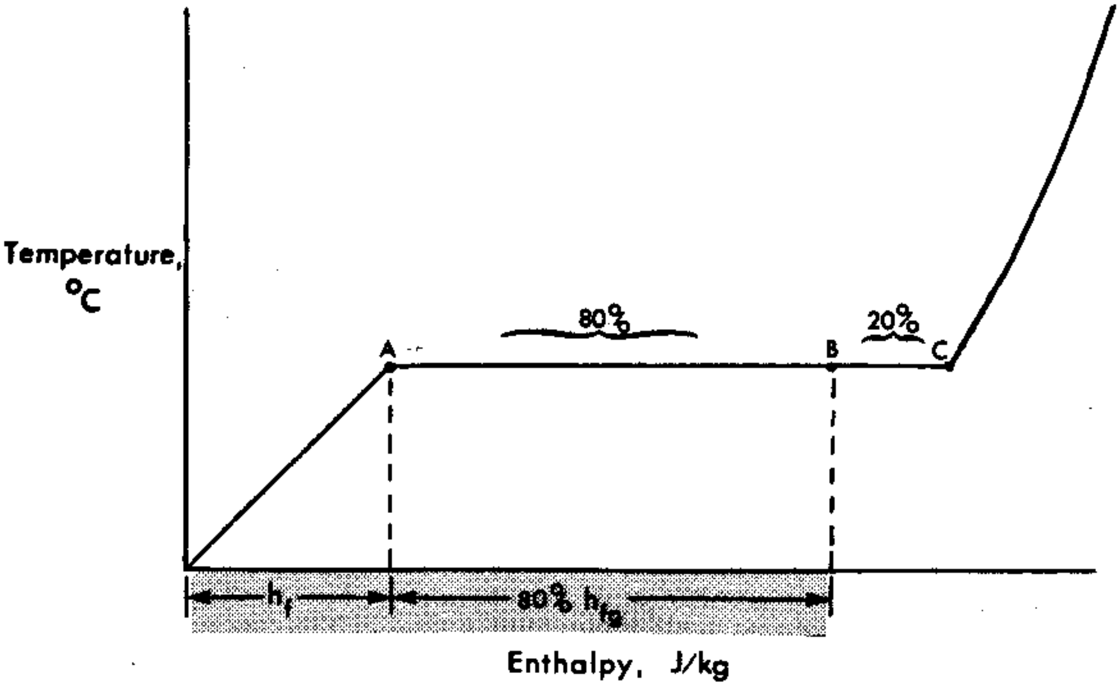

Fig. 2.4

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 of 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
and h_{fg} = 1712.9 kJ/kg

$$\begin{aligned} \text{Thus enthalpy of steam} &= 1087.4 + 0.85 \times 1712.9 \text{ kJ/kg} \\ &= 1087.4 + 1456 \text{ kJ/kg} \\ &= 2543.4 \text{ kJ/kg} \end{aligned}$$

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

<u>Q2.14</u> A low pressure turbine exhausts steam at 12% moisture and at a pressure of 6 kPa(a). Determine the enthalpy of the steam.

Q2.15 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.

Q2.16 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.

Q2.17 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.

Q2.18 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.

Q2.19 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.

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Superheated Steam

In module 1 on 'Basics', we define superheated steam as steam which exists at a temperature above the saturation temperature. Steam Tables 1 and 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(abs)bar	2.0			3.0			4.0			5.0			6.0			7.0		
t_s °C	120.2			133.5			143.6			151.8			158.8			165.0		
	h	s	v	h	s	v	h	s	v	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	640.1	1.860	1.093	670.4	1.931	1.101	697.1	1.992	1.10
Sat. Vapour	2706	7.127	885.4	2725	6.991	605.6	2738	6.894	462.2	2748	6.819	374.7	2756	6.758	315.5	2762	6.705	272
t °C																		
50	209.4	0.703	1.012	209.5	0.703	1.012	[illegible]	0.703	1.012	209.7	0.703	1.012	209.8	0.703	1.012	209.9	0.703	1.01
100	419.1	1.307	1.044	419.2	1.307	1.044	419.3	1.307	1.044	419.4	1.307	1.044	419.4	1.307	1.043	419.5	1.306	1.04
150	2769	7.279	959.5	2760	7.077	633.7	2752	6.929	470.7	632.2	1.842	1.091	632.2	1.842	1.091	632.3	1.841	1.09
200	2871	7.507	1080	2866	7.312	716.4	[illegible]	7.171	534.3	2855	7.059	425.0	2850	6.968	352.0	2844	6.886	299.
250	2971	7.710	1200	2968	7.518	796.4	[illegible]	7.380	595.2	2961	7.272	474.4	2958	7.183	393.9	2954	7.107	336
300	3072	7.894	1316	3070	7.703	875.3	3067	7.568	654.9	3065	7.461	522.6	3062	7.374	434.4	3060	7.300	371.
350	3174	8.064	1433	3172	7.874	953.5	3170	7.640	713.9	3168	7.634	570.1	3166	7.548	474.2	3164	7.475	405
400	3277	8.223	1549	3275	8.034	1031	3274	7.899	772.5	3272	7.795	617.2	3271	7.709	513.6	3269	7.636	439.
450	3381	8.372	1665	3380	8.184	1109	[illegible]	8.050	830.9	3377	7.945	664.1	3376	7.860	552.8	3375	7.778	473.
500	3487	8.514	1781	3486	8.326	1187	[illegible]	8.192	889.2	3484	8.088	710.8	3483	8.003	591.8	3482	7.931	506
550	3595	8.649	1897	3594	8.461	1264	[illegible]	8.327	947.4	3592	8.223	757.4	3591	8.138	630.8	3590	8.063	540.
600	3704	8.778	2013	3703	8.590	1341	3702	8.456	1005	3702	8.353	804.0	3701	8.268	669.6	3700	8.193	57
650	3815	8.901	2129	3814	8.714	1419	3814	8.580	1063	3813	8.477	850.4	3812	8.392	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.

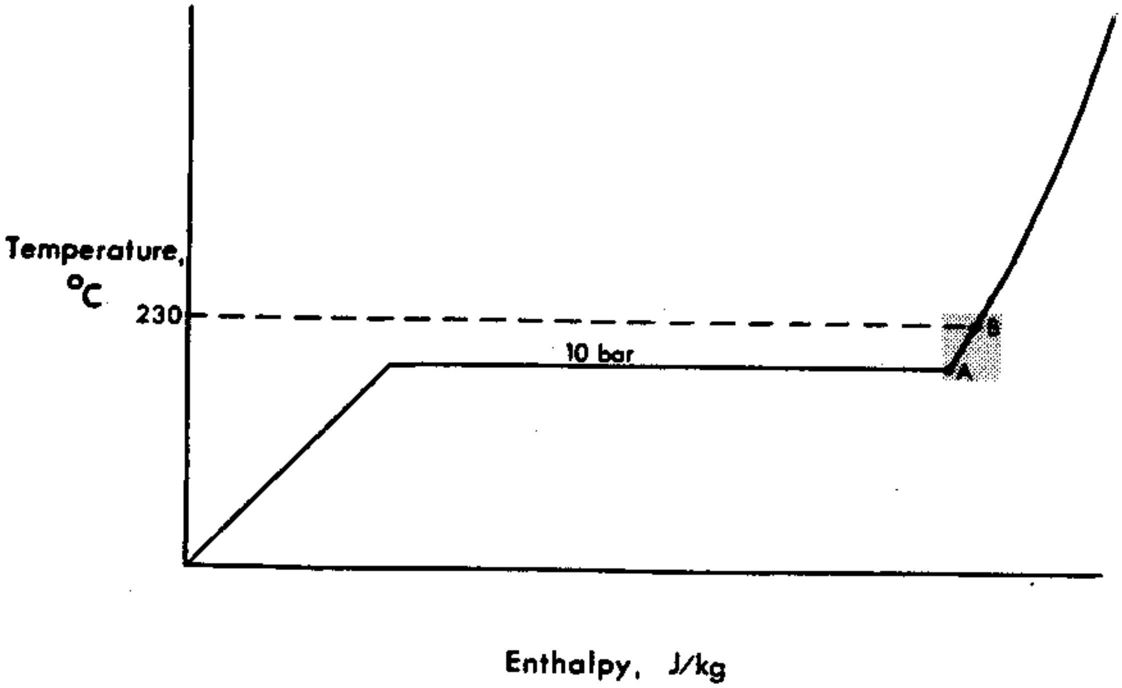


Fig. 2.5

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 = 116 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) = 2896.6 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 = 120.6 kJ/kg

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

Q2.20 Determine the enthalpy of steam at 20 bar and a temperature of 375°C.

Q2.21 380 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.

Q2.22 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)	12.7 kJ/kg	30°C	0.07375 bar

Q2.23 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?

Q2.24 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 $v_f = 1.0145\ \ell/kg$. Thus 30 kg will occupy $30 \times 1.0145\ \ell = 30.435\ \ell$.

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

Q2.25 A tank holds 3 m^3 of water at 90°C. How many kg of water are in the tank?

Q2.26 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.

Q2.27 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.

Q2.28 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.

$v = v_f + qv_{fg}$

$= 1.1082 + 0.88 \times 271.29$

$= \underline{239.8}$ ℓ/kg

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

Q2.29 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.

Q2.30 The low pressure steam in question Q2.29 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, and 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 and at the same time causing other pockets of vapour to condense.

The solution to this problem is to prevent the pressure falling 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 very slowly 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.

Q2.31 Briefly describe the process of "steam hammer" and explain how it could be avoided.

* * * * *

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.

MODULE 2 - ANSWERS

Q2.1

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.

Q2.2

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.

Q2.3

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

Q2.4

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.

Q2.5

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 (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.

<u>Note</u>: The better method for answering this question is to use Table 2 where interpolation is not necessary.

Q2.6

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_s is 187°C and you can see the value of h_s is 794.2 kJ/kg.

Q2.7

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 $t_s = 126°C$, $h_f = 529.2$ kJ/kg.

So the amount of heat added is the difference, ie, 592.2 - 146.6 = 382.6 kJ/kg.

Q2.8

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.

Q2.9

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).

Q2.10

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

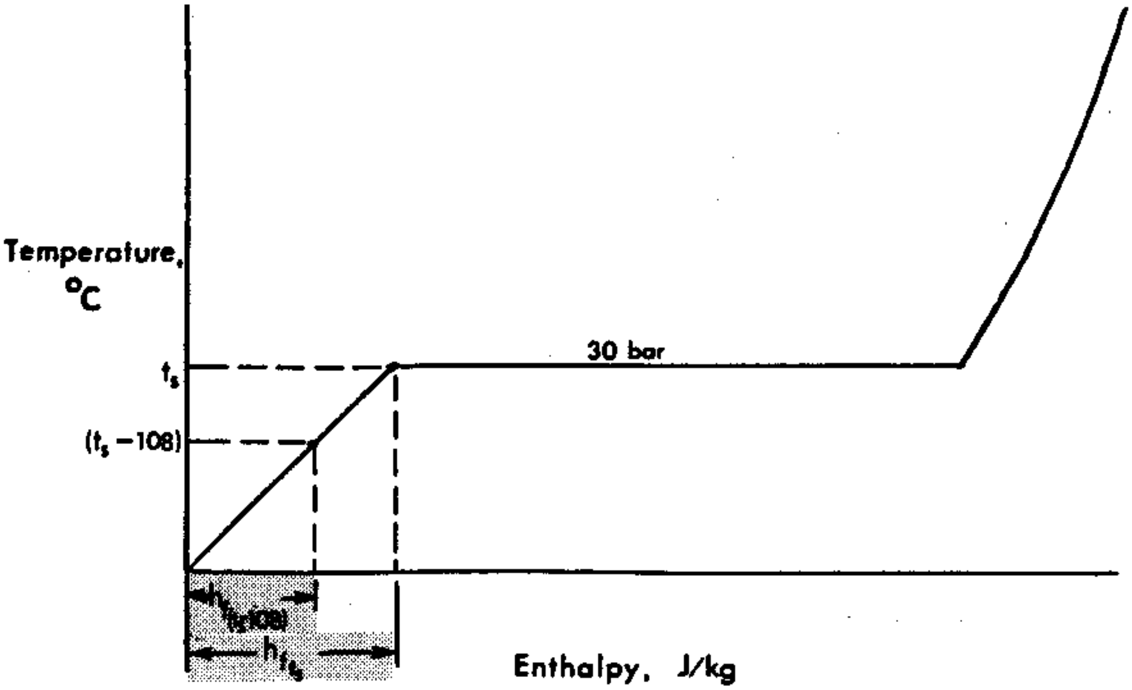


Fig. 2.6

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 - 592.2

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

Q2.11

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.

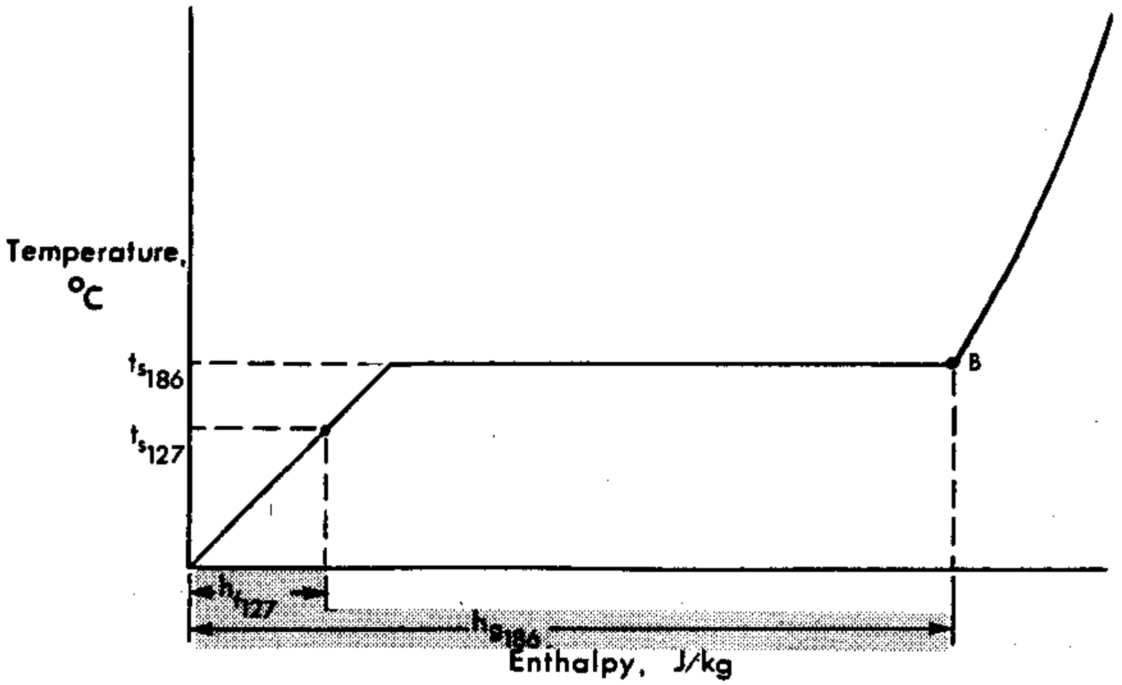


Fig. 2.7

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 if 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.

Q2.12

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.

Q2.13

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.

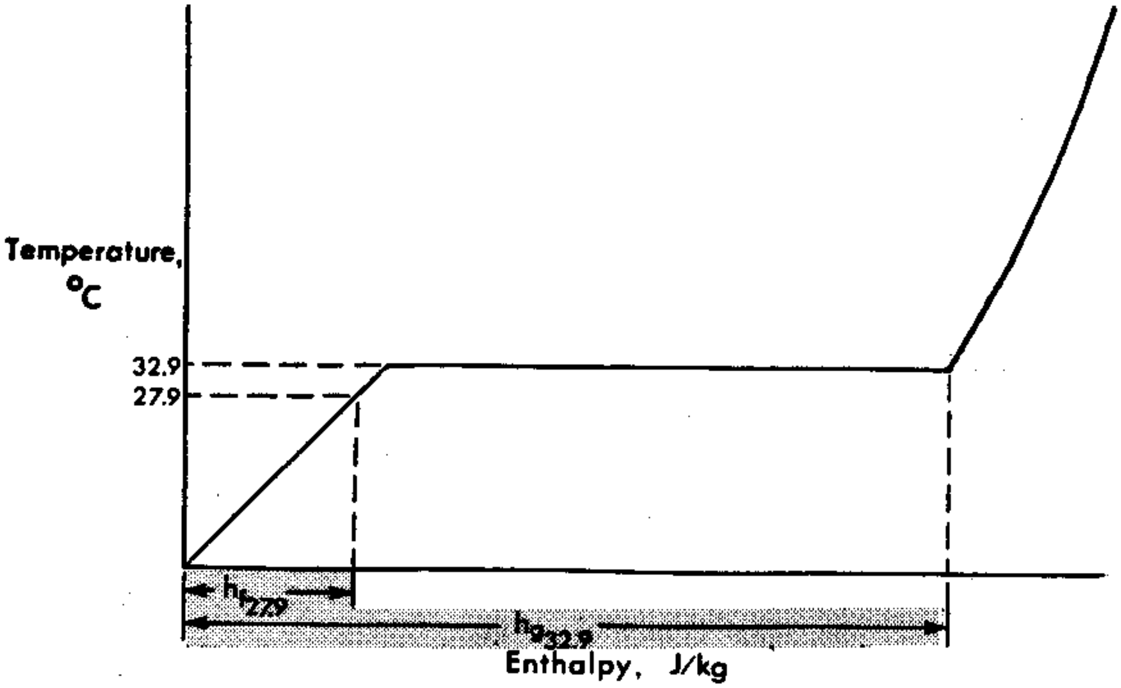


Fig. 2.8

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 116.9 kJ/kg (obtained by interpolation).

Again the change in enthalpy is the amount of heat rejected to the condenser per kg of steam, ie, 2561.6 - 116.9 = 2444.7 kJ/kg.

Q2.14

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 if $h_f + 0.88\ h_{fg}$.

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

Q2.15

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 4/12 x 100 = 33.3 kg.

Q2.16

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.

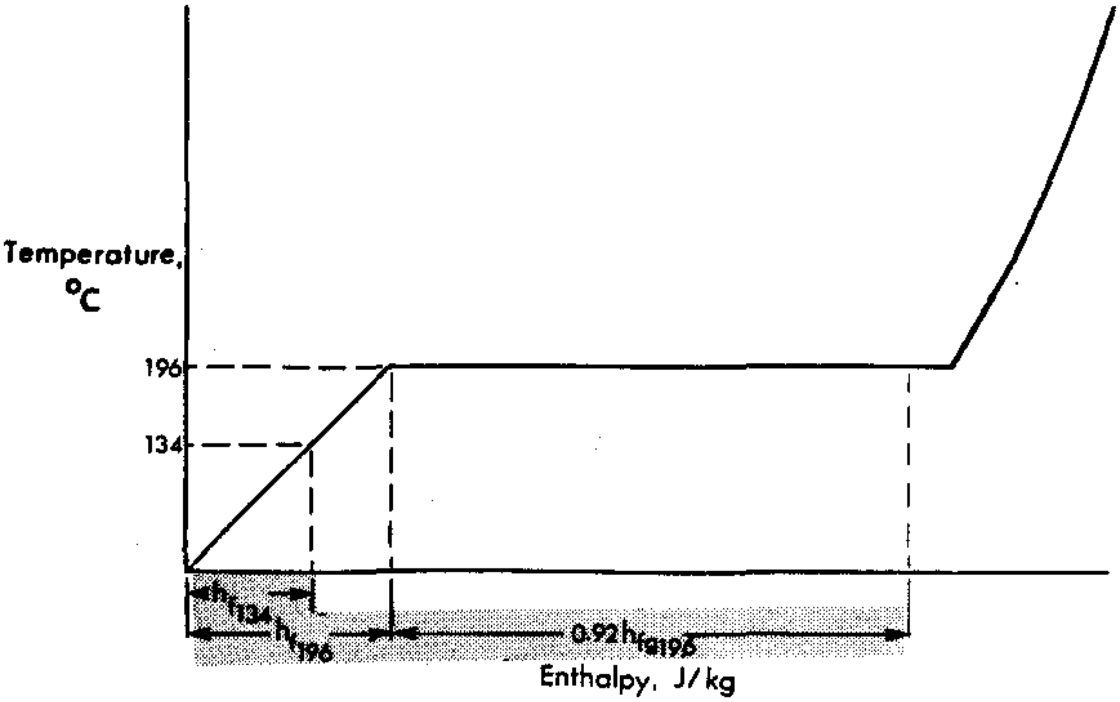


Fig. 2.9

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.

02.17

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

Q2.18

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.

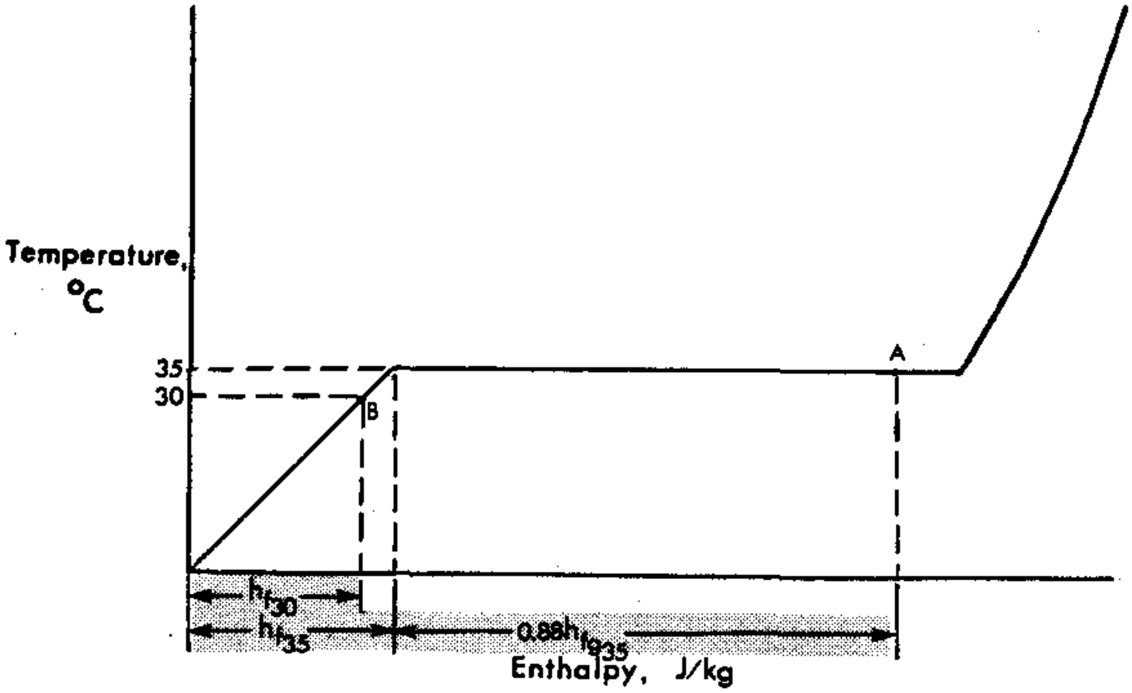


Fig. 2.10

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

= 2275.1 kJ/kg

The final condition is condensate at 30°C. h_{f30} = 125.7 kJ/kg

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

2275.1 - 125.7 kJ/kg

= 2149.4 kJ/kg

Q2.19

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.

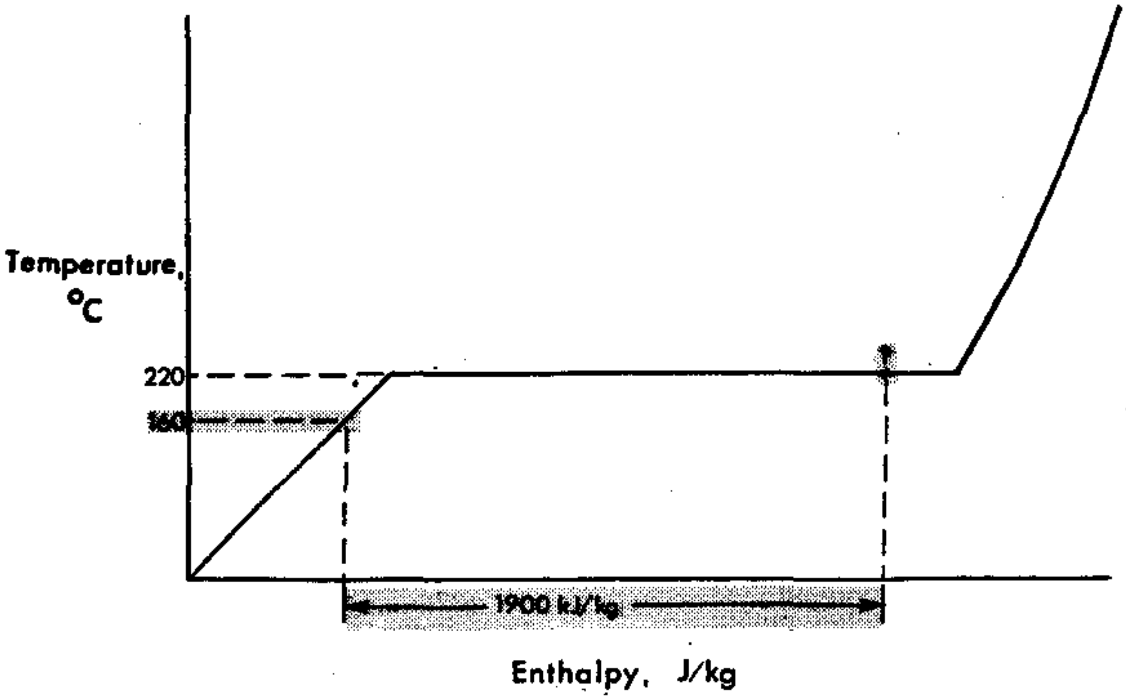


Fig. 2.11

$h_{f160} = 675.5$ 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

$$2575.5 = 943.7 + q \times 1856.2$$
$$1631.8 = q \times 1856.2$$
$$q = (1631.8/1856.2) \times 100$$
$$= \underline{87.9\%}$$

Q2.20

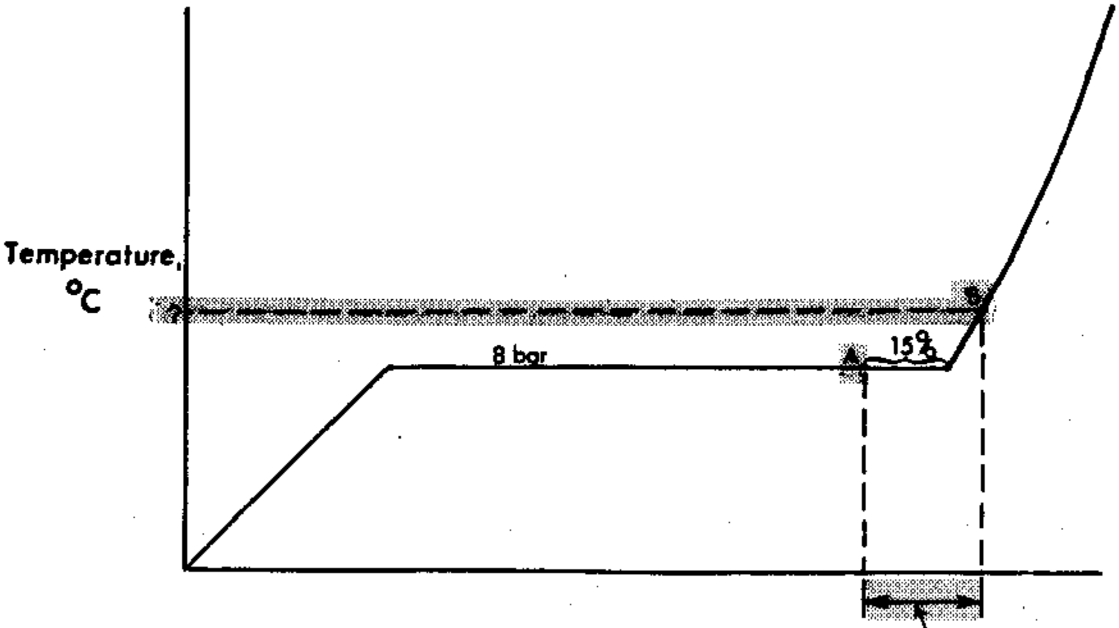
Using Table 3, under the pressure column of 20 bar, the value of enthalpy at 350°C is 3139 kJ/kg, and at 400°C is 3249 kJ/kg. The enthalpy at 375°C is the mean of these two values

$= (3139 + 3249)\ 0.5$

$=$ 3194 kJ/kg

Q2.21

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



Enthalpy, J/kg

Fig. 2.12

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

$h = 720.9 + 0.85 \times 2046.5$

$= 720.9 + 1739.5$ kJ/kg

$=$ 2460.4 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.

Q2.22

(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.

02.23

Using the temperature enthalpy diagram,

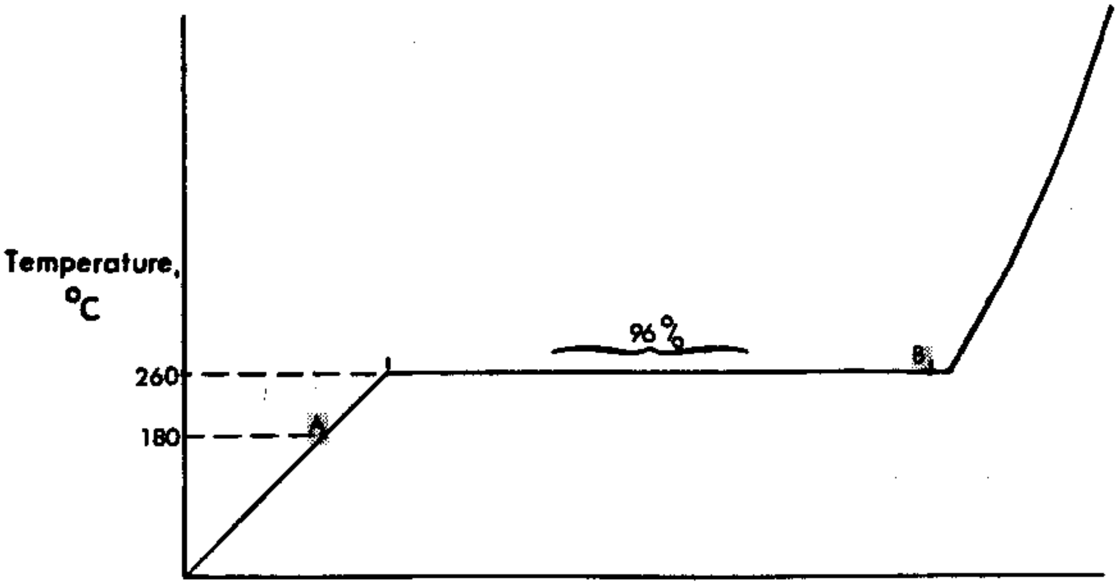


Fig. 2.13

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

Q2.24

Again use the temperature/enthalpy diagram.

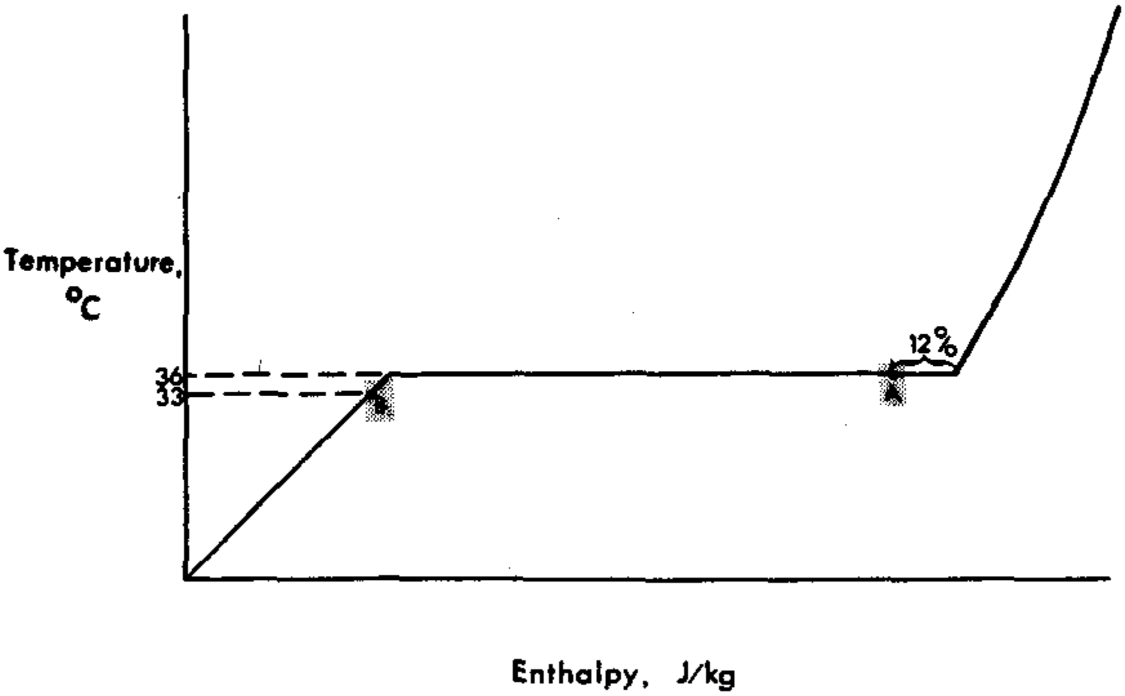


Fig. 2.14

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 = $\underline{3218.9}$ kJ/kg.

Q2.25

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

Q2.26

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 $\frac{0.1146}{1.0063} \times 100 = 11.4\%$

Q2.27

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.

Q2.28

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.

Q2.29

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 = 2819.3 ℓ/kg.

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

$$
\begin{aligned}
\text{Thus } v &= v_f + q v_{fg} \\
&= 1.0052 + 0.88 \times 28193.3 \\
&= 1 + 24810 \\
&= 24811 \ \ell/\text{kg}
\end{aligned}
$$

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

Q2.30

The volume of the low pressure steam is, as we already calculated in question Q2.29, 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.

Q2.31

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.

COURSE 225

HEAT & THERMODYNAMICS

MODULE 3

ENTROPY, THROTTLING AND MOLLIER DIAGRAM

Revised	Verified	Verified
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	Date 88-05-30	Date 88-07-29

Heat and Thermodynamics

MODULE 3

ENTROPY, THROTTLING AND 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.

Enabling Objectives

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

ENTROPY, THROTTLING AND MOLLIER DIAGRAM

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.

I am sure you will be glad to know that we will not concern ourselves with entropy beyond a simple state. You may recall in Module 2 '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 do not know the value of 'q', the dryness fraction. The steam is 5 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, $S_{g200} = S_{f(0.06\ \text{bar})} + qS_{fg(0.06\ \text{bar})}$

thus $6.4278 = 0.5209 + q \times 7.8104$

$5.9069 = q \times 7.8104$

therefore, $q = \frac{5.9069}{7.8104} = 76.6\%$

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

Q3.1 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.

Q3.2 Steam which is 4% wet at 15 bar is expanded, isentropically to 60°C. Determine the dryness fraction of the final steam condition.

Q3.3 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 without doing any mechanical work. 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.

There is a major problem with the throttling process which is not obvious. 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. Sounds fair enough doesn't it? The problem is that although the enthalpy is the same, the entropy has increased in this process and we cannot get as much work out of the steam. This factor becomes of major consideration when considering the control of governor steam valves. Suppose we have a turbine which has 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 fully opened when minimum throttling occurs. This method of control is called "throttle governing" and produces loss of efficiency if operating at any load <u>other than full load</u>. In peak load stations we use "nozzle governing" where the valves open one after the other, so that at any point in time there is, in principle, no more than one valve which is throttling the steam.

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.

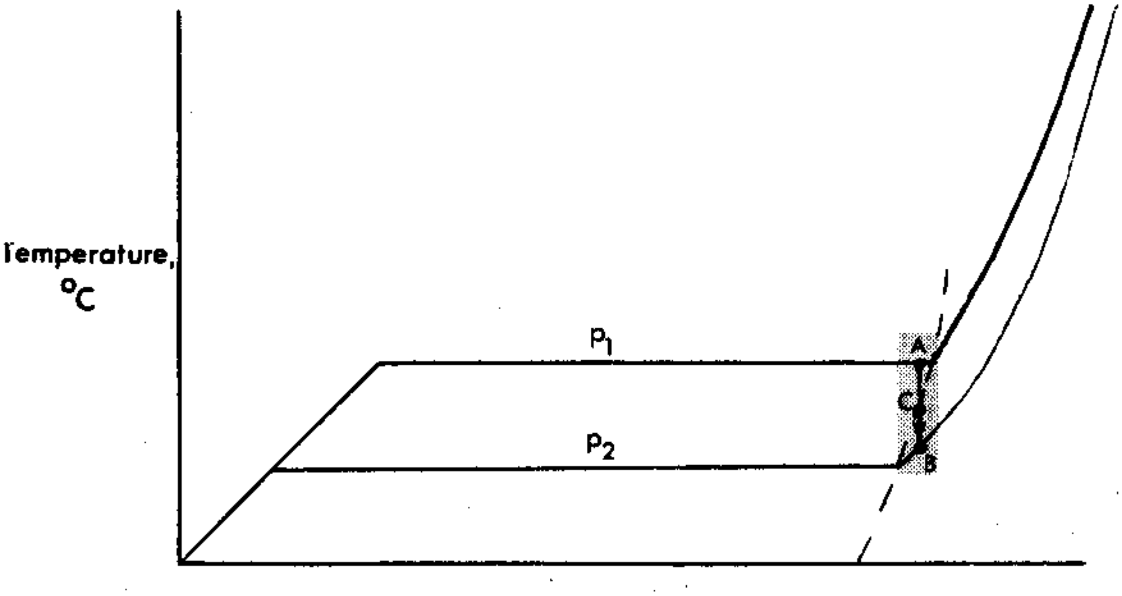

Fig. 3.1

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. Do not 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 is 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.

Thus $2688 = 1087.4 + q \times 1712.9$

$1600.6 = q \times 1712.9$ kJ/kg

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

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

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

Q3.4 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.

Q3.5 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 us 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

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.

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.

Lines of Constant Pressure

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

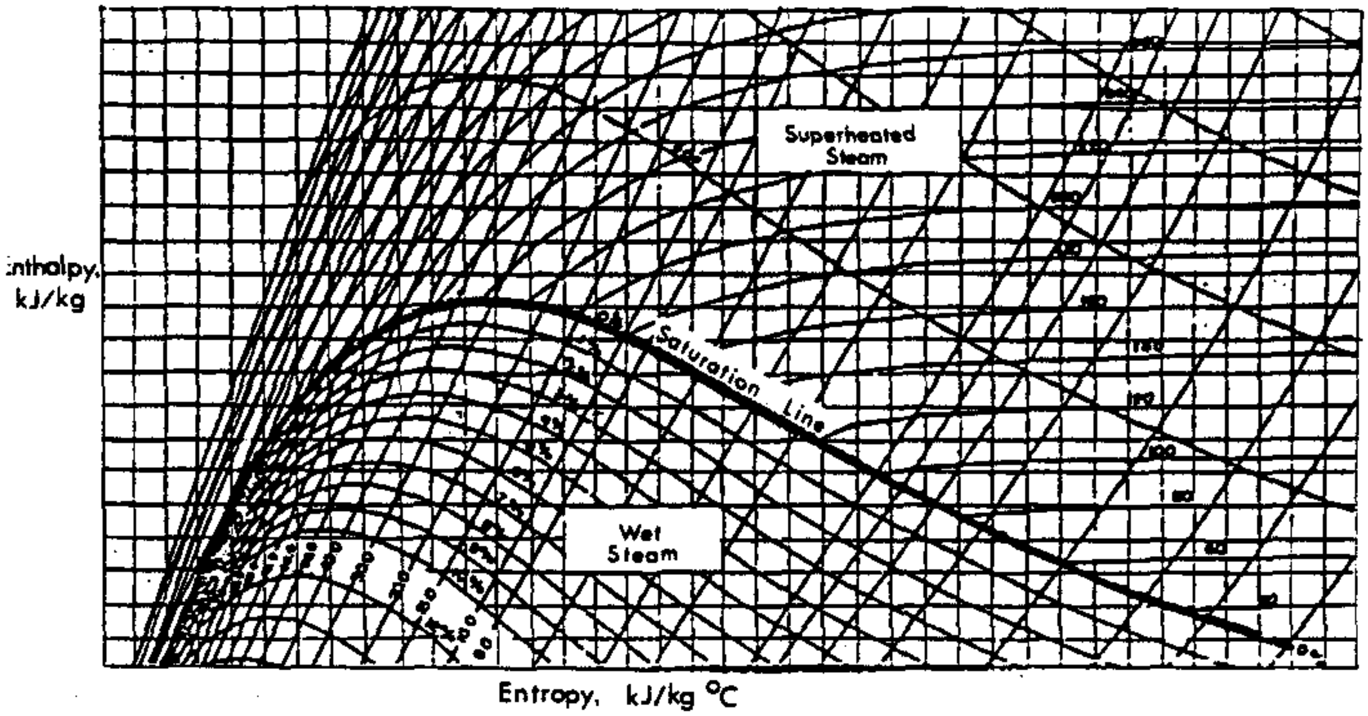
nthalpy,
kJ/kg
Superheated
Steam
Saturation Line
Wet
Steam
Entropy, kJ/kg °C

Fig. 3.2

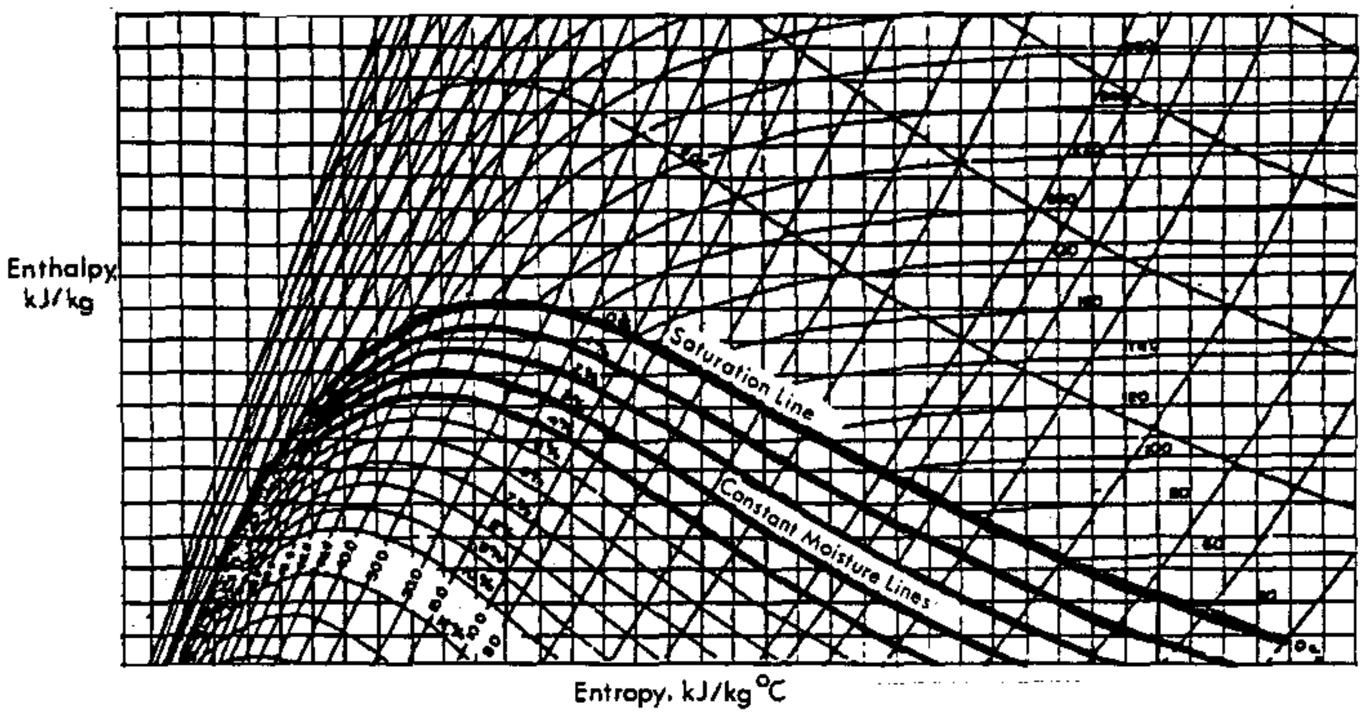
Enthalpy
kJ/kg
Saturation Line
Constant Moisture Lines
Entropy, kJ/kg °C

Fig. 3.3

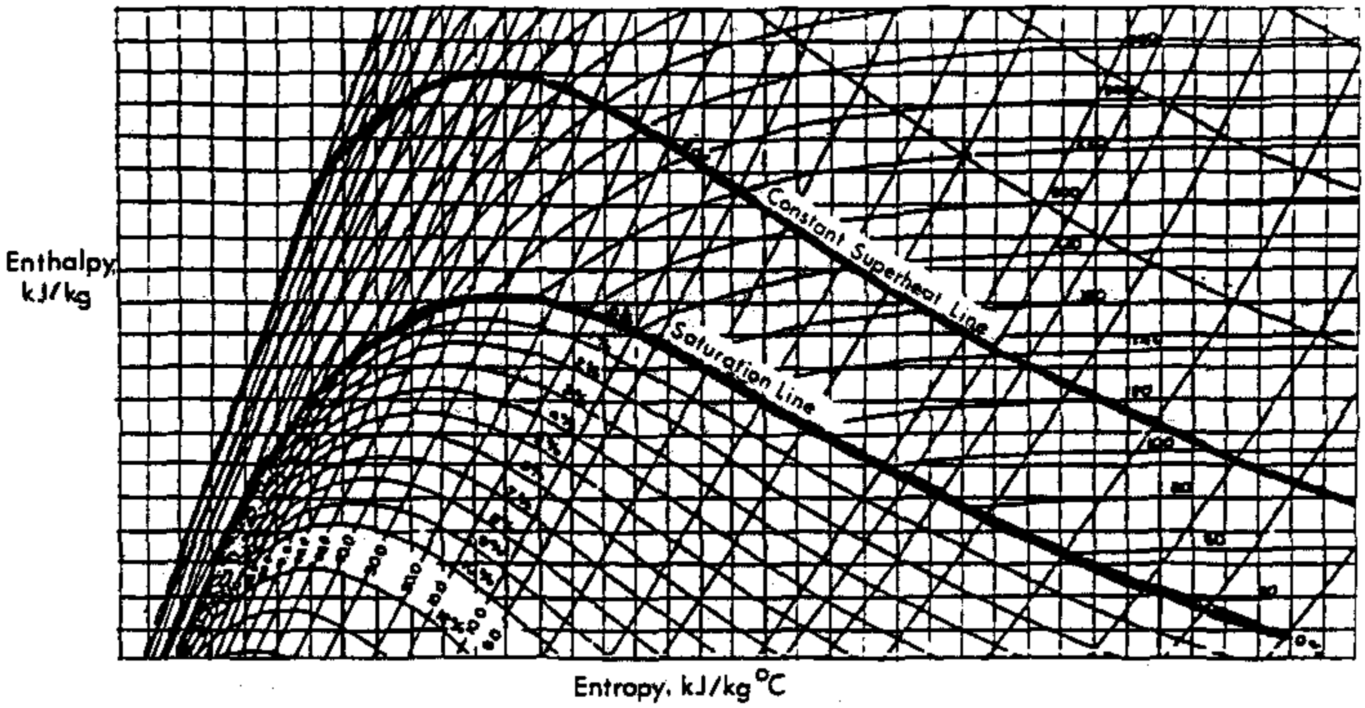
Enthalpy, kJ/kg
Constant Superheat Line
Saturation Line
Entropy, kJ/kg °C

Fig. 3.4

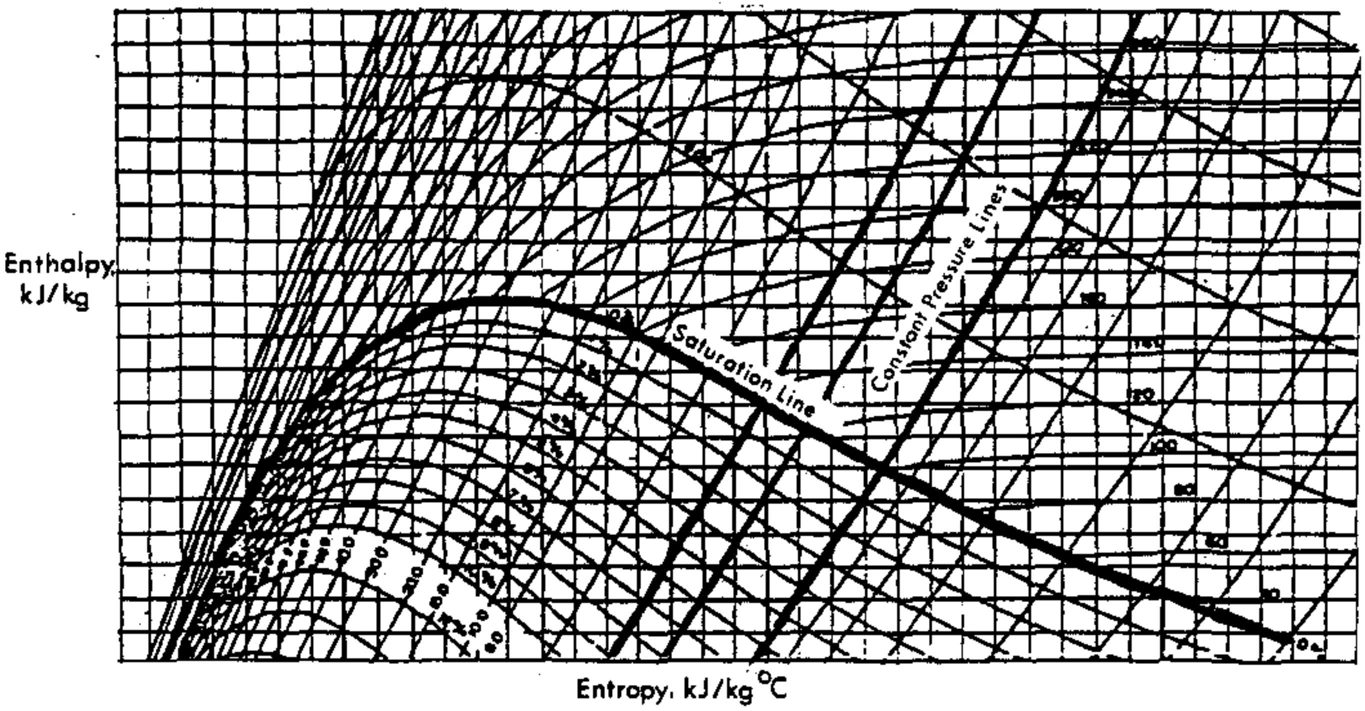
Enthalpy, kJ/kg
Constant Pressure Lines
Saturation Line
Entropy, kJ/kg °C

Fig. 3.5

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.

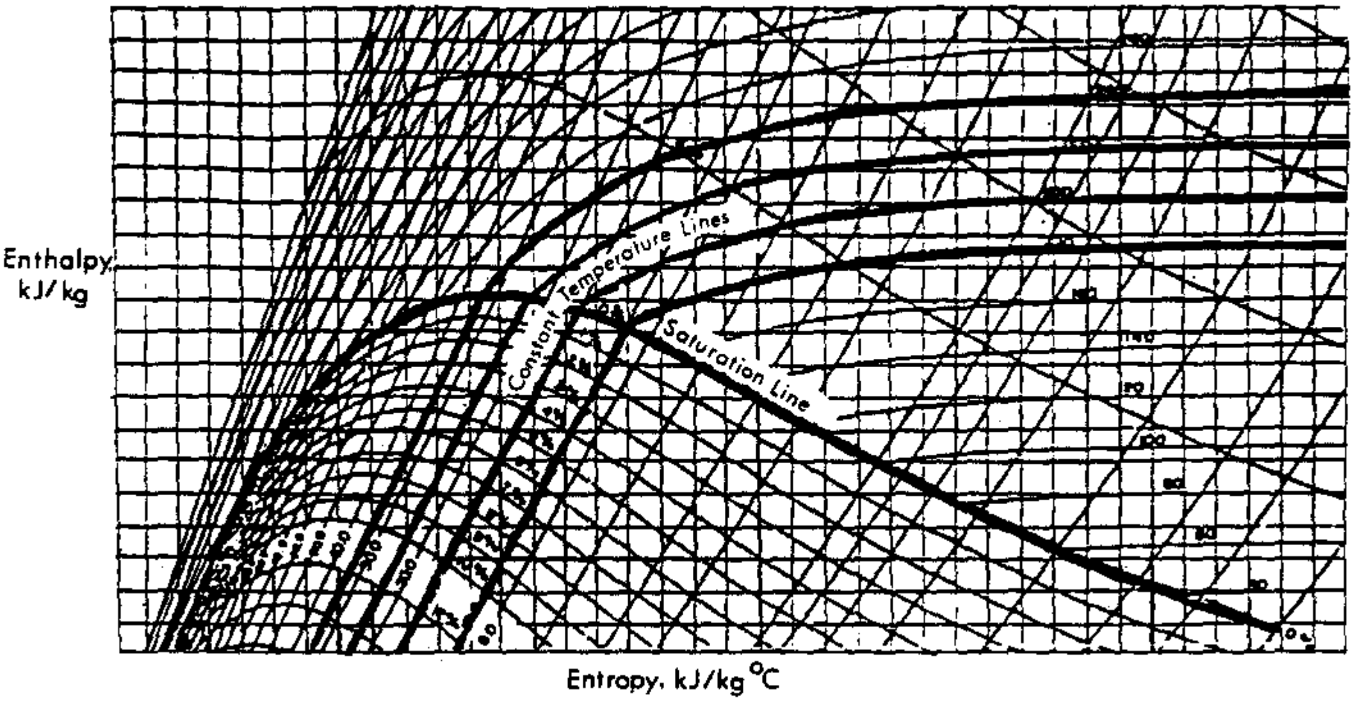

Fig. 3.6

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.

Q3.6 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 an 260°C:

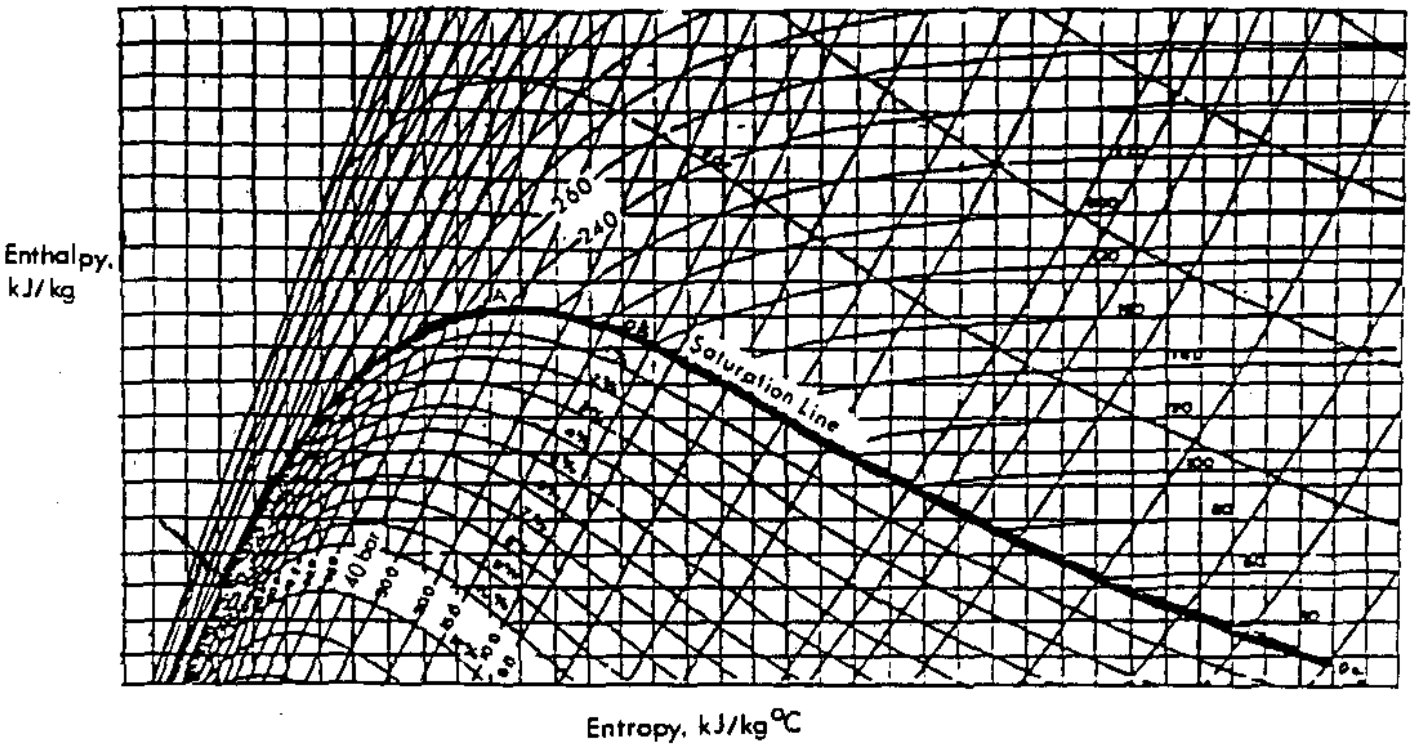

Fig. 3.7

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 of the turbine exhaust.

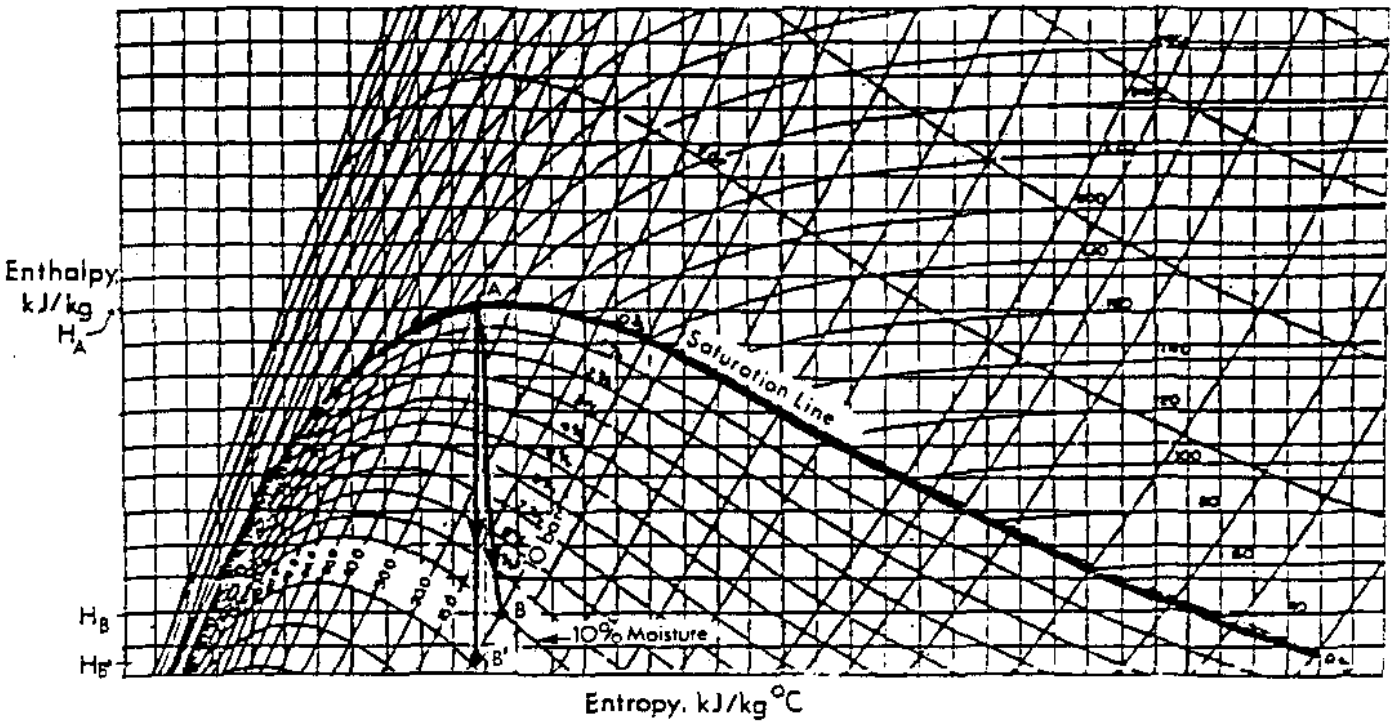

Fig. 3.8

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.

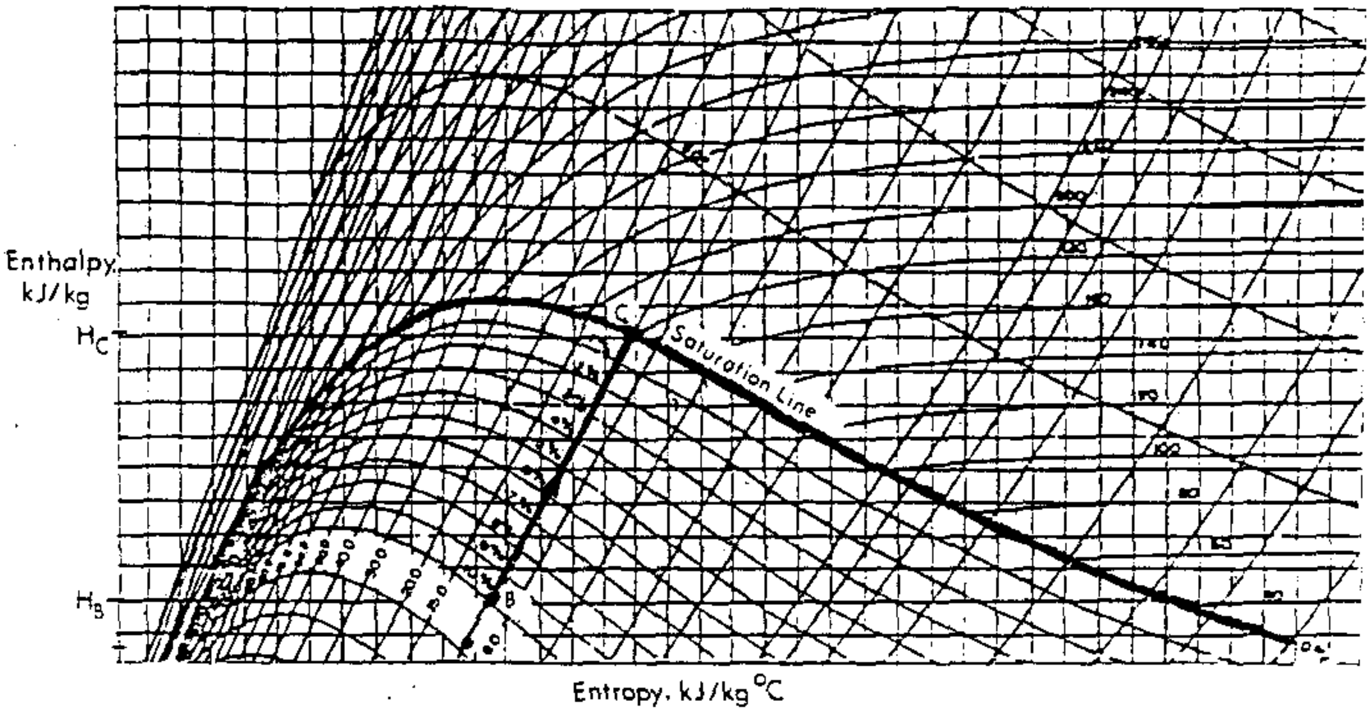

Fig. 3.9

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. If this is so, how is it that the enthalpy appears to have increased - good question.

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 us 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

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

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

$= \underline{2500}$ kJ/kg

When we pass the wet steam through the moisture separator we removed 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%.

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.

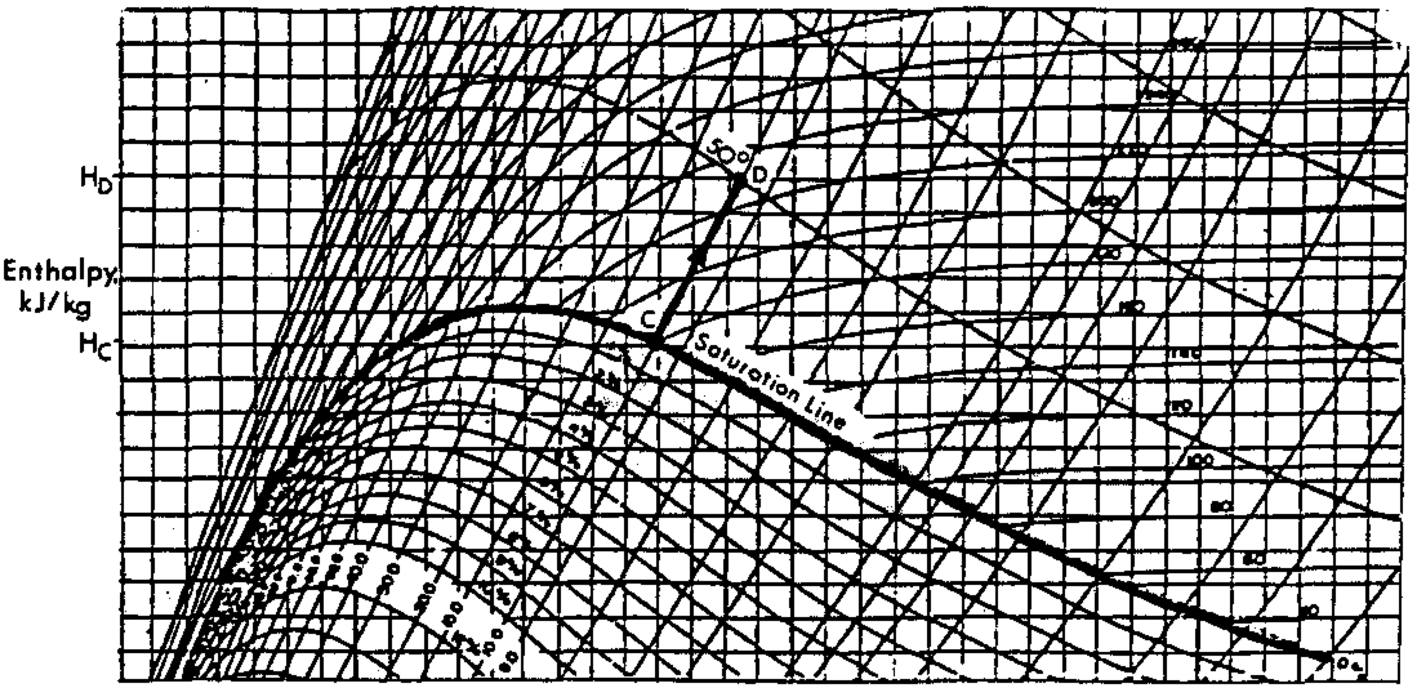

Fig. 3.10

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 a 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.

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.

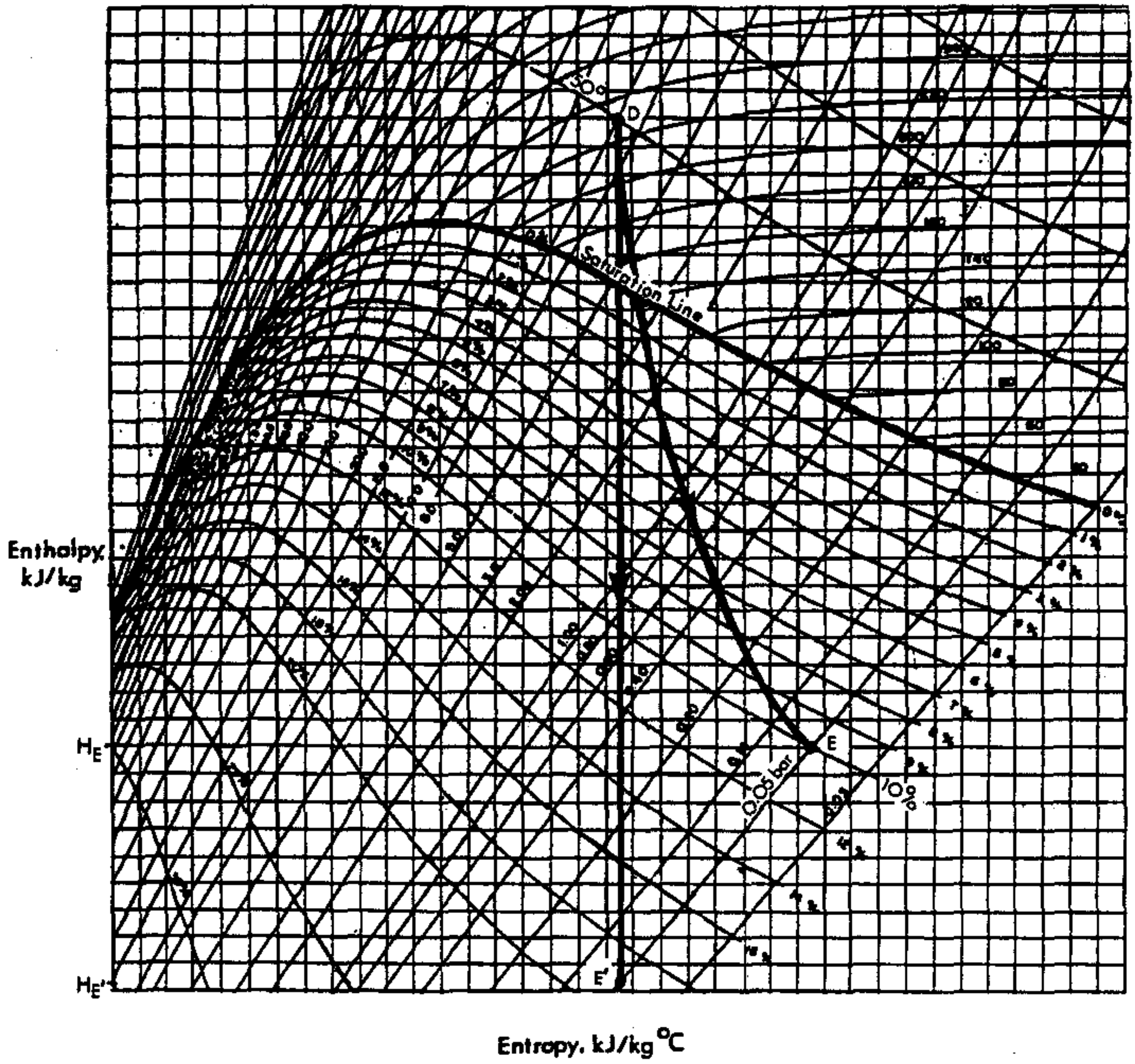

Fig. 3.11

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.

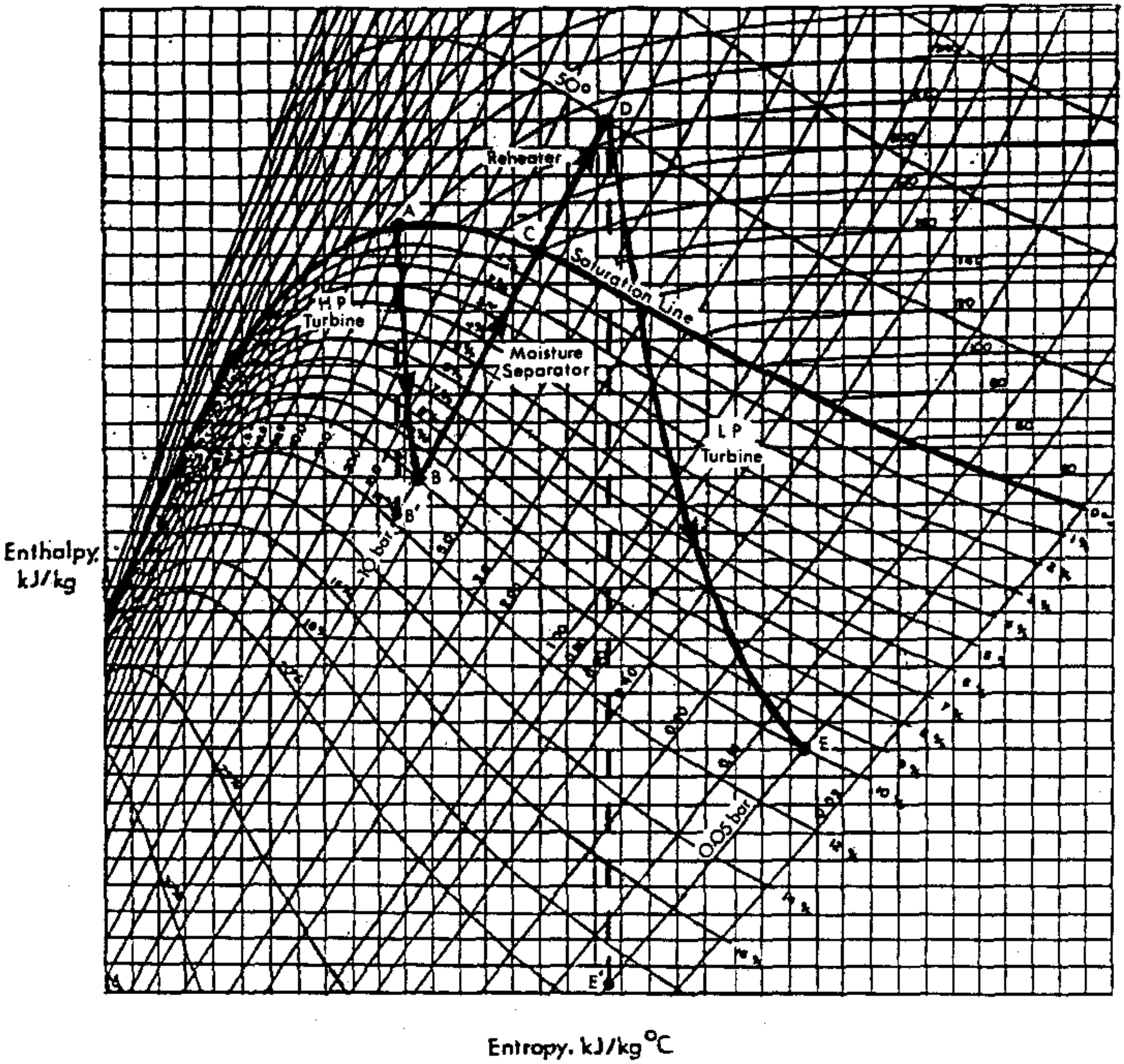

Fig. 3.12

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

Q3.7 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.

Q3.8 Explain how your sketch would change if you had to show the condensation process in the condenser associated with question Q3.7.

Q3.9 The mass flowrate of steam into the high pressure turbine, in question Q3.7 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.

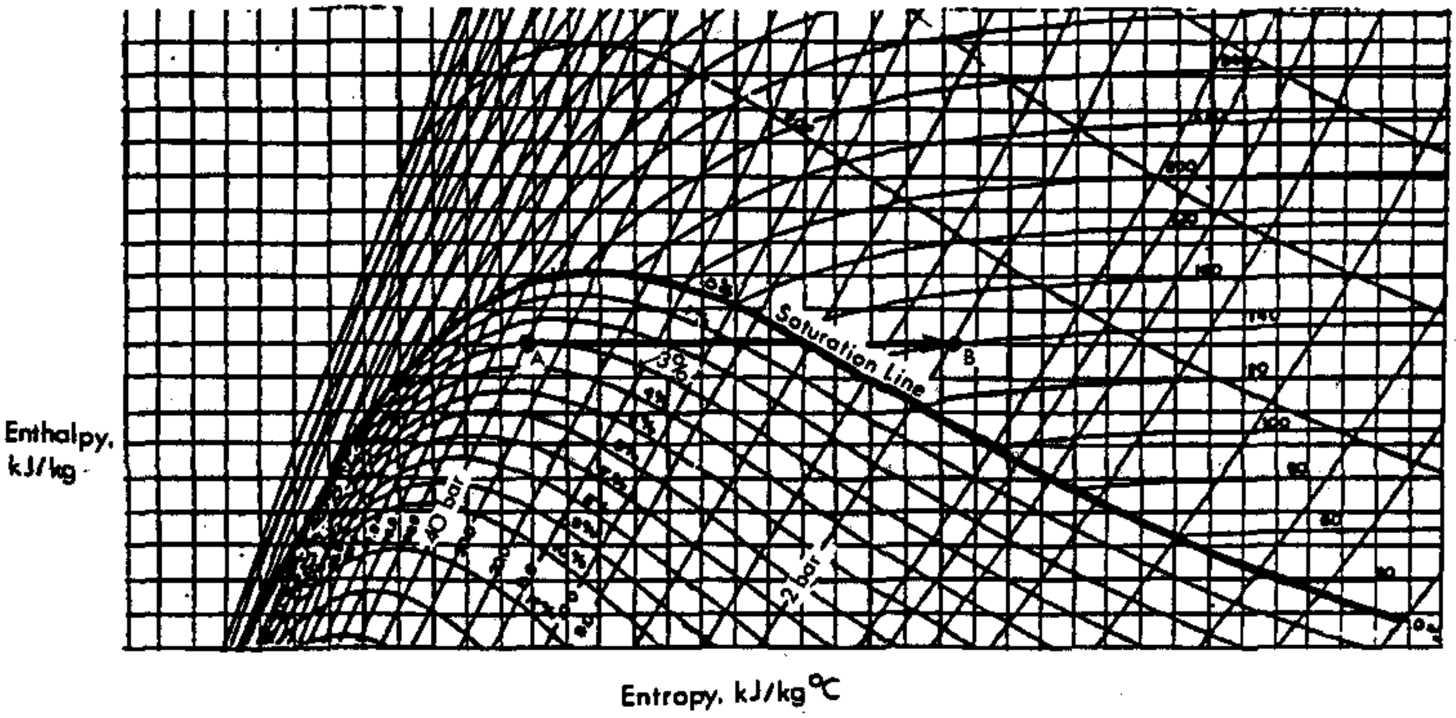

Fig. 3.13

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.

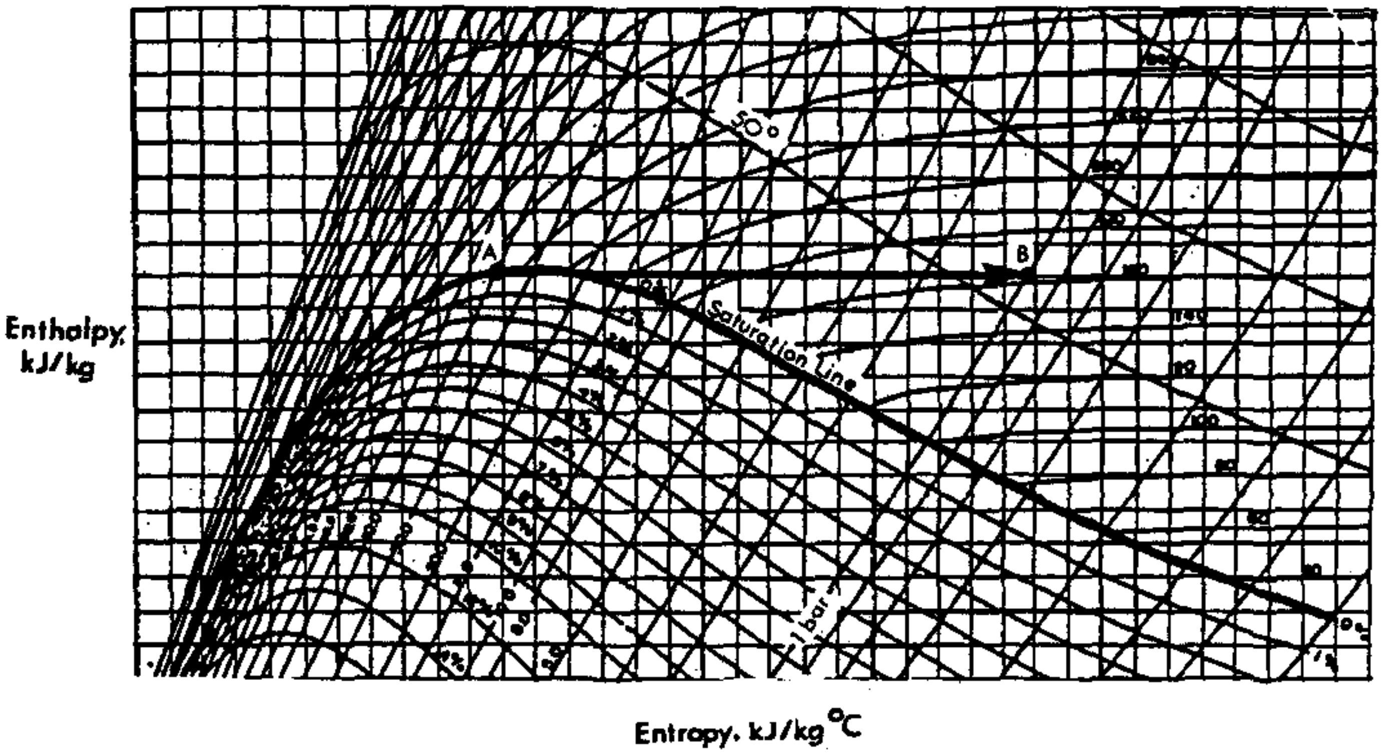

Fig. 3.14

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

<u>Q3.10</u> 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. Analyze 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 then end of the module.

* * * * *

MODULE 3 - ANSWERS

Q3.1

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

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

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

Equating the initial and final conditions,

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

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

$$5.4448 = q \times 6.0571$$

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

Q3.2

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:

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

$$5.4446 = q \times 7.0798$$

therefore, q = 76.9%

Q3.3

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.

Q3.4

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

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

$$2076.6 = 1 \times 2100.6$$

$$1 = \frac{2076.6}{2100.6}$$

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

Q3.5

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

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

$$1796.3 = q \times 1945.2$$

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

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

03.6

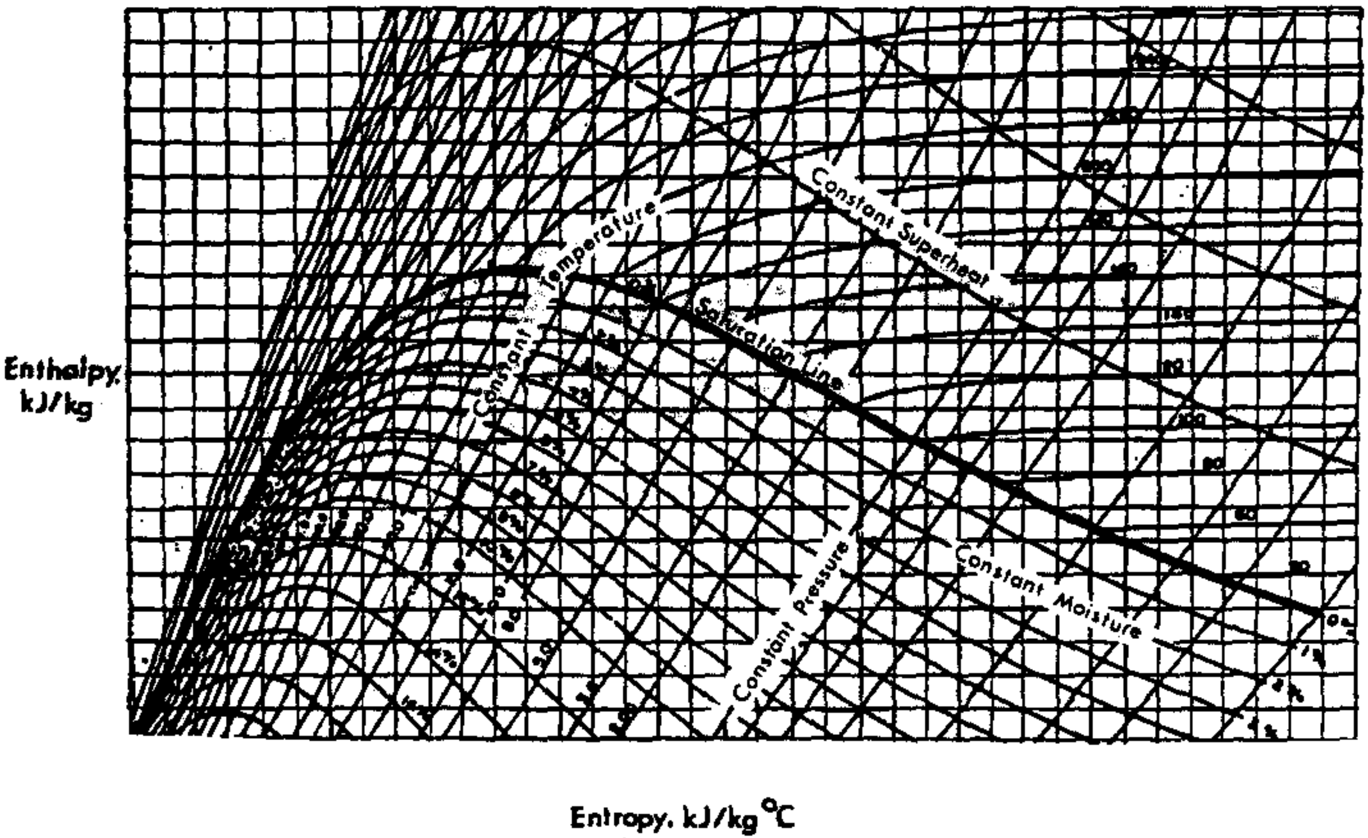
Enthalpy, kJ/kg
Constant Temperature
Constant Superheat
Saturation Line
Constant Pressure
Constant Moisture
Entropy, kJ/kg °C

Fig. 3.15

03.7

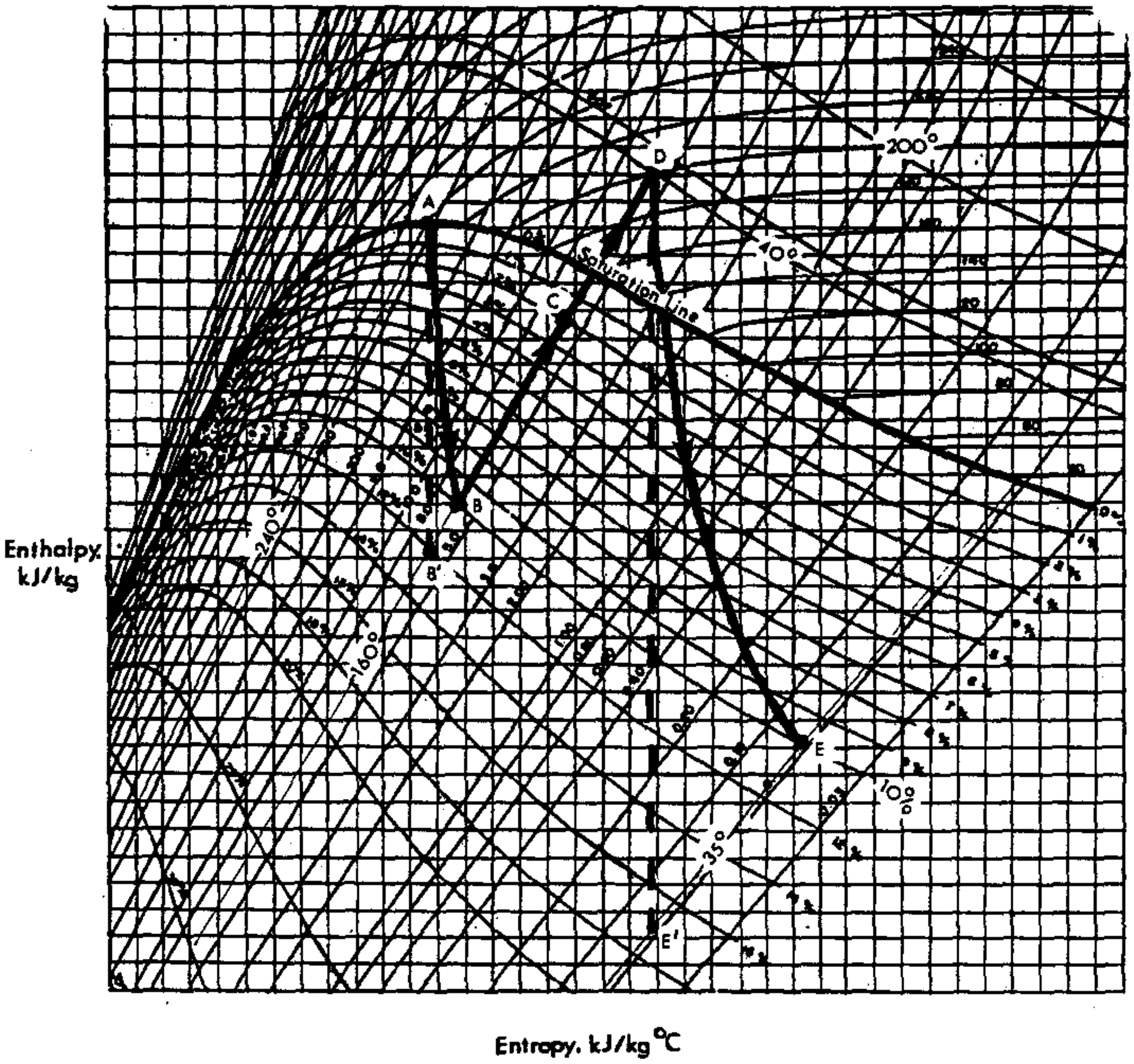
Enthalpy kJ/kg
Entropy. kJ/kg °C
A
B
B'
C
D
E
E'
Saturation Line
200°
40°
240°
160°
35°
10%

Fig. 3.16

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%.

Q3.8

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.

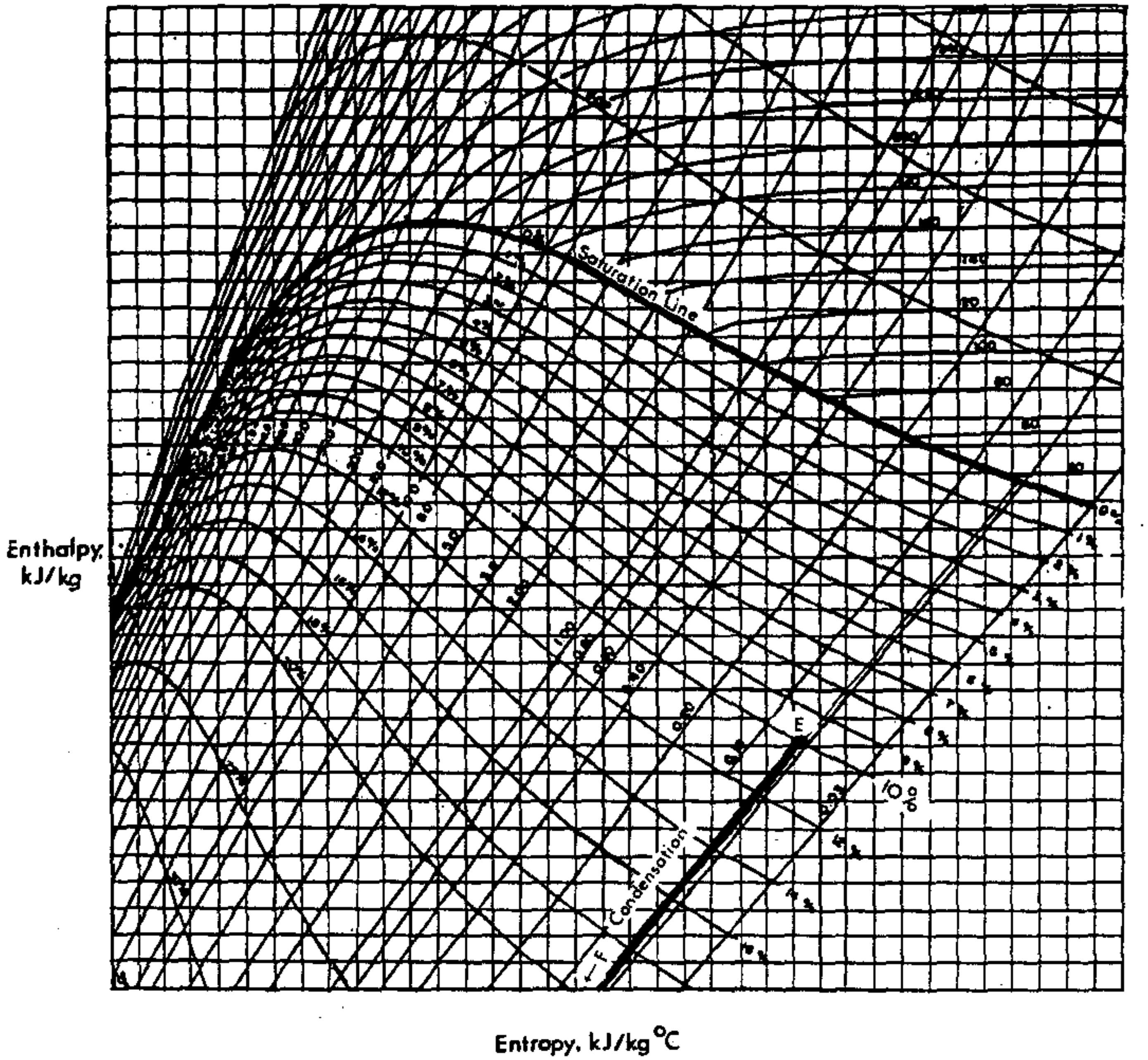

Fig. 3.17

03.9

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.

03.10

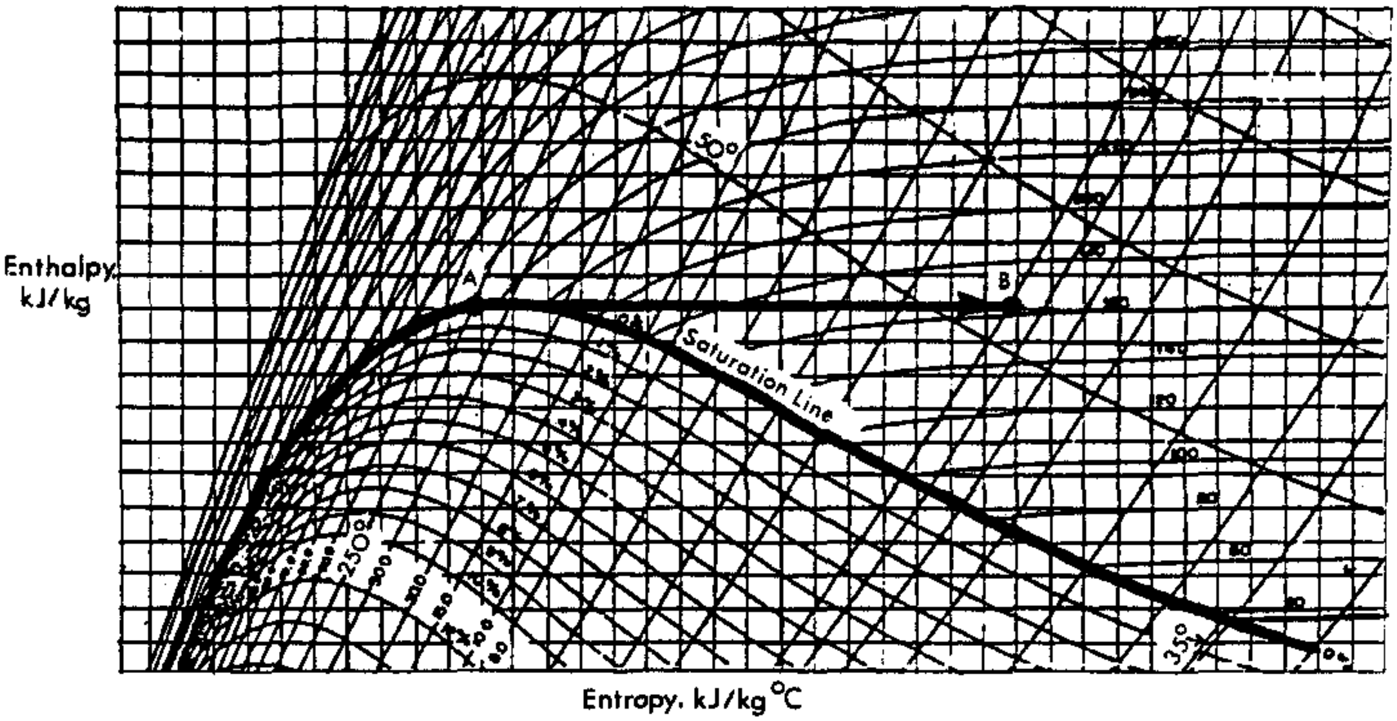

Fig. 3.18

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.

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.

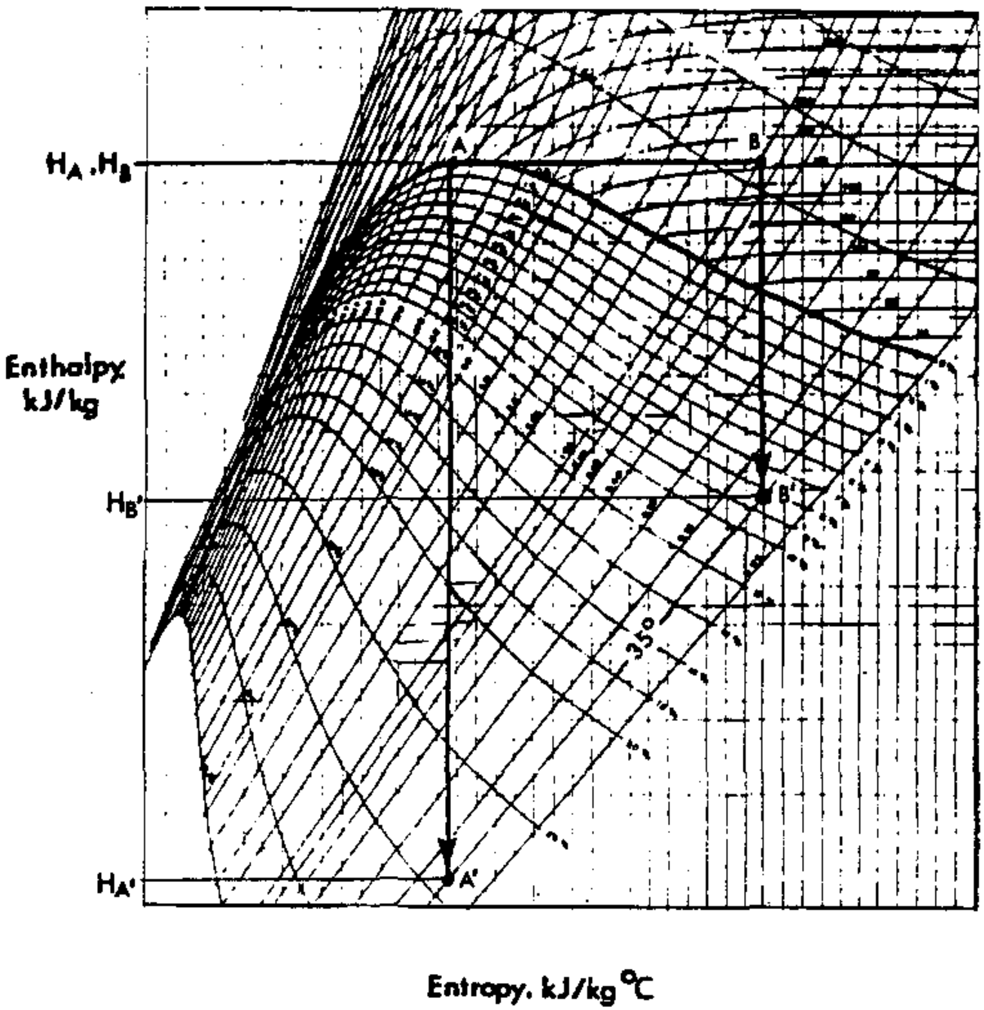

Fig. 3.19

<u>Note</u>: This reasoning is greatly simplified because it assumes isentropic expansion in the turbine and this is unrealistic.

COURSE 225

HEAT & THERMODYNAMICS

MODULE 4

TURBINE WITH REHEAT

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	Date 88-05-30	Date 88-07-29

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Heat & Thermodynamics

MODULE 4

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.

TURBINE WITH REHEAT

This module is an extension of the principles that we examined in Module 3. 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.

As a first approximation let us consider that 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.

For a more accurate calculation we must perform a mass balance across the moisture separator. Consider the sketch below where $\dot{m}$ represents mass flow and q steam quality.

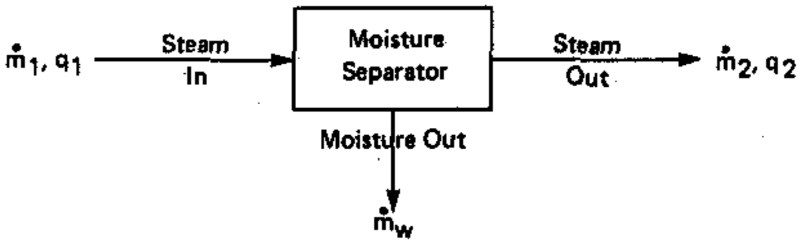

Fig. 4.1

For a total mass flow balance $\dot{m}_1 = \dot{m}_2 + \dot{m}_w$. However, if we consider only a water mass balance $\dot{m}_1(1-q_1) = \dot{m}_2(1-q_2) + \dot{m}_w$.

Combining these two equations enables us to calculate $\dot{m}_w$, the mass flow rate of water extracted from the steam

$$\dot{m}_1(1-q_1) = (\dot{m}_1 - \dot{m}_w)(1-q_2) + \dot{m}_w$$

which reduces to

$$\dot{m}_w q_2 = \dot{m}_1 q_2 - \dot{m}_1 q_1 \qquad \text{or} \qquad \dot{m}_w = \dot{m}_1 \frac{q_2 - q_1}{q_2}$$

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.

Q4.1 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.

Q4.2 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.

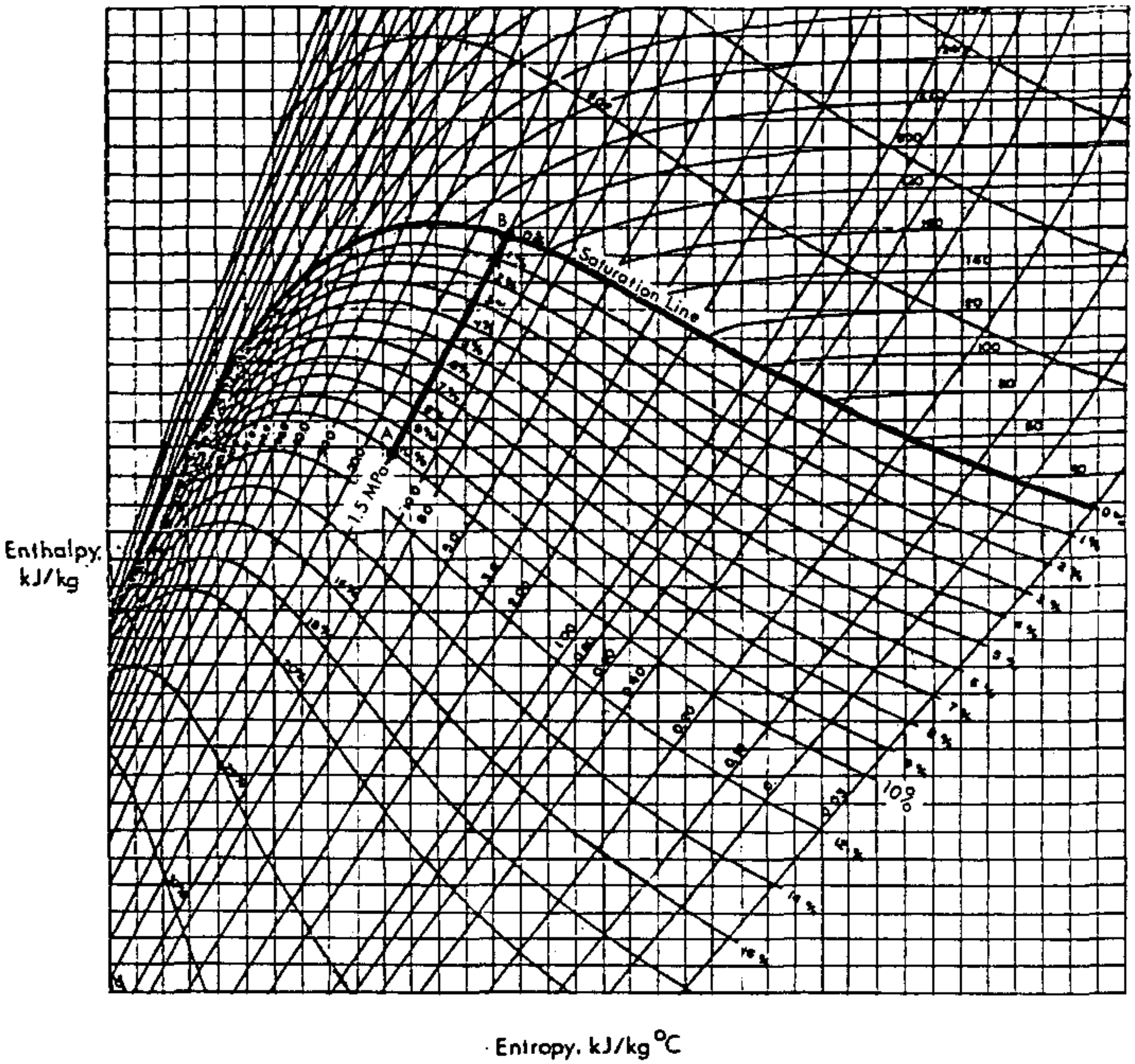

Fig. 4.2

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 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.

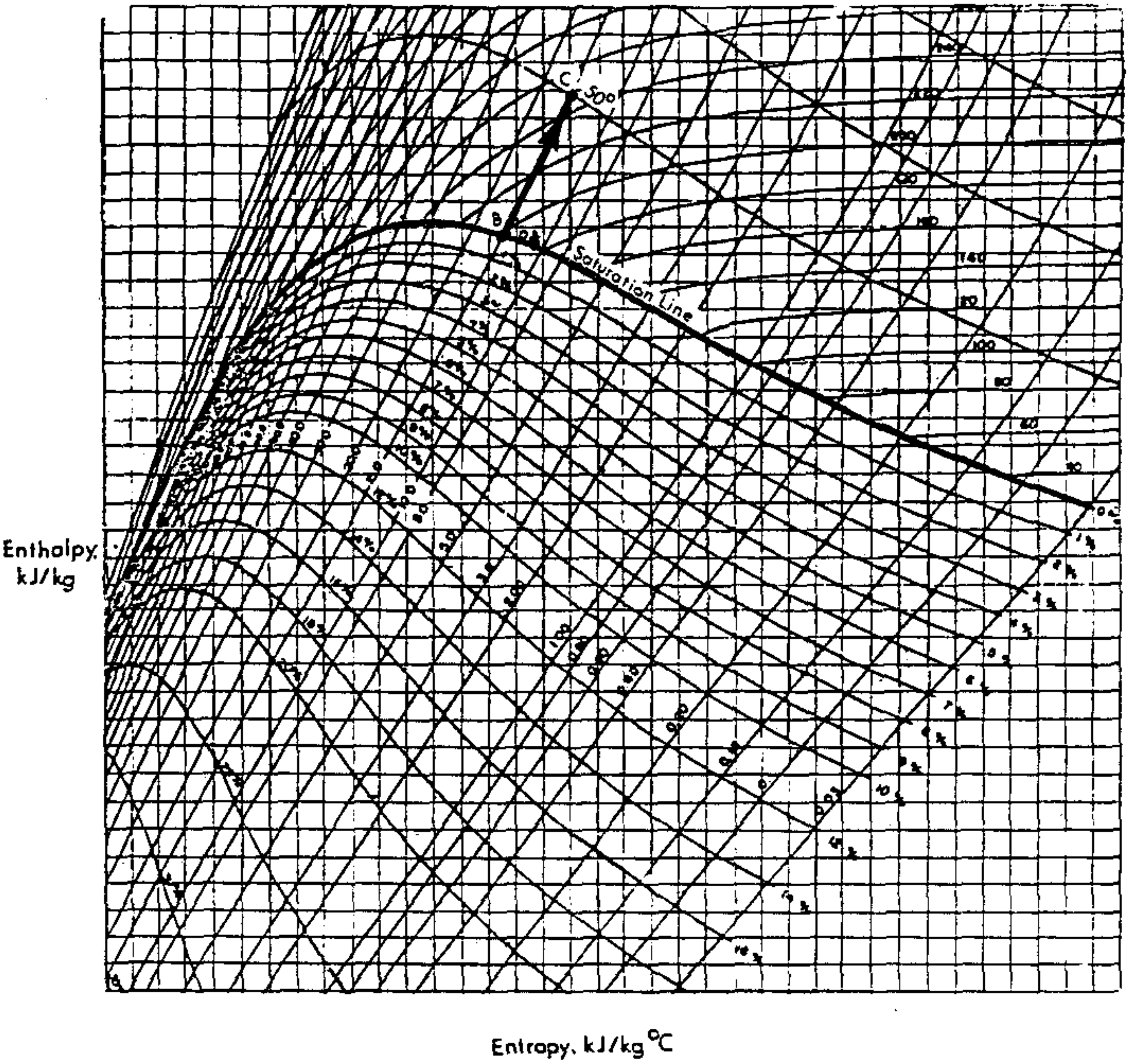

Fig. 4.3

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.

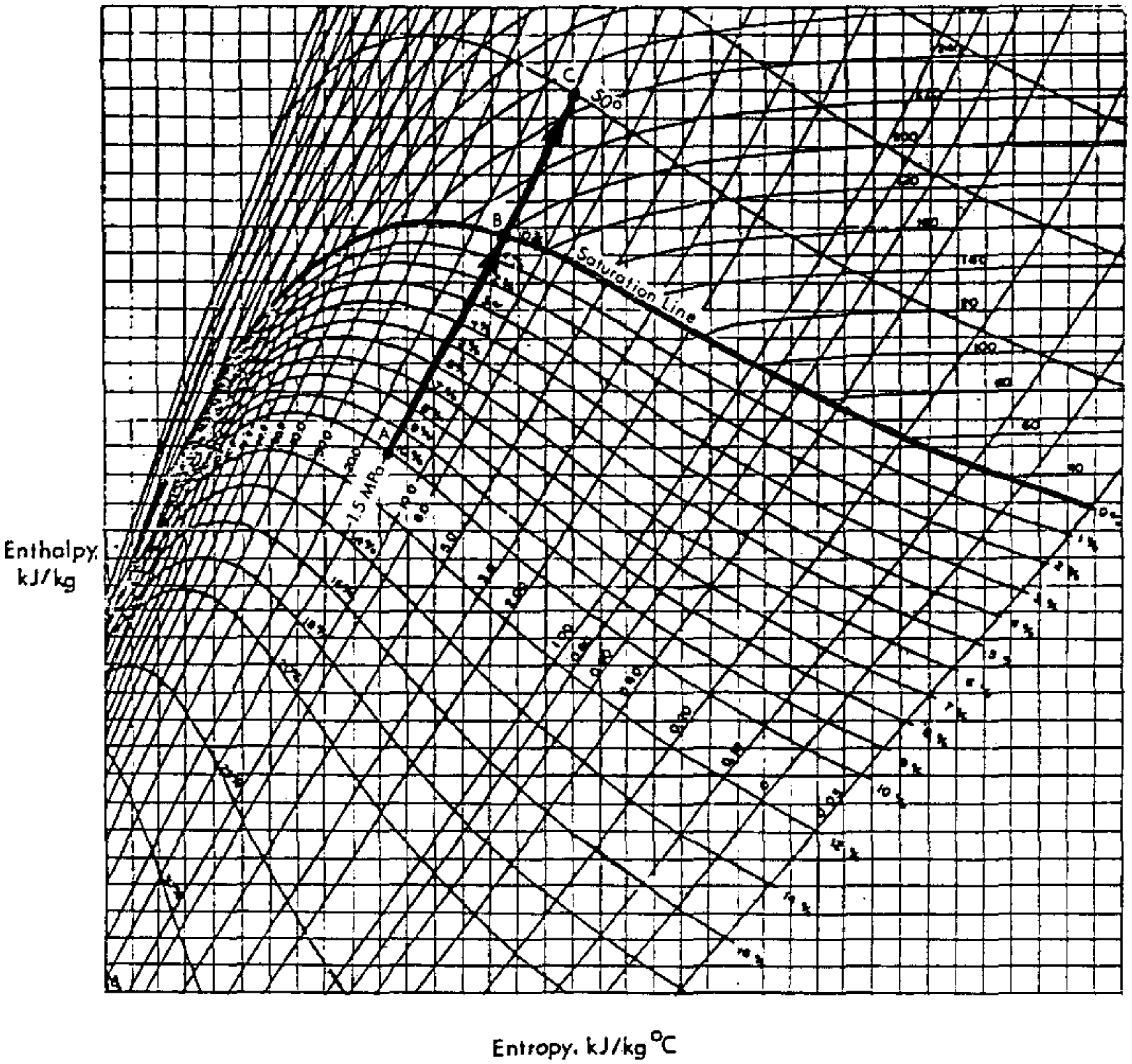

Fig. 4.4

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 <u>the heat lost by the heating steam</u> equals <u>the heat gained by the process steam</u>.

<u>Heat Lost by the Heating Steam</u>

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.

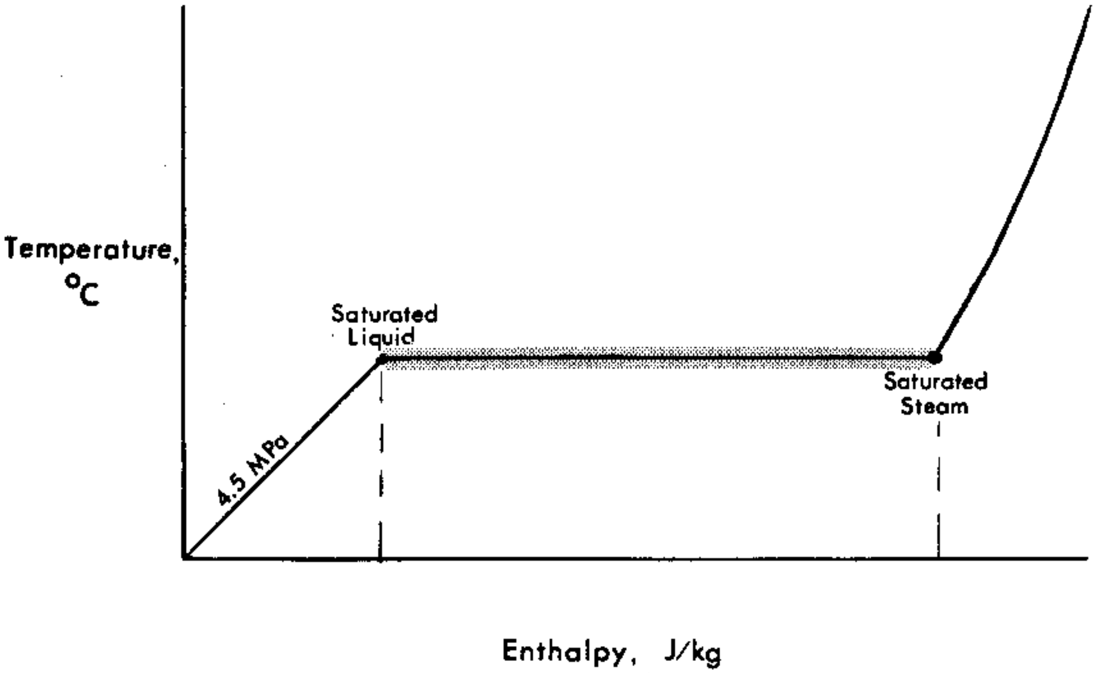

Fig. 4.5

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

= <u>2924.4</u> 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 3.

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.

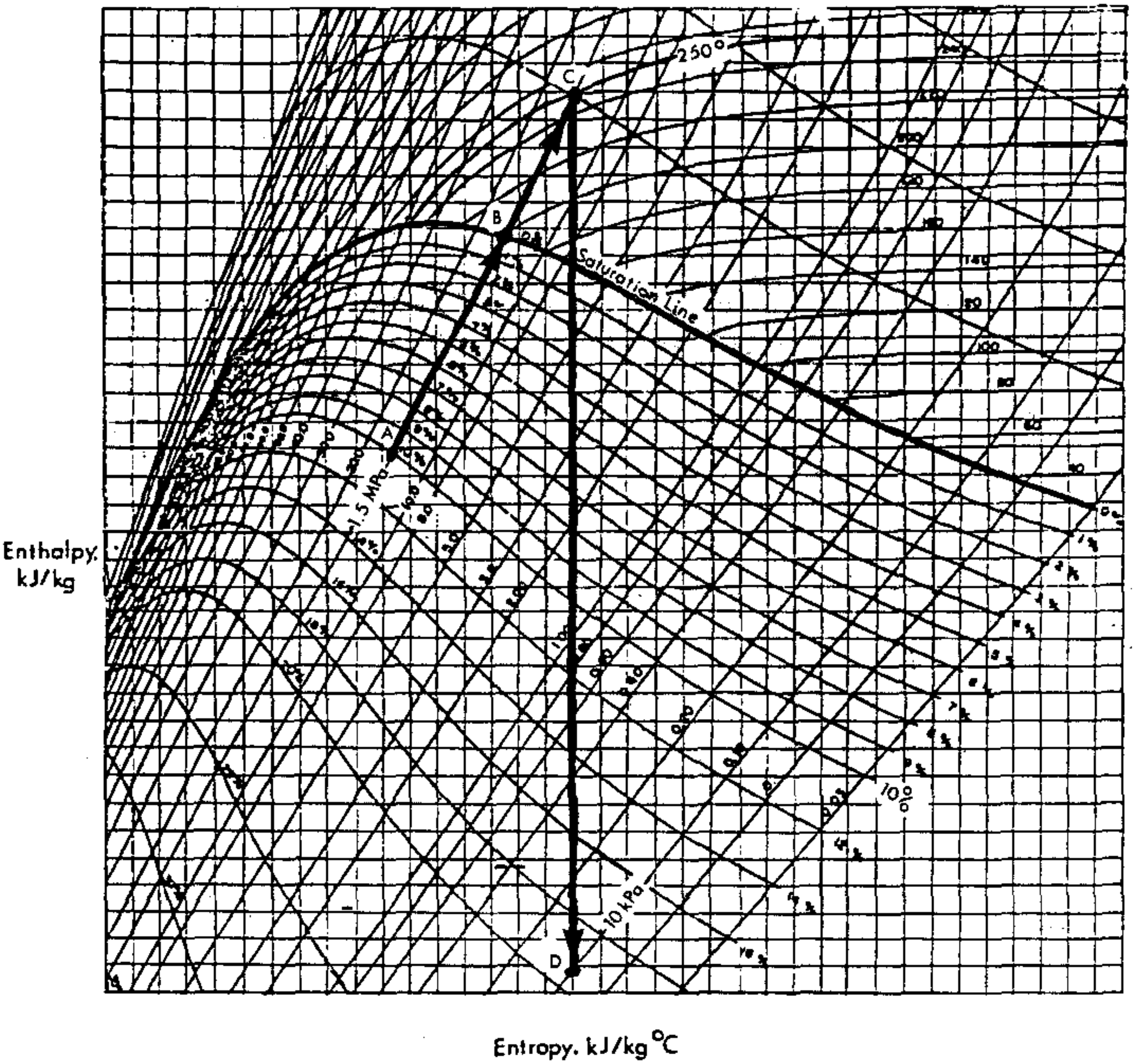

Fig. 4.6

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.

Q4.3 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.

Q4.4 800 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.)

Q4.5 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)

Q4.6 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.

* * * * *

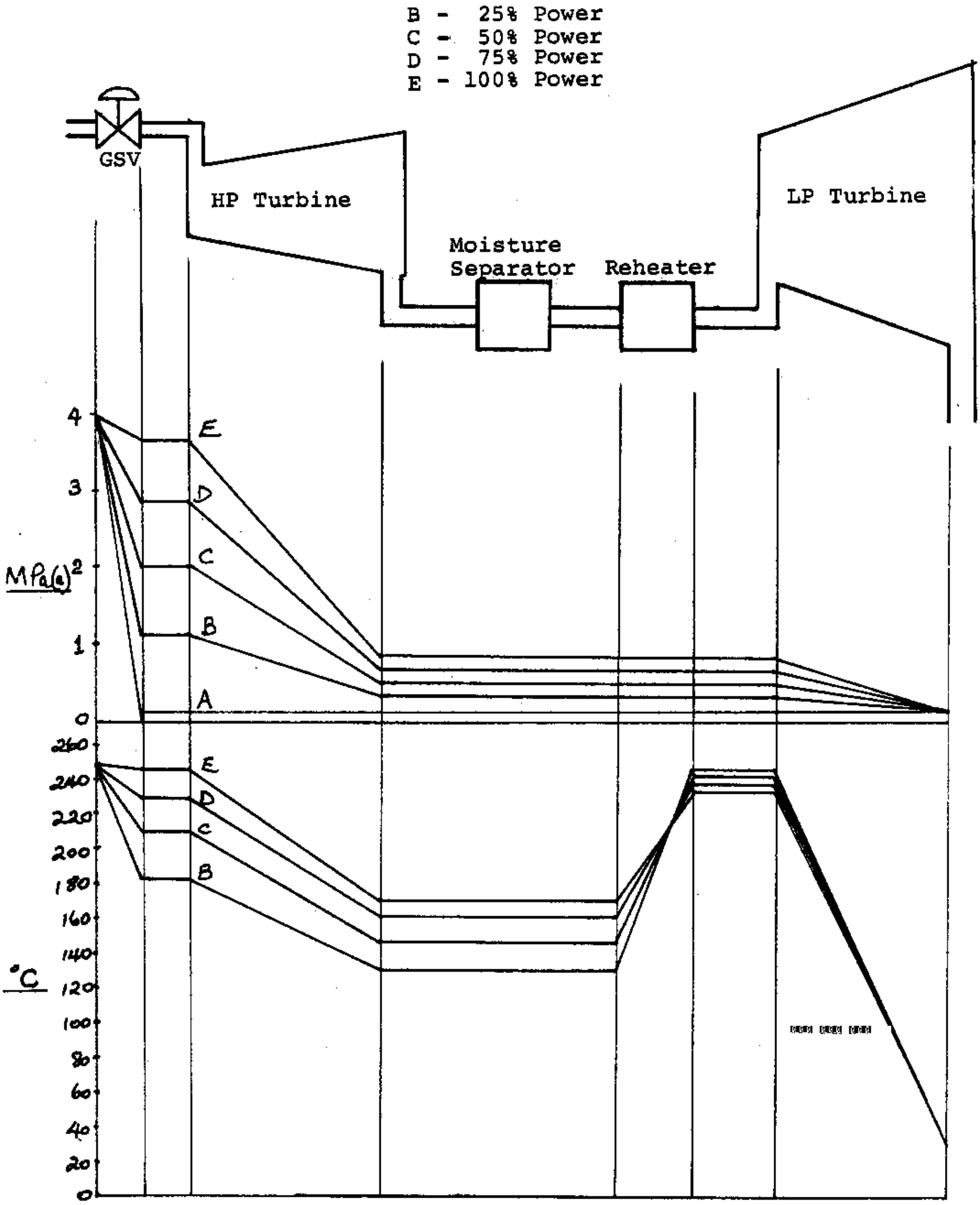

Fig. 4.7

Note: Actual pressure drops through the turbine will be non linear.

The condition just described 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).

Q4.7 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 line 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. The actual temperature at which the steam is entering the high pressure turbine is slightly higher due to superheat supplied by the throttling action of the GSV.

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 about 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.

Q4.8 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.

* * * * *

MODULE 4 - ANSWERS

Q4.1

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). This corresponds to initial steam quality of 90.6% and of course a final quality (as given) of 99.6%.

Using the formula developed by doing a mass balance across the moisture separator

$$\dot{m}_w = \dot{m}_1 \frac{q_2 - q_1}{q_2}$$

$$= 700 \times \frac{0.996 - 0.906}{0.996}$$

$$= 63.3 \text{ kg/s}$$

The flowrate of steam from the moisture separator will be the difference between steam flow into the separator and the moisture removed, ie, 700 kg/s - 63.3 kg/s = 636.7 kg/s.

Q4.2

(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_s 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

Q4.3

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.

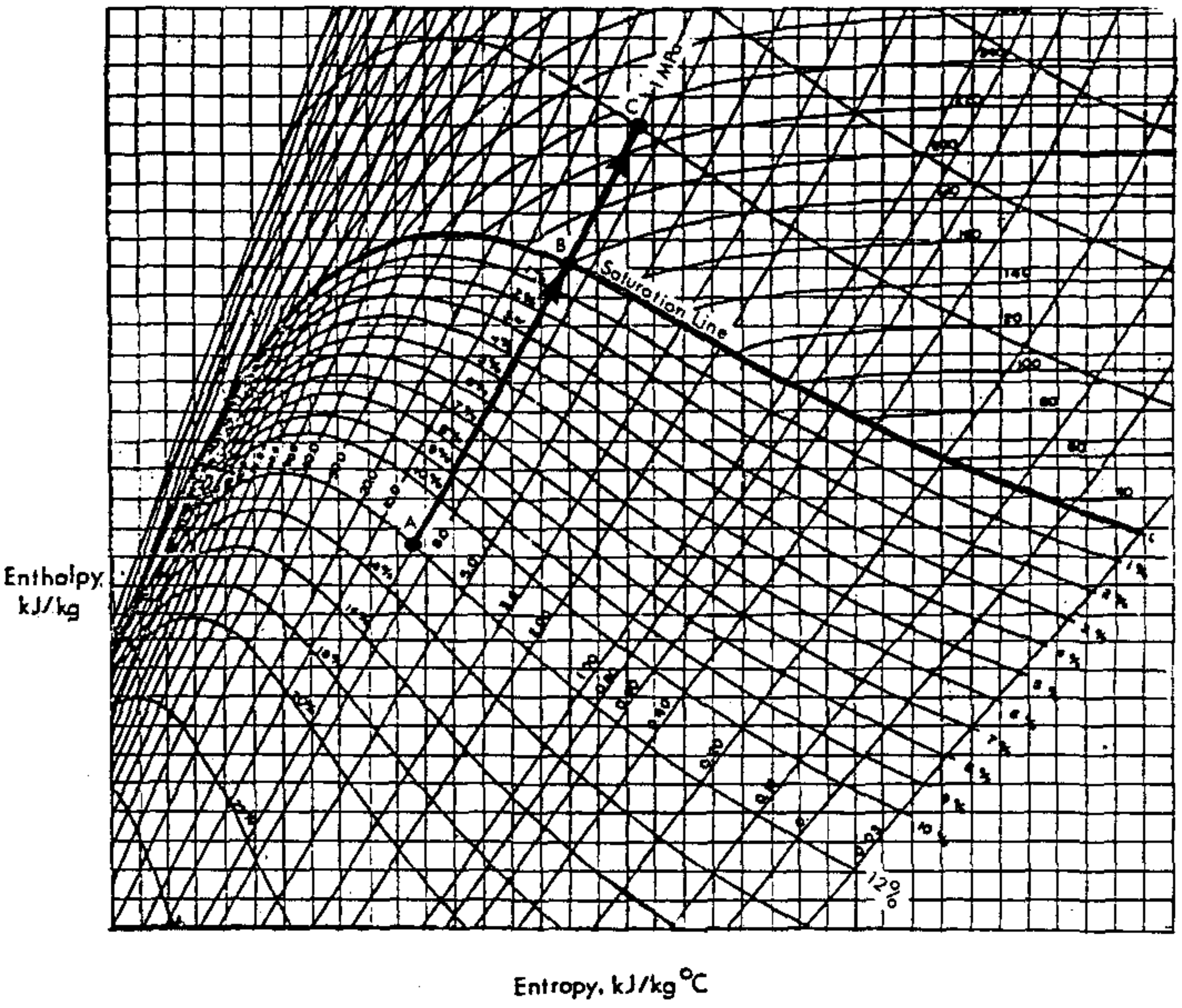

Fig. 4.8

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).

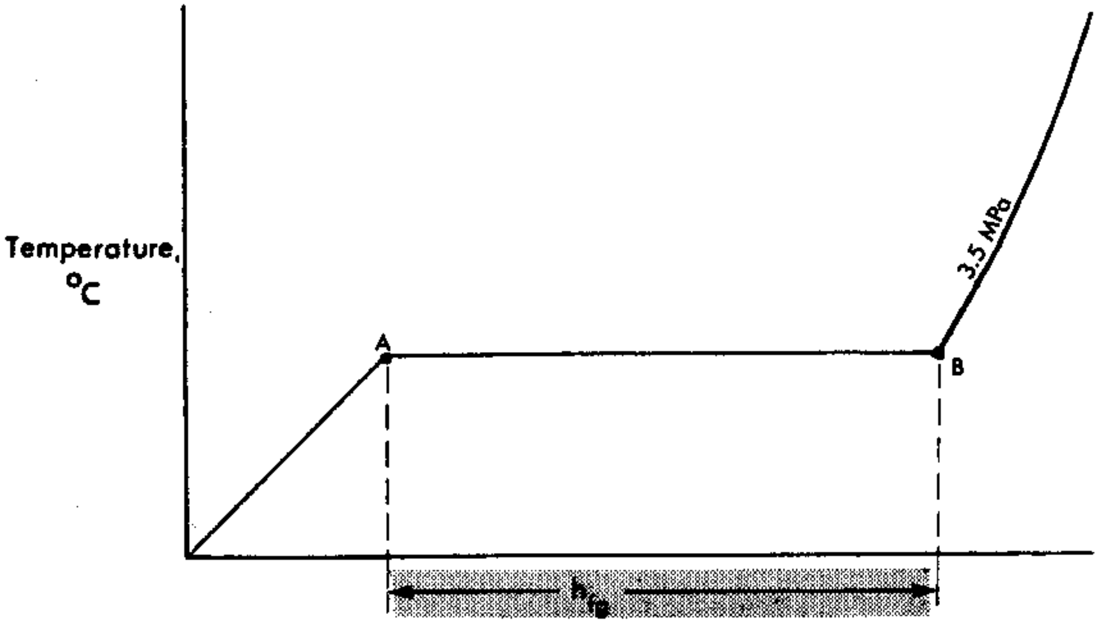

Fig. 4.9

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 30.3 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
$\frac{70}{116}(50^\circ\text{C}) + 200^\circ\text{C} = 230^\circ\text{C}$.

04.4

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.

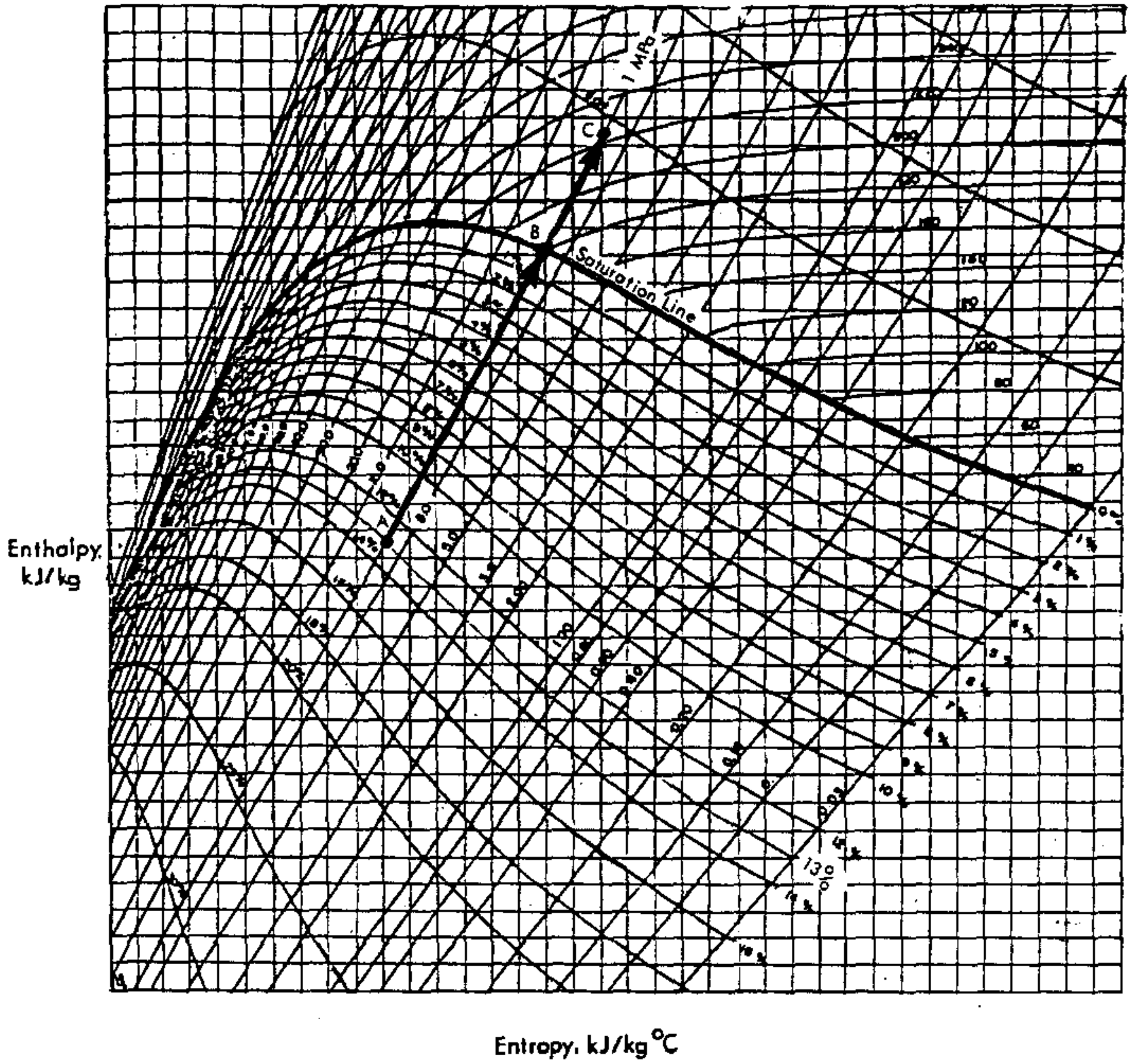

Fig. 4.10

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_s = 233.8°C.

The temperature of the condensate is
$t_s - 6.8 = 233.8 - 6.8 = 227°C$.

$h_{f227} = 976.2$ kJ/kg.

So the heat lost per kg of heating steam is
$2802.3 - 976.2 \doteq 1826.1$ 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,

$= 41.5 \times 1826.1$

$= 75783$ 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.

Q4.5

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).

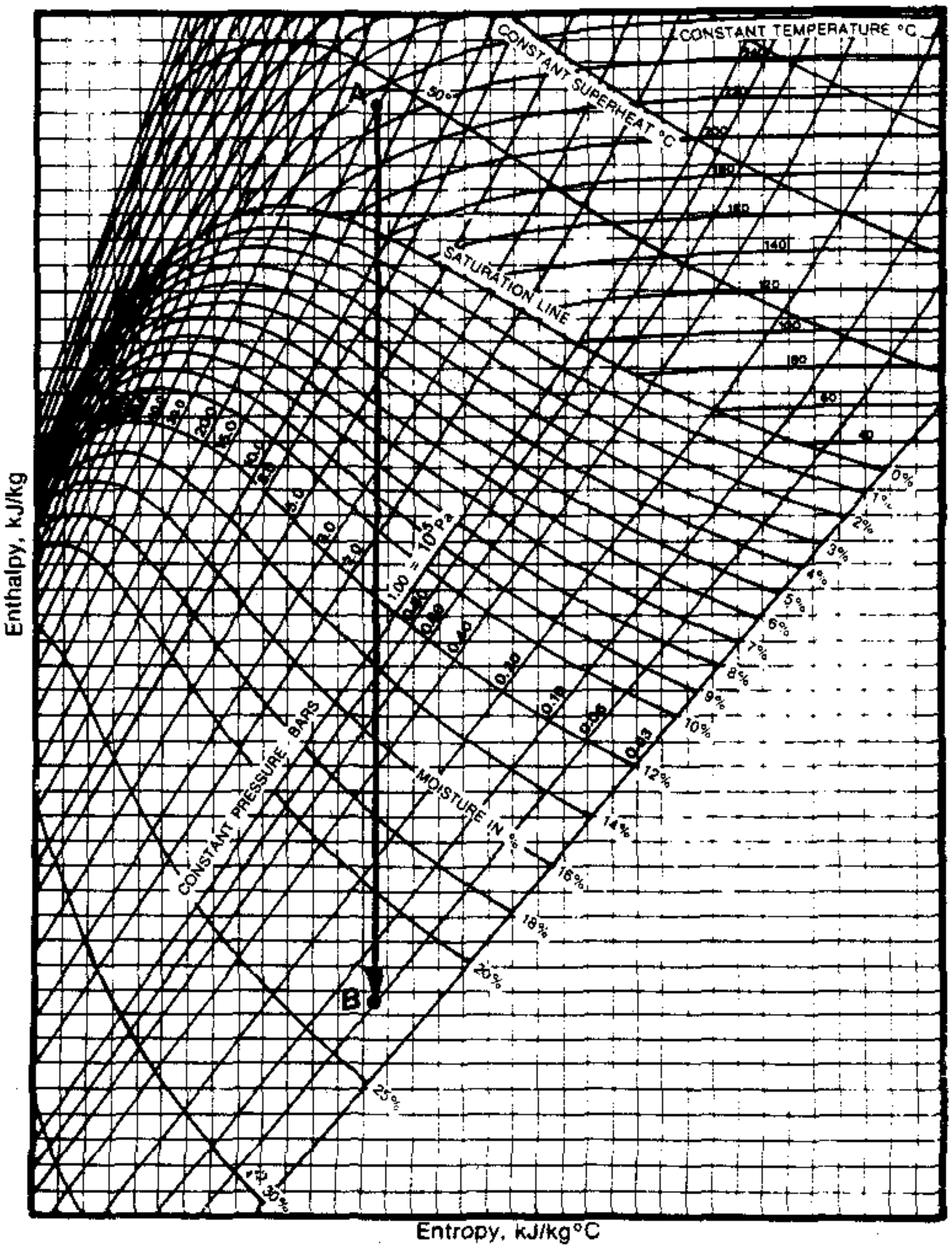

Fig. 4.11

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 kg/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%.

Q4.6

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.

Q4.7

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

The GSVs 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 throttling process will cause the steam to become superheated and its final temperature (immediately downstream of the GSVs) will be approximately 160°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.

Q4.8

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 T = 121°C at 25% load to T = 79°C at 100% load.

With a smaller temperature 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 <u>time</u> 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, <u>the difference between the heating steam temperature and turbine steam temperature</u> at the reheater outlet, <u>increases</u>, due to the <u>decreased time</u> 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.

COURSE 225

HEAT & THERMODYNAMICS

MODULE 5

FEEDHEATER OPERATION

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MODULE 5

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 balance 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.

FEEDHEATER OPERATION

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 lubricating 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 the same amount of 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.

Consider the following problem:

Q5.1 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 the following two questions and compare your answers with those at the end of the module.

Q5.2 *What happens to the pressure of the engine coolant in an* automobile after the engine is shutdown?

05.3 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 and thus prevent thermal shock in the boiler pre-heater. The feedwater flows through the tubes and receives its heat from steam in the heater shell. 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 ($h_{f_{\text{steam in}}}$) - Enthalpy Out ($h_{f_{\text{out}}}$)]

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.

Q5.4 How is steam flow established to a feedheater? Why is the feedheater shell pressure normally lower than the turbine extraction point pressure?

B5.5 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 heater because 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.

Q5.6 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.

Q5.7 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.

Q5.8 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

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

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

(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

$$= \text{flow} \times \text{enthalpy}$$

$$= 588 \times 118.3 = \underline{69560} \text{ kJ}$$

$$\text{kg} \times \text{kJ/kg}$$

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.

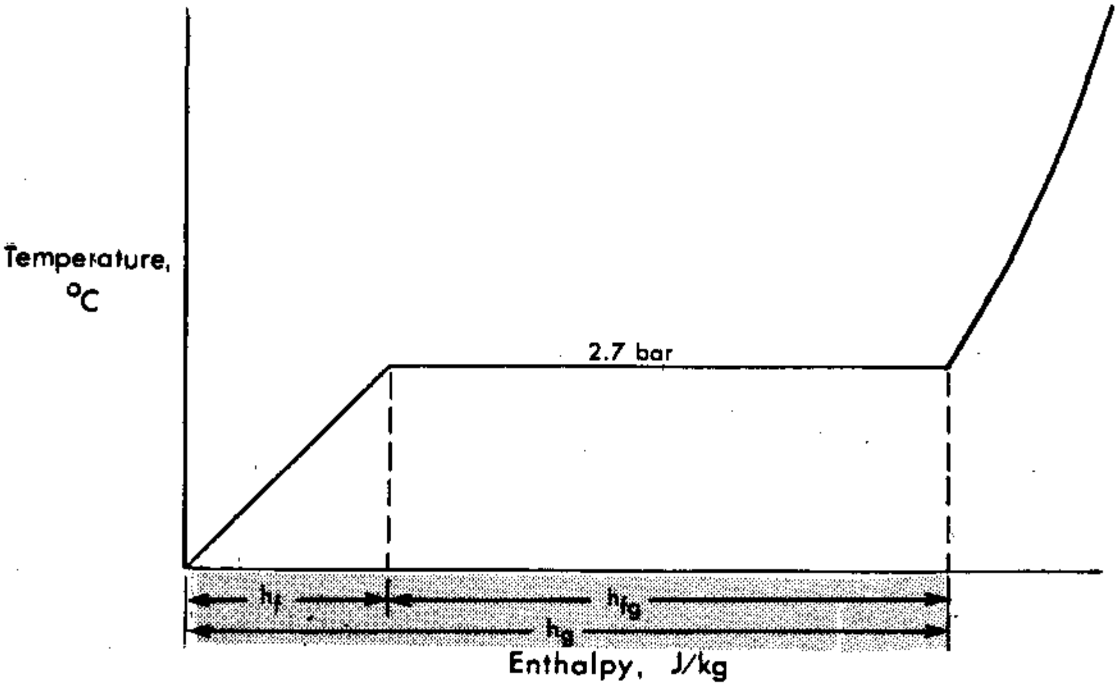

Fig. 5.1

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 = m x 2173.6 kJ per second, where 'm' is the mass flowing per second, ie a mass flow rate.

Equating heat gained to heat lost:

69560 = m x 2173.6

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 kJ/kg

$h_{f_{58}}$ = 242.7 kJ/kg

Change in enthalpy = 355.9 - 242.7 kJ/kg

= <u>113.2</u> kJ/kg

Heat gained by the feedwater every second

= mass x change in enthalpy

= 521 x 113.2 kJ

= <u>58977</u> 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.

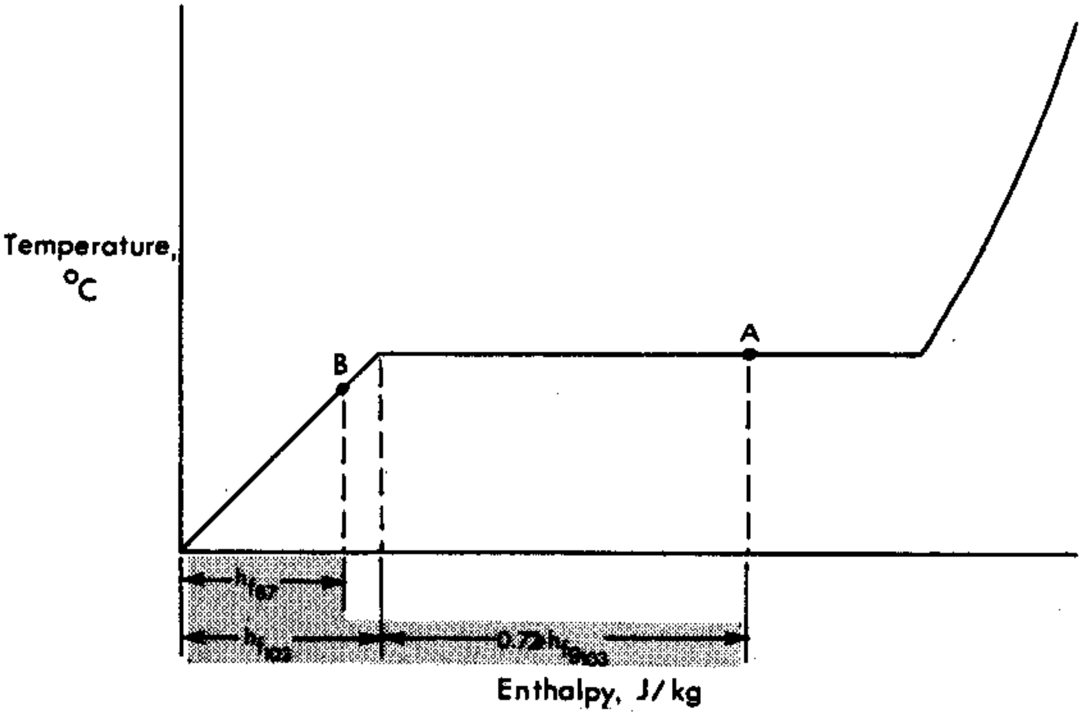

Fig. 5.2

Enthalpy at point A = $h_{f_{103}} + 0.72\ h_{fg_{103}}$

= $431.7 + 0.72 \times 2248.9$

= $\underline{2050.9}$ kJ/kg

Enthalpy at point B = $h_{f_{87}}$ = $\underline{364.3}$ kJ/kg

Enthalpy change of steam = $2050.9 - 364.3$

= $\underline{1686.6}$ kJ/kg

Heat gained by feedwater = Heat lost by steam.

58977 = $1686.6 \times m$

m = $58977/1686.6 = \underline{35}$ kg/s

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

Q5.9 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.

05.10 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 cycle efficiency increases when the average temperature at which heat is supplied to the water/steam mixture in the boiler is as high as possible. This can happen when the steam generator is supplying only the latent heat of vapourization, ie, when the inlet feedwater is not subcooled.

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.

Q5.11 (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?

Q5.12 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 cycle efficiency in a system with no feedheating against the same system equipped with feed heating.

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 cycle efficiency with and without feedheating using saturated steam extracted from a turbine at 120°C. State any assumptions that are made.

Assumptions

1. Boiler produces saturated steam at 4 MPa(g).
2. Turbine exhaust temperature is 35°C.
3. 10% of the steam flow in the turbine is extracted for feed heating.
4. Assume turbine exhaust is 10% wet.
5. Assume no subcooling in the condenser.
6. Neglect pump work.
7. Ignore pressure and heat losses in the piping.

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 (a) No feedheating

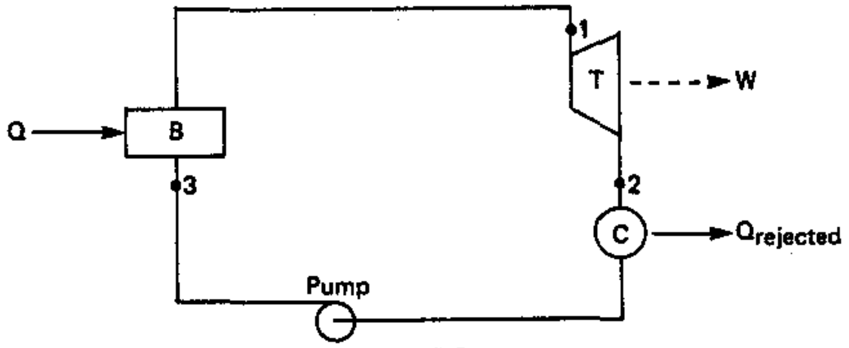

Fig. 5.3

Assume 1 kg/s of steam from the boiler. The enthalpy of this steam at the turbine inlet (1) is

$$h_1 = h_{g_{4MPa}} = 2800.3 \text{ kJ/kg}$$

The enthalpy of the turbine exhaust steam (2) is calculated using the familiar formula:

$$h_2 = h_{f35} + q_2 h_{fg35}$$

$$= 146.6 + 0.9(2418.8)$$

$$= 2323.5 \text{ kJ/kg}$$

The turbine work is calculated as follows:

$$W = \dot{m}(h_1 - h_2)$$

$$= 1(2800.3 - 2323.5)$$

$$= 476.8 \text{ kJ/kg}$$

The heat supplied to the working fluid is found using the formula $Q = \dot{m}(h_1 - h_3)$ where $h_3 = h_{f35} = 146.6$ kJ/kg.

$$Q = 1(2800.3 - 146.6)$$

$$= 2653.7 \text{ kJ/kg}$$

The thermal efficiency is calculated as follows:

$$\eta = \frac{W}{Q}$$

$$= \frac{476.8}{2653.7} \times 100\%$$

$$\simeq 18\%$$

Case (b) With feedheating

Additional Assumptions:

1. Ten percent of steam is extracted from the turbine.
2. Enthalpy of extracted steam is 2500 kJ/kg (any value between 2800.3 and 2323.5 kJ/kg).
3. Extraction steam and feedwater mix together in the feedheater.
4. Feedheater does not lose any heat from extracted steam.

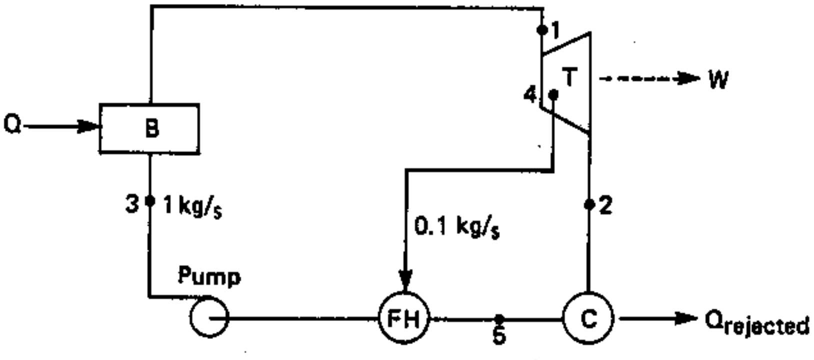

Fig. 5.4

The turbine work is calculated as follows:

$$W = \text{work from 1-4} + \text{work from 4-2}$$

$$= 1(h_1 - h_4) + 0.9(h_4 - h_2)$$

$$= 1(2800.3 - 2500) + 0.9(2500 - 2323.5)$$

$$= 459.2 \text{ kJ/s}$$

In order to calculate the heat supplied in the boiler, we have to calculate the enthalpy of boiler feedwater. To do this we must balance the heat transferred in the feedheater.

$$\dot{m}_4h_4 + \dot{m}_5h_5 = (\dot{m}_4 + \dot{m}_5)h_3$$

$$h_3 = \frac{\dot{m}_4h_4 + \dot{m}_5h_{f35}}{\dot{m}_4 + \dot{m}_5}$$

$$= \frac{0.1(2500) + 0.9(146.6)}{0.1 + 0.9}$$

$$= 381.9 \text{ kJ/kg}$$

The heat supplied in the boiler is given by

$$Q = \dot{m}_3(h_1 - h_3)$$
$$= 1(2800.3 - 381.9)$$
$$= 2418.4 \text{ kJ/s}$$

Now calculating the thermal cycle efficiency gives

$$\eta = \frac{W}{Q}$$

$$= \frac{459.2}{2418.4}$$

$$\simeq 19\%$$

Therefore, feedheating reduces the amount of work produced by the turbine, but also reduces to a larger extent the amount of heat added in the boiler. This results in a higher cycle efficiency.

In relative terms this increase in efficiency is ~5.6% [(19-18)/18 x 100%]. This has been achieved by only one feedheater where in practice we have several feedheaters and cycle efficiency will increase accordingly. Note though that there is an optimum level above which an increase in feedheating capacity shows no increase in cycle efficiency.

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

Q5.13 Explain why steam is extracted for feedheating and not allowed to do further work in the steam turbine.

Q5.14 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.

* * * * *

MODULE 5 - ANSWERS

05.1

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. (If you want to get technical, it's due to the molecules not vibrating 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.

05.2

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 <u>closed</u> fluid heat transfer systems could you come up with?

05.3

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.

05.4

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.

05.5

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.

Q5.6

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 T_1	Same(G)	Increase
Outlet Temp T_2	Increase	N/A
Feedwater T_2-T_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.

05.7

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.

05.8

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 little throttling 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.

Q5.9

Using the temperature/enthalpy diagram, we can see that the heat lost by the steam is the difference between $h_{g_{180}}$ and $h_{f_{160°C}}$.

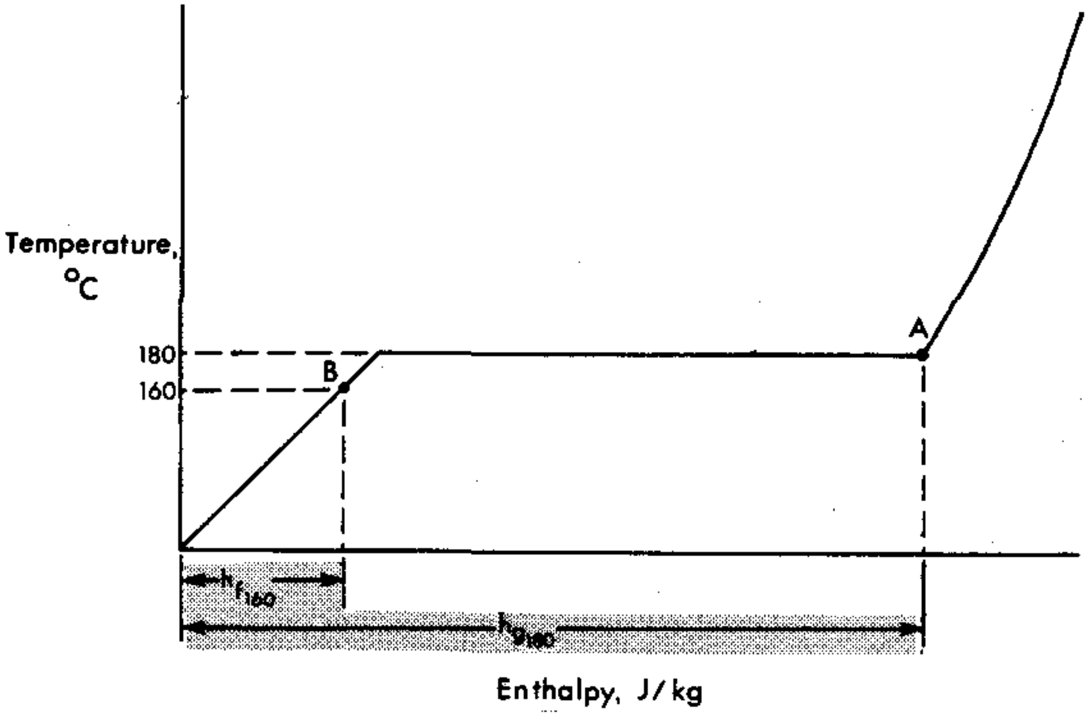

Fig. 5.5

Enthalpy difference of the steam = $h_A - h_B$

= $h_{g_{180}} - h_{f_{160}}$

= 2776.3 - 675.5

= <u>2100.8</u> kJ/kg

Heat lost by steam = <u>m x 2100.8</u> kJ per second.

Heat gained by the feedwater = $h_{f_{174}} - h_{f_{150}}$

= 736.7 - 632.1

= <u>104.6</u> kJ/kg

Heat gained per second = Mass x enthalpy change

= 1000 x 104.6

= 104600 kJ

The heat lost by the steam = heat gained by the feedwater

m x 2100.8 = 104600 kJ

m = 104600/2100.8

m = <u>49.8</u> kg/s

05.10

In this example, we know everything about the steam and have to find the feedwater temperature.

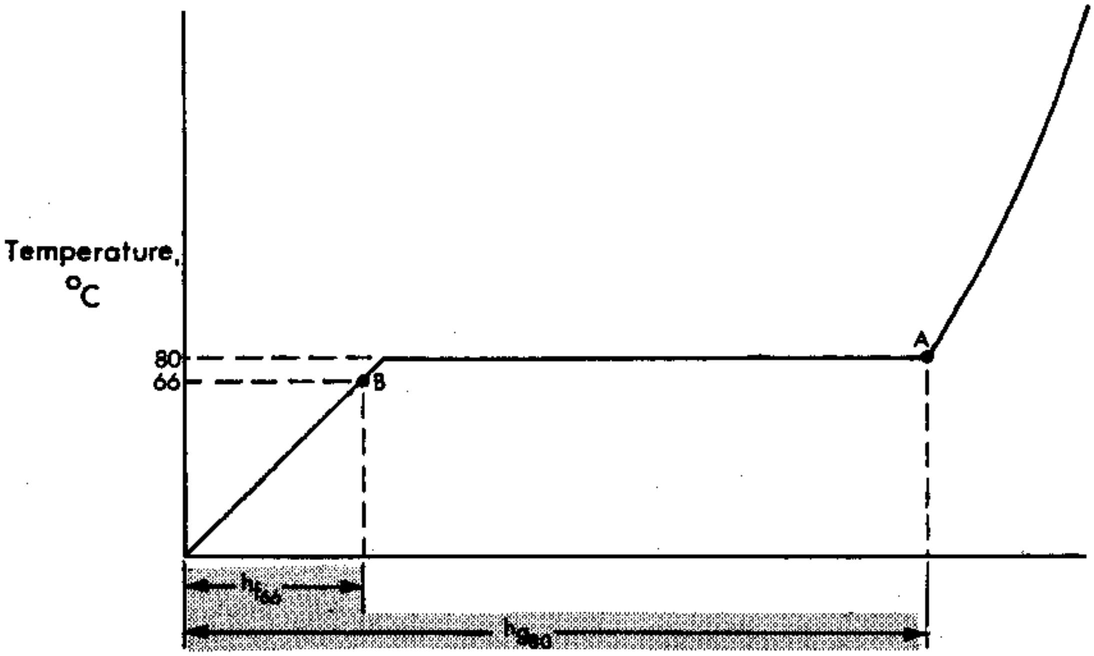

Fig. 5.6

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

$$= \text{mass} \times \text{enthalpy change}$$

$$= 60 \times 2367.6$$

$$= \underline{142056} \text{ kJ}$$

Heat gained per second by the feedwater

$$= \text{mass x enthalpy change}$$

$$= \text{mass x } (h_{f_x} - h_{f_{36}})$$

$$= 850 \text{ x } (h_{f_x} - 150.7) \text{ kJ}$$

Heat lost by steam = Heat gained by feedwater

$$142056 = 850 \text{ x } (h_{f_x} - 150.7) \text{ kJ}$$

$$142056/850 = h_{f_x} - 150.7 \text{ kJ}$$

$$167.1 = h_{f_x} - 150.7$$

therefore, h_{f_x} = <u>317.8</u> 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

<u>05.11</u>

(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.

Q5.12

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.

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 HT 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 unloader did not operate, an increased pressure in the condenser would reduce the enthalpy drop across the turbine. This pressure increase would be too small to cause any measurable change in steam flow. Would the turbine power level change?

Q5.13

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.

05.14

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.

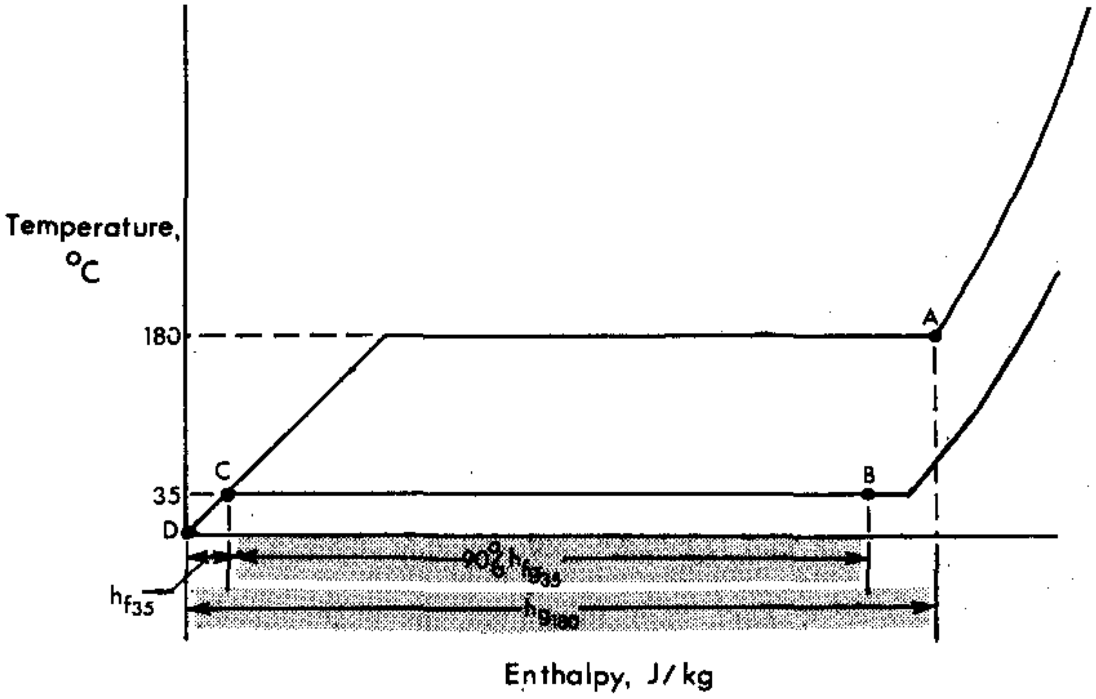

Fig. 5.7

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 $= 0.80 \times 599.4$

$= \underline{479.5}$ 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.

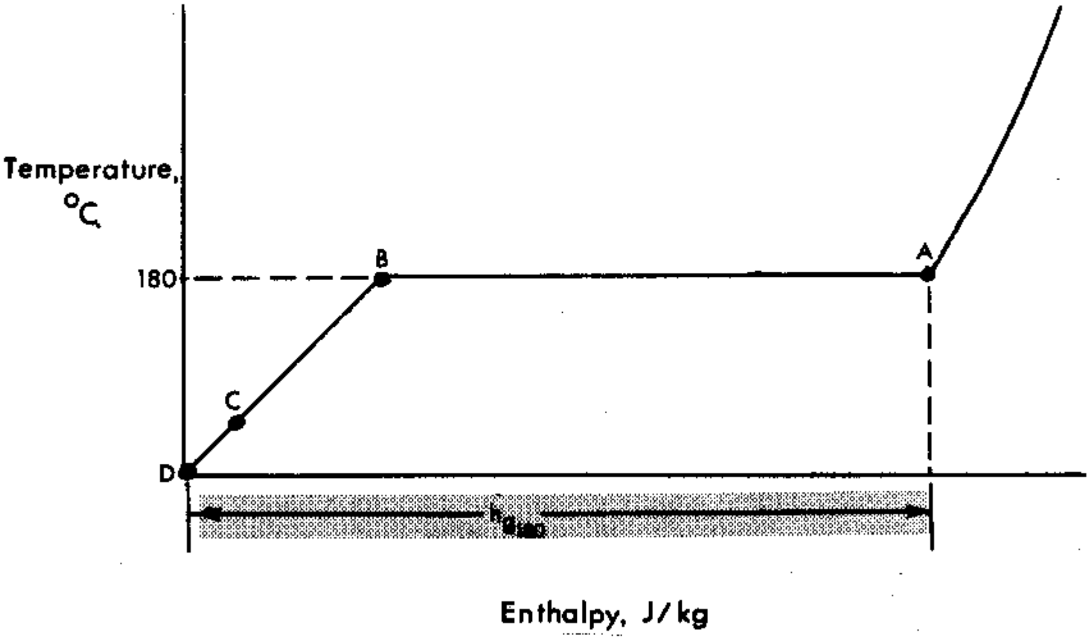

Fig. 5.8

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.

COURSE 225

HEAT & THERMODYNAMICS

MODULE 6

CONDENSER PERFORMANCE

Revised	Verified	Verified
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0036k3

Heat & Thermodynamics

MODULE 6

CONDENSER PERFORMANCE

Course Objectives

1. You will be able to explain <u>four</u> 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 <u>two</u> 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.

CONDENSER PERFORMANCE

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, more, in fact, than the turbine could produce.

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 turbogenerator 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.

06.1 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 8. 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 the 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 about 28°-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.

Q6.2 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.

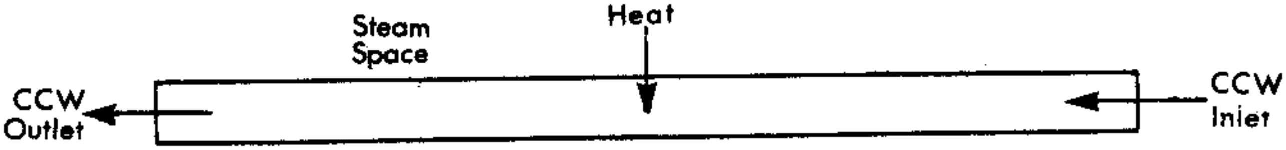

Fig. 6.1

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 $(T_s - T_{wa})$.

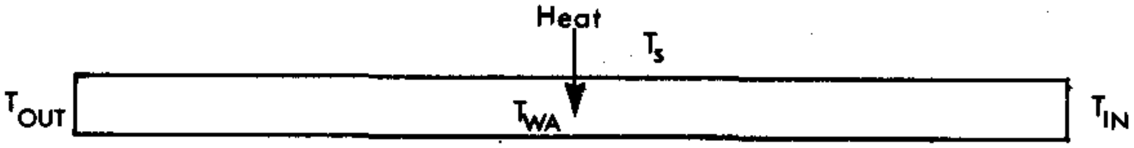

Fig. 6.2

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 and the available enthalpy decreases. However, the steam flowrate essentially remains constant because the increase in condenser pressure will be of the order of a few kPa compared to a pressure difference of the order of 4 MPa between GSVs and the condenser. This is assuming condenser pressure has not reached a level at which the vacuum unloader operates.

The changes may be reflected by recording in table form.

	Steam	CCW
Flowrate	Same	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.

Q6.3 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. The system finds a new operating point with a lower CCW outlet temperature, lower condenser pressure and temperature, and essentially the same steam flow.

	Steam	CCW
Flowrate	Same	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.

Q6.4 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, a pressure chosen to optimize turbine performance and feedwater cycle efficiency. Deviations from the design value of condenser pressure can create problems, as we will see later on. Such deviations can be caused by any of 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. Another possibility is reduction of CCW flow due to accumulated gas in the water boxes (which can be confirmed by checking the vacuum priming system).

The result of reduced CCW flow will be an increase in CCW outlet temperature, and hence an increase in CCW average temperature. This will, in turn, cause steam temperature and pressure to go up in order to maintain a constant ΔT between the steam and cooling water sides. Turbine exhaust temperature will increase, as will condensate temperature. These effects are summarized in the Table 1 on page 9.

Fouling of the Heat Transfer Surfaces

Fouling is caused by contaminants being deposited on the heat transfer surfaces. Contaminants can be algae, corrosion scale, oil or other deposits on either the CCW side or the steam side of the condenser tubes.

Fouling reduces the heat transfer coefficient for the condenser tubes, and therefore forces up the steam space temperature (and pressure) in order to maintain the same heat transfer rate across the tubes. As in the case of a CCW flow reduction, turbine exhaust temperature and condensate temperature will both increase. There will, however, be no discernible change on the cooling water side (Table 1 - page 9).

Change in CCW Inlet Temperature

Cooling water inlet temperature will vary with the season and the weather conditions. An increase in CCW inlet temperature will result in a corresponding increase in CCW outlet temperature, and hence an increase in average temperature on the cooling water side. Steam side temperature and pressure will increase to compensate. Turbine exhaust and condensate temperatures will both increase.

Air Ingress

Since the condenser operates at a pressure below atmospheric, leaks will allow air to enter rather than allowing steam to escape. If air is drawn into the condenser it will impair heat transfer from the steam side by "blanketing" the condenser tubes and reducing the transfer coefficient. Steam space temperature and pressure will rise in order to maintain the heat transfer rate, while conditions on the cooling waterside should show no significant change. Turbine exhaust temperature will increase, as will condensate temperature - but there will be a ΔT between these two values, with condensate temperature lower than it should be.

This rather unexpected effect arises as follows. In normal operation, very little air enters the condenser. One air extraction pump has no difficulty extracting it, and its effect is very small. As the leak rate increases, however, the air - in addition to impeding heat transfer across the tubes - begins to collect in the region of the condenser where steam pressure is lowest (ie, near the suction of the air extraction pumps).

Now, according to Dalton's Law of partial pressures, the temperature of the steam at any point in the condenser is dependent only on the partial pressure of the steam, not on the total pressure of the steam and air. At the turbine exhaust, the quantity of steam is much greater than the quantity of air, so the steam temperature at that point will be very close to the saturation temperature corresponding to total condenser pressure. If the latter were 7.0 kPa(a), for example, steam temperature would be 39°C.

At the extraction pump suction, however, the ratio of steam to air is much lower, the actual value depending on how bad the air inleakage is. If the ratio were 50:50, and the pressure was 6.0 kPa(a) at that point, the partial pressure of the steam would be only 3.0 kPa(a); any condensate forming there would have a saturation temperature of only 24°C. Naturally, only a relatively small quantity of condensate of such low temperature will be produced, because there isn't much steam in that region. There will be enough, however, to keep the overall condensate temperature from rising as high as the overall pressure would lead us to expect. In other words, the condensate will appear to be subcooled.

Apparent condensate subcooling is not the only characteristic feature of air inleakage. The level of dissolved oxygen in the condensate will increase as more air leaks into the condenser, and of course the load on the air extraction pump will increase, too. In fact, if the standby pump cuts in during normal operation, this can almost always be taken as a sign of worsening air inleakage.

Flooding of Condenser Tubes

If a problem of level control arises in the condenser hotwell, the lower heat transfer surfaces may become covered by condensate. This flooding will reduce the heat transfer surface available for condensing the steam. This will result in an increase in steam space temperature and pressure.

Since some tubes are flooded the cooling water causes subcooling of the condensate. The sensible heat removed from the condensate is small in comparison with the latent heat of vapourization and no noticeable increase in CCW outlet temperature will be experienced.

For example, to condense steam at 5 kPa(a) with a moisture content of 10% requires heat removal of 2 180 kJ/kg. To subcool the condensate by 5°C approximately 21 kJ/kg of extra heat must be removed, ie, 1% more. (Subcooling by much more than this is not possible as it is limited by CCW inlet temperature.) If the CCW temperature differential was 10°C at full power, then 1% more heat removal would change the temperature differential by 0.1°C which is not easily detectable.

Table 1 shows changes (relative to "normal" condenser conditions) which can be used as a guide in determining the cause for any increase in condenser pressure. The table assumes that the regulating system will attempt to keep turbine-generator output constant and the GSV opening remains unchanged.

Changing Condition	1 CCW Inlet Temp.	2 CCW Outlet Temp.	2-1 CCW ΔT Change	3 Cond. Press.	4 Turbine Exhaust Temp.	5 Cond. Temp.	4-5 Steam Side ΔT Change
CCW Flowrate Decrease	Same	Incr.	Incr.	Incr.	Incr.	Incr.	Zero
Condenser Tube Fouling	Same	Same	Zero	Incr.	Incr.	Incr.	Zero
CCW Inlet Temp. Increase	Incr.	Incr.	Zero	Incr.	Incr.	Incr.	Zero
Air Ingress	Same	Same	Zero	Incr.	Incr.	Incr.	Incr.
Tube Flooding	Same	Very* Small Increase	Very* Small Increase	Incr.	Incr.	Decr.	Incr.

Table 1

*May not be measurable.

Q6.5 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 simplicity, we'll assume that the turbine expansion is isentropic which means that the expansion is represented by a vertical line on the diagram.

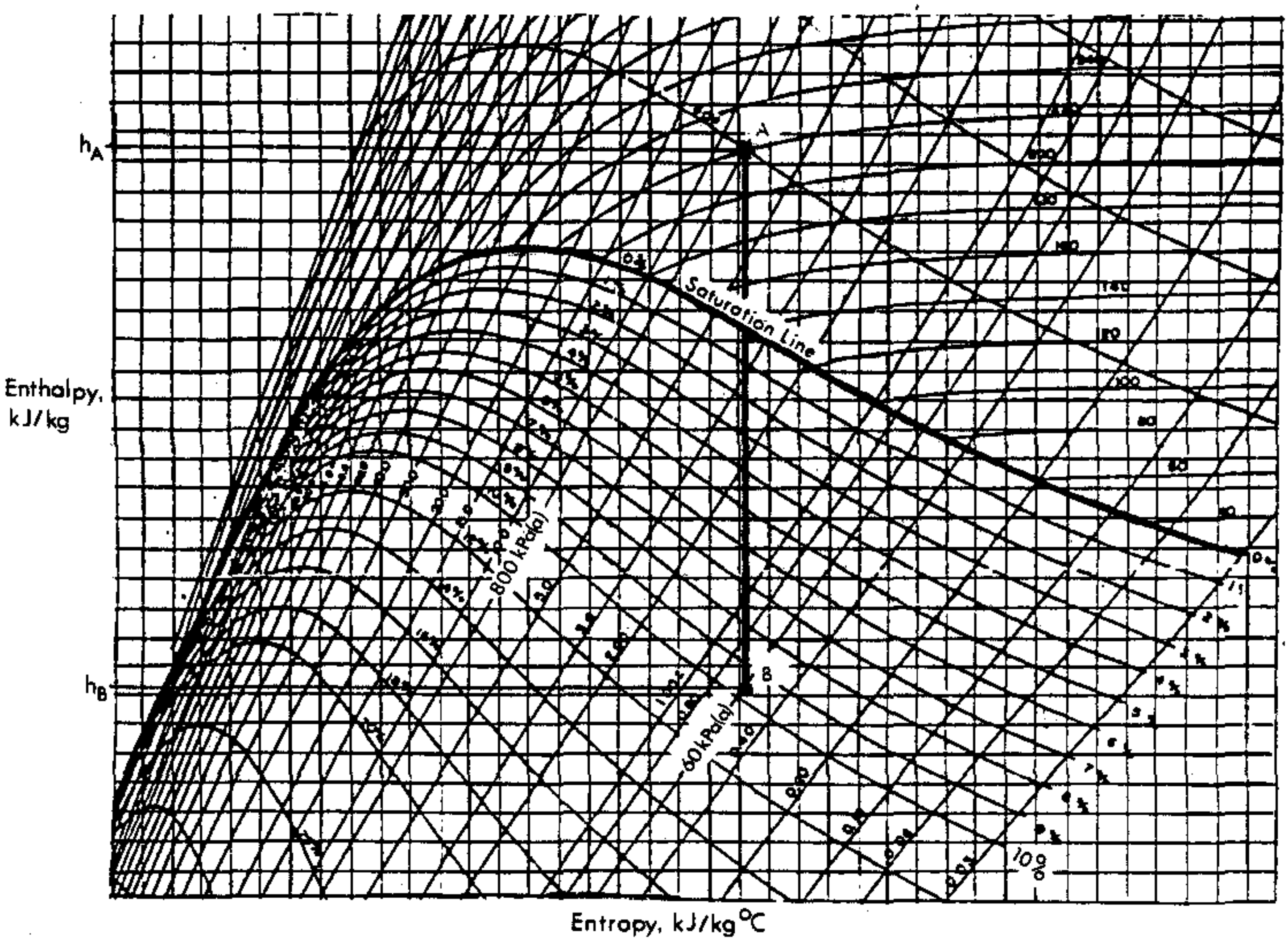
h_A
h_B
Enthalpy,
kJ/kg
Entropy, kJ/kg °C
A
B
Saturation Line
800 kPa(a)
60 kPa(a)
10%

Fig. 6.3

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.

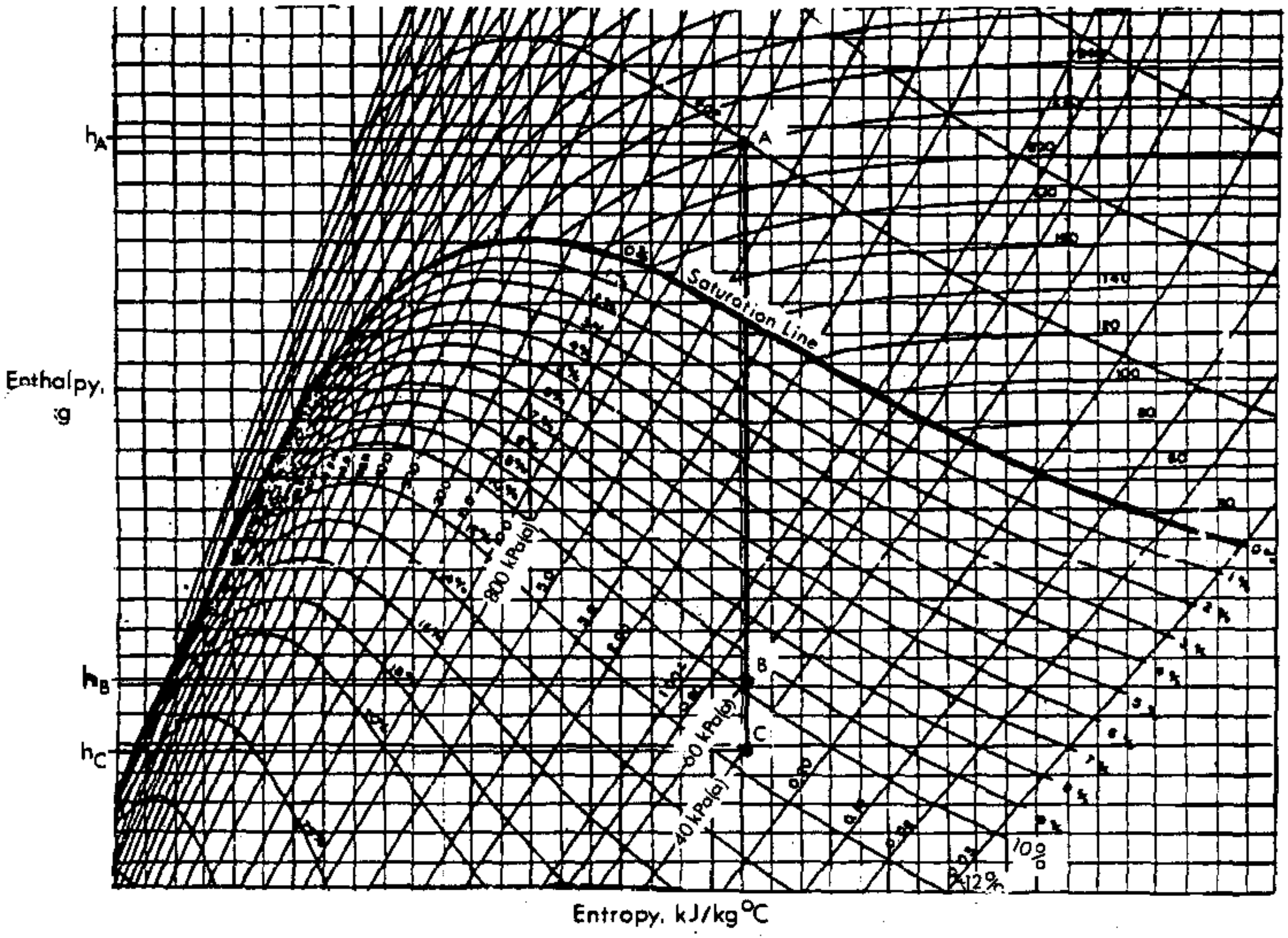

Fig. 6.4

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.

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 increased flow induced vibration.

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. 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 component life. This reduced life is due to increased stresses as a result of accelerated erosion and overpowering of the last stage of the turbine. Condenser tubes would experience considerable erosion and flow induced vibration.

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 lower enthalpy drop available from the steam. A reduced steam flowrate due to the lower pressure difference which exists between the GSVs and the condenser will only become noticeable if condenser pressure goes very high and the unloader fails to operate.

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.

Thermal expansion of the blading can close up the radial tip clearances which would cause rubbing and consequent damage. Heating of blades is a problem at low power where the cooling effects from steam flow are much reduced.

The vacuum unloader reduces the turbine load in the event of a high condenser pressure.

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 if full steam flow is maintained 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.

Q6.6 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 due to low CCW inlet temperatures. Describe two turbine related problems which would result from operating at this condition for any significant length of time.

Q6.7 If you were faced with the situation in question Q6.6, what would be your recommendations for operating the turbine?

Q6.8 Explain why a vacuum unloader and vacuum trip facilities are considered necessary protective devices on 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.

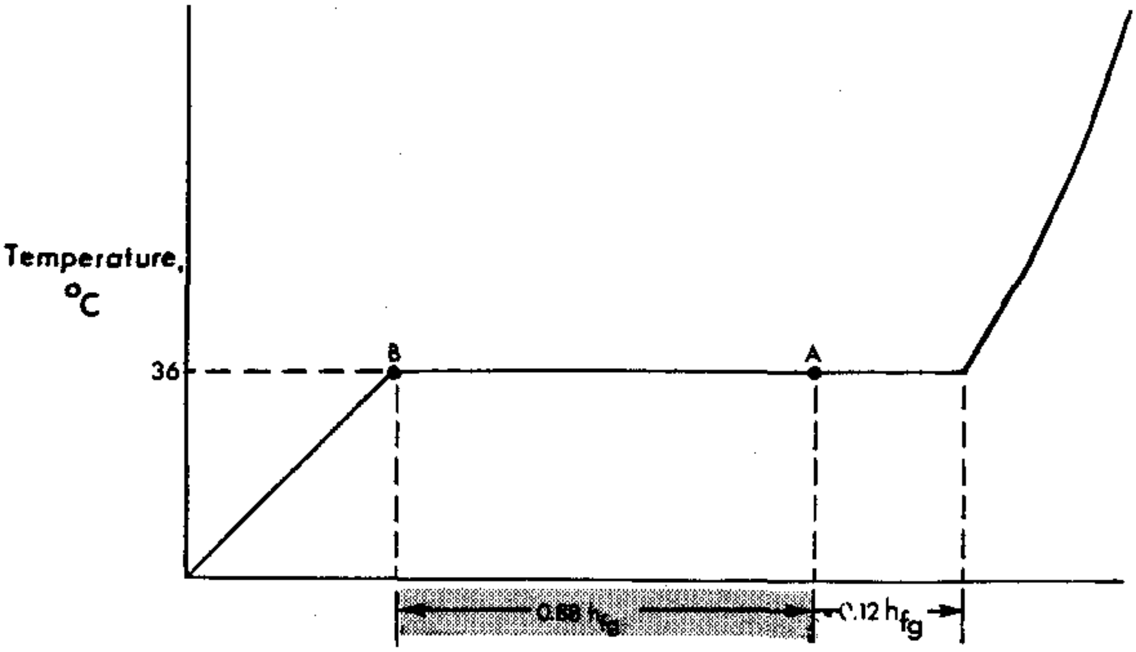

Fig. 6.5

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_{fg36}

<u>From Table 1</u> 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,

ie 2126.4 x 680 = <u>1445952</u> 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).

Heat gained $= h_{f_{14}} - h_{f_4}$

$= 58.75 - 16.80$

$= 41.95$ kJ/kg.

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 = 34468 kg of CCW are required to remove 1445952 kJ of heat.

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.

Q6.9 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, determine the CCW flowrate required.

Q6.10 45×10^3 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.

* * * * *

MODULE 6 - ANSWERS

Q6.1

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 comparable to the size of the turbine and will 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. Creating a high vacuum at the turbine exhaust thereby improving cycle efficiency.
3. A significantly reduced treated water usage and plant incurs a much lower capital and operating expense.

Q6.2

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 10°-15°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.

Q6.3

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 hence the enthalpy drop across the turbine.

The system settles out with lower CCW temperature, lower condenser temperature and pressure and essentially the same steam flowrate to the condenser.

	Steam	CCW
Flowrate	Same	Same
Inlet Temp	X	Decrease
Outlet Temp	X	Decrease
Ave Temp	Decrease	Decrease
Pressure	Decrease	X

Q6.4

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.

The 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

Q6.5

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 for 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 as well as the condensate temperature increasing, 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 coefficient. Condenser temperature and pressure will rise to compensate, and condensate temperature will also go up - though not as much as expected. The effect of the partial pressure of air in the condenser will make it appear as if the condensate is subcooled in comparison to the higher turbine exhaust temperature. An additional giveaway to air ingress will be a marked increase in the dissolved oxygen concentration 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.

Q6.6

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 condenser tubes and flow induced vibration will result in premature fatigue failure of the components.

Q6.7

Before you can make a recommendation, you must ensure 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 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.

Q6.8

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 400-500 m/s and the frictional skin heating effects on the rotating blades become very significant as the temperature and pressure rise.

Thermal expansion elongates the moving blades. As the temperature of the blades rises, and the blades stretch, they may close the radial blade clearances with the turbine casing and the results could be catastrophic.

Unloading is carried out to reduce the heat transfer load on the condenser and prevent a further increase in pressure. Overheating becomes more troublesome when steam flow is reduced.

Q6.9

The heat lost by the condensing steam is equal to the heat gained 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.

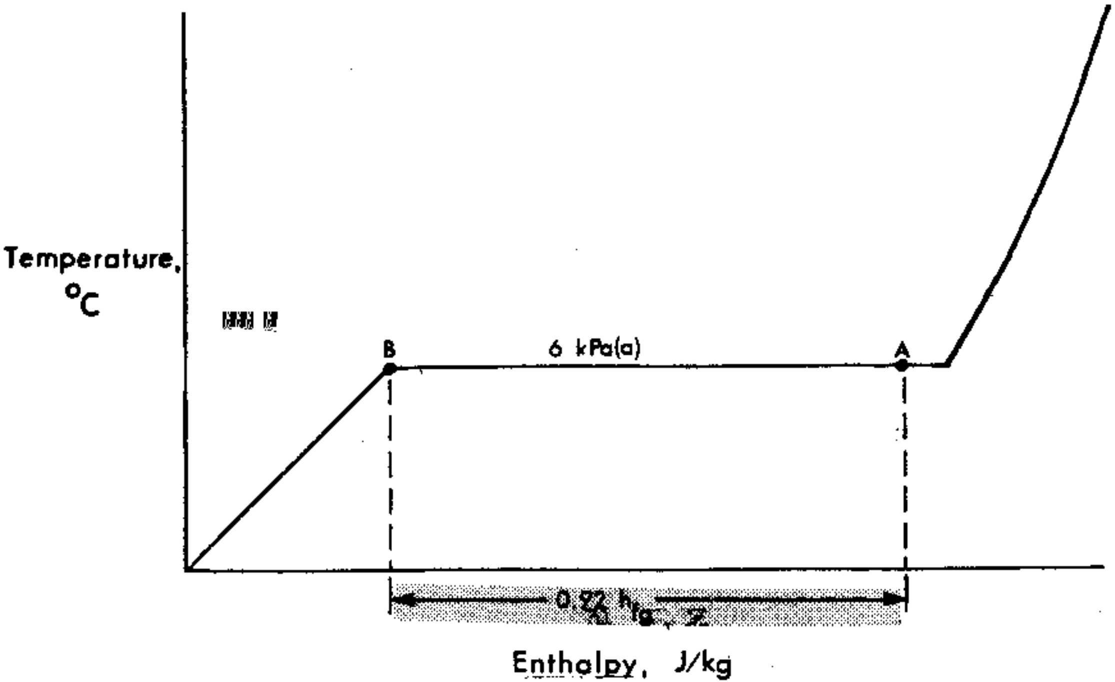

Fig. 6.6

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) = <u>2416</u> kJ/kg

Heat lost per kg of steam = 0.92 x 2416

= <u>2222.7</u> 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).

Thus heat gained per kilogram of CCW = $h_{f_{12}} - h_{f_2}$

= 50.38 - 8.39

= 42 kJ/kg.

Every kg of CCW removes 42 kJ of heat until 1578131 kJ have been removed every second.

CCW flow required to remove 1578131 kJ = $\frac{1578131}{42}$ = 37584 kg/s.

Q6.10

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.

Heat gained per kg of CCW = $h_{f_{12}} - h_{f_3}$

= 50.38 - 12.60

= 37.8 kJ.

Total heat gained by CCW equals enthalpy rise (37.8 kJ) multiplied by the CCW flowrate (45×10^3 kg/s).

Total heat gained by CCW = $37.8 \times 45 \times 10^3$

= 1.7×10^6 kJ/s.

This is equal to the heat lost by the condensing steam in the condenser. The heat lost is uncomplicated in this example.

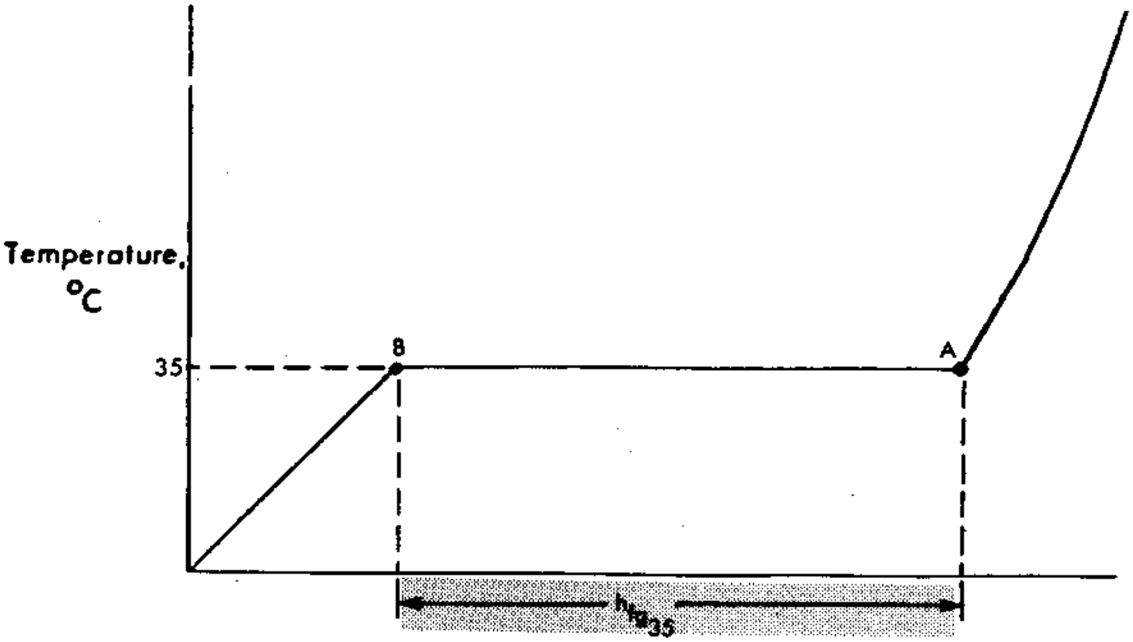

Fig. 6.7

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 <u>all</u> the latent heat of vapourization at 35°C.

From table 1 h_{fg} at 35°C = <u>2418.8</u> kJ/kg.

This heat is gained by the CCW and steam is continually condensed giving up 2418.8 kJ/kg until 1.7 x 10^6 kJ of heat are transferred to the CCW every second.

The steam flow required to transfer 1.7 x 10^6 kJ/s

= 1.7 x 10^6/2418.8 kg/s

= <u>703</u> kg/s.

COURSE 225

HEAT & THERMODYNAMICS

MODULE 7

STEAM GENERATOR

Revised	Verified	Verified
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Heat & Thermodynamics

MODULE 7

STEAM GENERATOR

Course Objectives

1. You will be able to explain how the temperature difference between the steam generator and the HT system changes during a "crash-cool" exercise.

2. You will be able to state how the HT 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 two 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.

STEAM GENERATOR

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 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 manoeuvering 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 HT system to the steam generator depends upon the temperature difference which exists between the D_2O and the light water 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 HT system in order to transfer the same quantity of heat.

Q7.1 Explain how the temperature difference between the HT system and the steam generator changes during a "crash-cool" exercise.

Q7.2 Explain how an increase in thermal resistance, across the steam generator tubes, affects the average HT 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.

Q7.3 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.

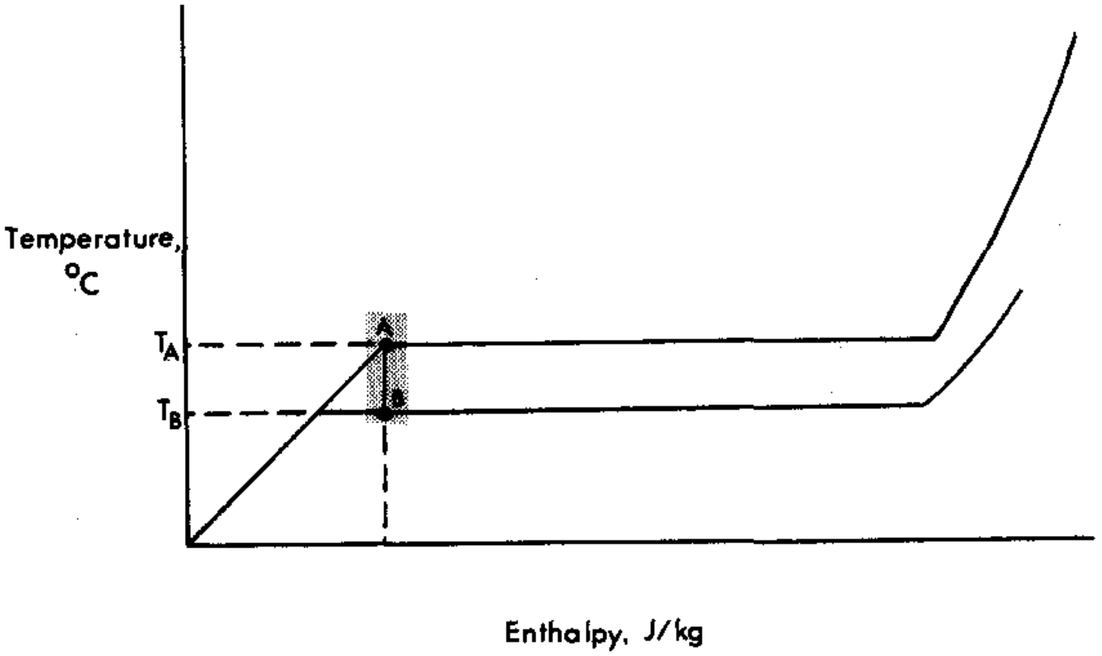

Fig. 7.1

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.

Q7.4 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.

Q7.5 Explain why it is undesirable 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 two potential problems with a very low steam generator level. First, 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 undesirable trend.

Secondly, if the level in the steam generator falls any further the tube bundle will be uncovered and dry out will occur. The reduced heat transfer area immediately impairs the heat transfer across the tubes causing HT temperature and pressure changes which will be discussed in Module 8. The dissolved solids existing in the steam generator will "bake out" on the tube surfaces and impede future heat transfer.

Normal control action should maintain level in the correct operating range, but if sudden shrink causes too low a level it is accommodated initially with an alarm which may allow operator action. If this is not successful and level continues to drop, there will be a power reduction, by setback or stepback depending on the design of the particular unit. A reactor trip would follow if the level dropped even further. The effect of reducing reactor power rapidly is to preserve boiler inventory. This gives time to correct the problem, if that is not possible, to transfer to an alternate means of removing decay heat.

Answer the following questions and compare your answer with the notes at the end of the module.

Q7.6 Explain why the level in the steam generator initially falls on sudden reduction of steam flow.

Q7.7 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

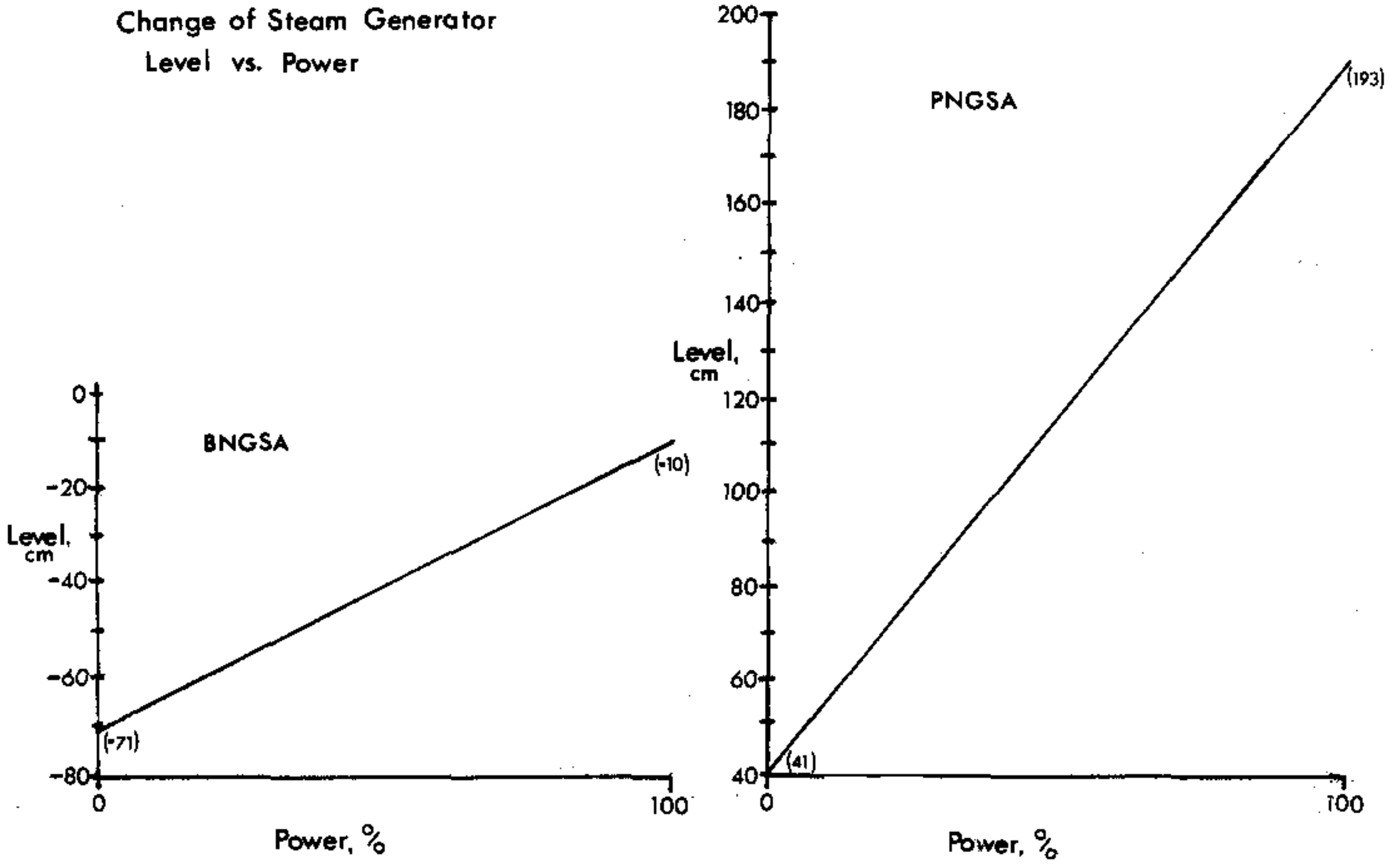

Fig. 7.2

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.

Q7.8 Why do you think this difference exists? Compare your answer with the notes at the end of the module.

Q7.9 State the three elements which are used in a boiler level control program. Explain how level control is effected at low power levels.

Q7.10 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 the governor system 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 (Deaerator, 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.

Q7.11 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 8 "Reactors". At this point this is the set of conditions that have to be met by the steam pressure control programs at each station.

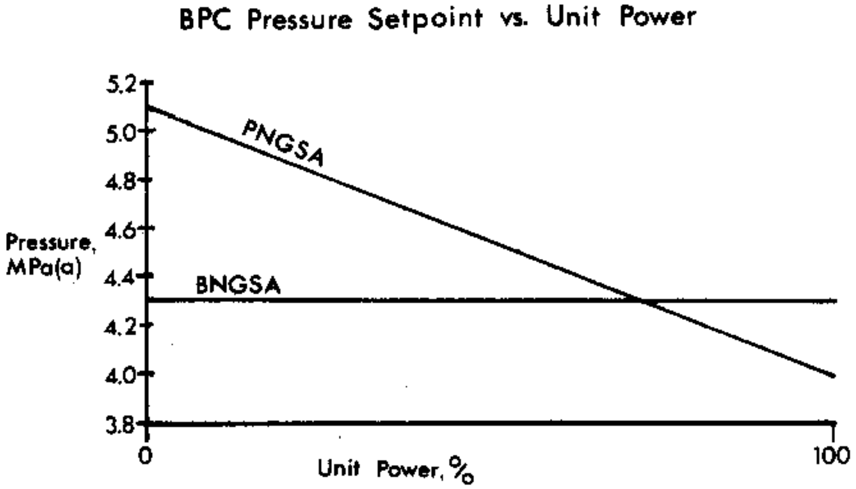

Fig. 7.3

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.

<u>Q7.12</u> 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 manoeuvering 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.

Q7.13 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.

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 in a controlled manner. It is at this point that the shutdown cooling takes over.

Q7.14 Explain why the BPC program terminates at 170°C when in the 'cooldown' mode.

* * * * *

MODULE 7 - ANSWERS

Q7.1

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 HT system and the steam generator which increases the rate of heat removal from the reactor and reduces the time for reducing reactor temperature.

Q7.2

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 HT 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 HT temperature.

Q7.3

Using the steam table, we can compare the specific volume of liquid v_f at 170°C and 250°C using table 1,

v_f at 170°C = 1.1144 ℓ/kg

v_f at 250°C = 1.2513 ℓ/kg.

Change in volume = 1.2513 - 1.1144

= 0.1369 ℓ/kg.

This percentage increase in volume = (0.1369/1.1144) x 100

= 12.3%.

Obviously there is some increase in level solely due to this expansion effect.

Q7.4

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.

Q7.5

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.

Q7.6

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.

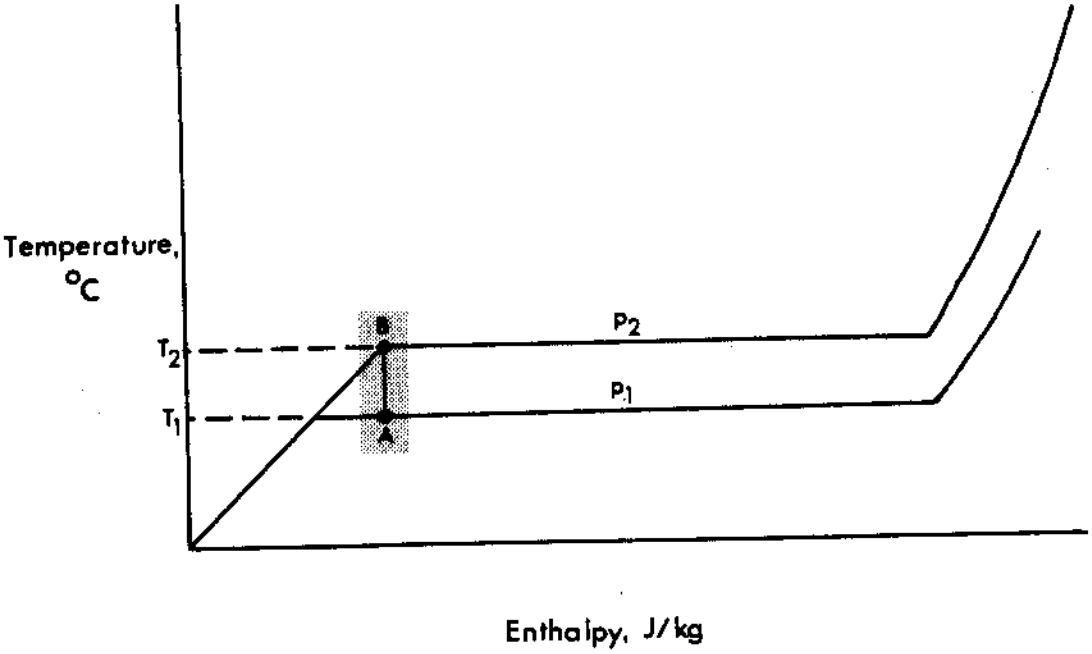

Fig. 7.4

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.

Q7.7

There are basically two 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 desirable situation.

Secondly, 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.

Q7.8

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.

Q7.9

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.

Q7.10

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.

Q7.11

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.

Q7.12

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% FP.

Q7.13

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.

07.14

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 at a controlled rate.

This happens at around 170°C. As a result, this is the termination point of cooldown using BPC. Further cooling of the HT system will take place using the shutdown cooling circuits.

COURSE 225

HEAT & THERMODYNAMICS

MODULE 8

REACTOR

Revised	Verified	Verified
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April 1988

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Heat & Thermodynamics

MODULE 8

REACTOR

Course Objectives

The student will be able to:

1. State the parameter which is monitored to ensure fuel operating limits are not exceeded in non-boiling channels and briefly explain why this parameter cannot be used to ensure safe fuel operation for boiling channels.
2. Briefly describe two methods that are used to monitor that heat production in boiling channels is kept within specified limits.
3. Briefly explain how fuel channel blockage can be detected and state the major problem resulting from channel blockage.
4. Briefly explain four major reasons for a high HT system pressure and three major reasons for a low HT system pressure.
5. Briefly explain how a loss of heat transport coolant may be detected.
6. Briefly explain the immediate and longer term effects of losing feedwater supply to the steam generators.
7. Briefly explain how a loss of coolant accident would produce fuel failures assuming no protective action occurred.
8. Briefly explain how the temperature and quality of the HT coolant change when bulk boiling occurs.
9. Briefly explain why crash cooling is necessary for a LOCA which results in a very low rate of pressure decrease in the heat transport system.
10. Explain how HT thermosyphoning is established and how the reactor outlet header temperature is used as a datum for the control of thermosyphoning.

REACTOR

Introduction

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 dependent systems, eg, the moderator system, the primary heat transport system and the steam system. It is virtually impossible to discuss one system without referring to another.

The Heat Transport (HT) system has three sources of heat input:

(a) Fission heat.
(b) Decay heat from fission products.
(c) HT pump heat.

When at power the fission heat is, by far, the largest of these three terms (~93% FP). The maximum heat from decay of fission products is, typically, only 6% FP. At low power, the pump heat input to the HT system becomes significant (~1% FP).

The main purpose of the HT system is to remove the heat from the three sources ie, decay and fission heat in the fuel bundles and the pump heat. With the reactor at power, this is done by circulating the heat transport fluid through the steam generators. In the event that the steam generators are not available as a heat sink for the heat transport system, the reactor is shutdown because there is no backup heat sink capable of removing full 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 which is much less because it is only the decay heat of fission products and HT pump heat.

<u>Q8.1</u> State the three sources of heat to the primary heat transport system and the two <u>main heat exchanger processes</u> which are used to remove this heat. Compare your answer with the notes at the end of the module.

* * * * *

Fuel Bundle and Channel Heat Transfer

Before we look at temperature and pressure effects in the HT system, let us have a look at a fuel channel and examine more closely some of the conditions which exist.

As a result of design considerations (discussed more fully in Materials 228 or Reactor, Boilers and Auxiliaries 233), uranium dioxide (UO_2) was chosen as the fuel for CANDU reactors. As UO_2 is a ceramic material, its thermal conductivity is very low and the pellet core temperature is therefore much higher than the surface temperature. Fortunately, UO_2 has a high melting point (approximately 2800°C) and can tolerate relatively high temperatures at the pellet core.

The temperature profile of a fuel element may be seen from Figure 1.

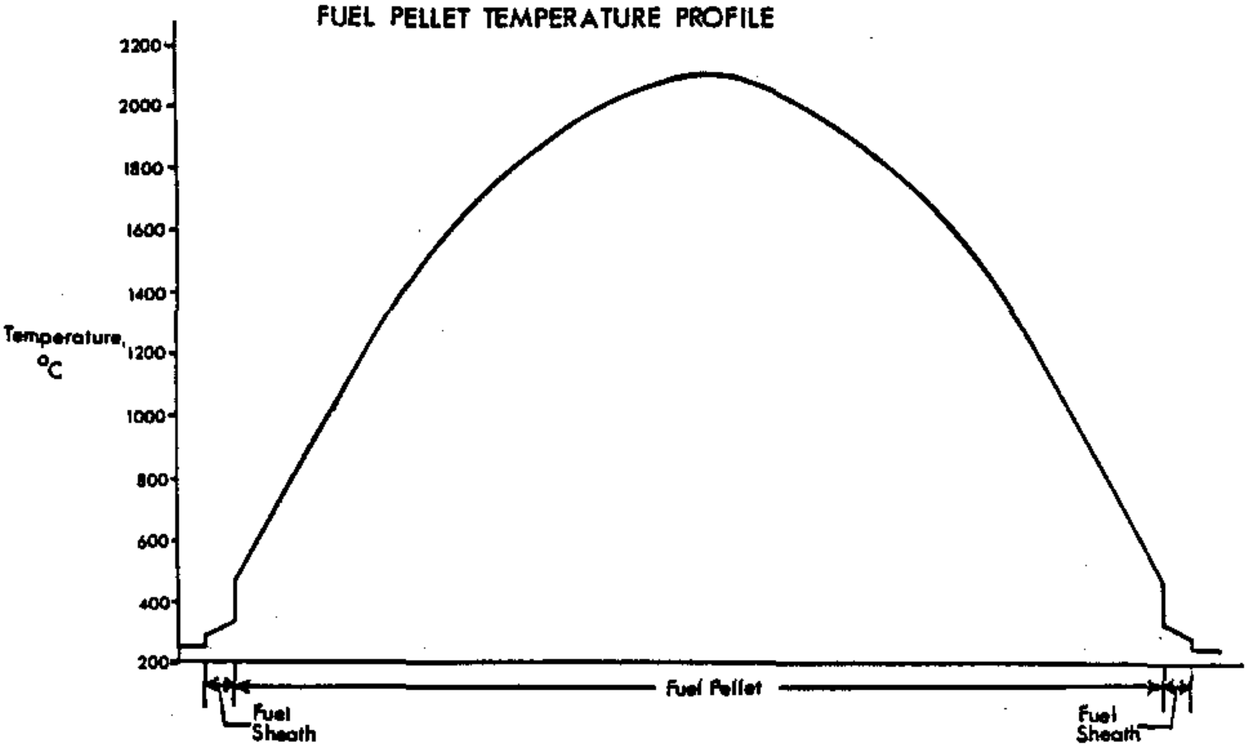


Figure 1
Fuel Pellet Temperature Profile

From Figure 1, you can see how effective the thermal resistance in the fuel element becomes. In a distance of 7 mm, which is a little over 1/4", the temperature has dropped from 2100°C in the centre of the fuel element to around 500°C at the inner surface of the sheath. The outer surface of the sheath is at a maximum temperature of about 305 to 326 °C dependent on the specific power plant.

Bruce NGS-A and -B, Darlington and CANDU 600 reactors have smaller diameter fuel elements allowing the higher sheath temperature of about 326° C. The maximum centre line temperature of the fuel pellets is typically lower than that shown in Figure 1.

We can gather from the discussion so far that a fuel element/bundle has temperature limitations. In fact, the metallic fuel sheath (Zircaloy 4) has both a temperature and strain limit which are set to maintain structural integrity of the sheath. The UO_2 fuel pellet has only a temperature limit which must not be exceeded if excessive release of fission products is to be avoided. These temperature limitations result in the setting of bundle power limits and subsequently channel power limits to ensure that the fuel is not subjected to excessive temperatures.

There are basically two ways of approaching the temperature/power limitations:

(a) Increased heat production.

(b) Impaired cooling of fuel.

Increased Heat Production

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.

The neutron flux distribution along a fuel channel is a familiar shape and is shown in Figure 2. It represents the amount of power being produced at a point in the channel and we can see that the bundles in the centre of the channel are subjected to higher neutron flux than those bundles in the outer sections. This means these central bundles are operating at a higher power level and producing more heat.

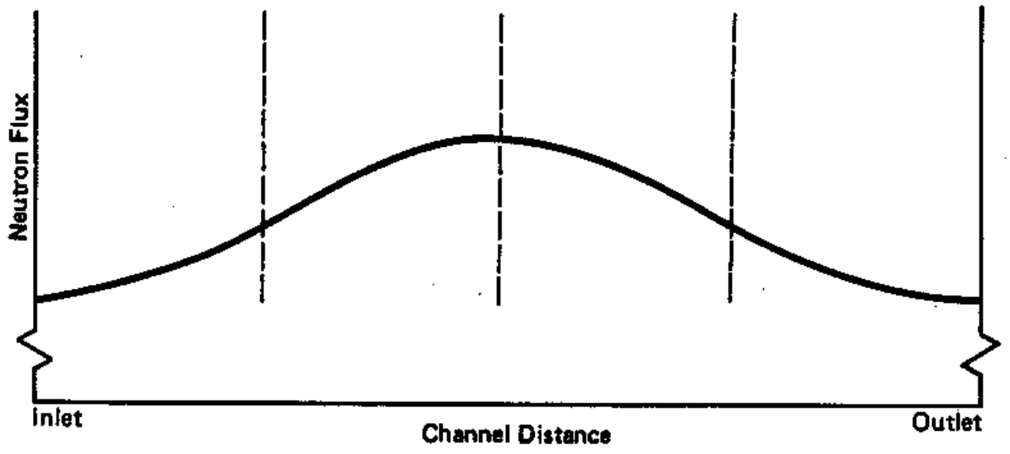


Figure 2
Neutron Flux vs Core Channel Distance in Nonboiling Fuel Channel

Figure 3 shows the coolant temperature along the channels as a result of the flux distribution illustrated in Figure 3.

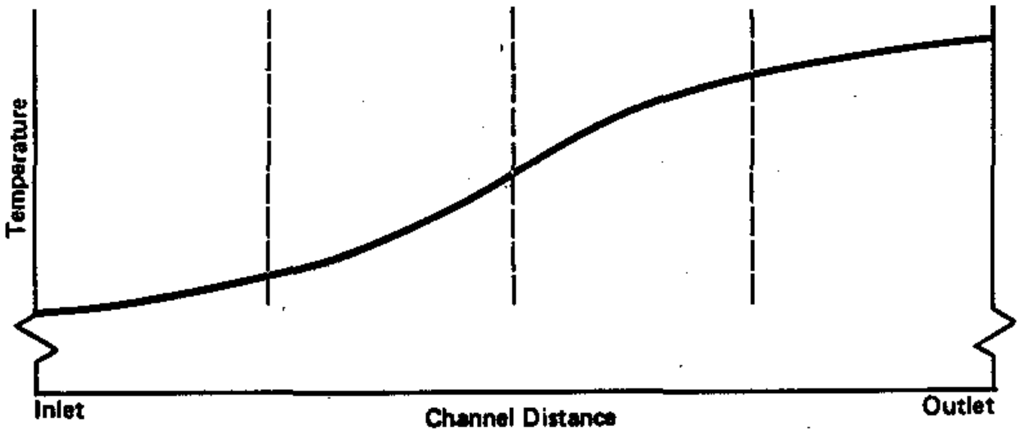


Figure 3
Temperature vs Core Channel Distance in Non-boiling Fuel Channel

Figures 2 and 3 represent typical neutron flux and temperature profiles for a non-boiling channel. Variations in flux resulting from reactivity device movements, local transient xenon effects, fuelling direction, etc, will affect the neutron flux profile and consequently the temperature profile. In addition, the distribution of thermal power along a channel may not correspond exactly to the flux shape due to variations in fuel burn up and decay heat contributions.

Our main concern is that the fuel bundles which occupy the central to end positions in the channel are not being subjected to conditions beyond the fuel operating limits.

If conditions exist such that neutron flux levels are higher at any point along the channel, the heat production in the bundle increases at that point leading to increased heat transfer to the coolant. If the coolant is not boiling at this point, then its temperature will rise. If the coolant is boiling, then vapour production will increase. Both of these conditions may lead to excessive boiling and possible dryout towards the channel outlet. As previously discussed (Module 1), dryout is a dangerous condition because it may *lead to a breach of the fuel and fuel sheath integrity.*

How do we determine whether heat production is within specified limits?

In the case of a non-boiling channel, we monitor the temperature rise across the channel as the most effective method of ensuring bundle power and channel power are kept within specified (license) limits.

The power of individual bundles is not measured but can be estimated because we know the channel's thermal power output (mass flow rate x specific heat x temperature rise) and the flux shape along the channel. The channel thermal power, which can also be considered as the sum of the bundle powers, is directly related to the temperature rise across the channel. A maximum allowable temperature rise is set which is equal to the point at which the highest powered bundles approach their operating limits.

In the case of a boiling channel, monitoring the channel temperature rise does not ensure that there is only limited boiling and proper cooling of the fuel. This is because the coolant temperature at the channel outlet is equal to the saturation temperature corresponding to the local pressure. Regardless of the amount of boiling, this temperature remains constant as long as the outlet pressure is constant and there is still some liquid present. (This also precludes the presence of superheated steam.)

For a boiling channel, we monitor the amount of steam produced in the channel to ensure there is sufficient liquid present to maintain adequate fuel cooling. This information can be determined by either of the methods described below.

(a) Using a group of specially selected channels (called FINCHs) which have been fully instrumented, volumetric flow rates for channel inlet and outlet can be compared.

If there is no boiling, the volumetric flow rates will be equal and if there is boiling, the outlet flow rate will exceed the inlet flow rate. The difference allows us to calculate the amount (percentage) of steam present at the channel outlet.

Predictions of steam quality in channels other than FINCHs can be made (with the aid of a computer program) from FINCH data and a knowledge of flux shape in the other channels.

(b) Using a combination of flux shape monitoring and bulk power measurements.

A representative flux map of the core is prepared with the aid of computer simulations and the measurements of a large number of strategically placed, self-powered vanadium detectors. Bulk thermal power is determined by measuring heat production on the secondary side (a combination of boiler steam and feedwater flows and boiler temperature measurement).

Flux mapping in conjunction with bulk power measurements (both thermal and neutronic) are used to help detect slowly developing local high power conditions such as bundle or channel overpowering.

Q8.2 Briefly explain how channel outlet temperature is used to monitor channel/bundle power limits in non-boiling fuel channels. Why is this parameter not useful for monitoring limits in boiling channels?

Q8.3 Briefly explain two methods used to monitor steam quality and ensure adequate fuel cooling in boiling channels.

* * * * *

Impaired Cooling of Fuel

At this point we will only deal with approaching the temperature/power limitations by reduced coolant flow. The situation resulting from reduced coolant pressure is covered later in this module when covering HT pressure control.

A measured increase in fuel channel temperature rise may not be due to an increase in power, it could result from reduced coolant flow, ie, a channel blockage. Let us consider what happens when there is a reduction in channel mass flow rate while channel power and channel inlet temperature remain constant.

Channel power is the product of the mass flow rate and the change in enthalpy occurring across the channel, ie,

$$\text{Channel Power} = \dot{m}\,(h_{out} - h_{in})$$

Using this equation and conditions identified let us see what this produces.

Power is constant.

Enthalpy of coolant into the channel is constant because the channel inlet temperature is constant.

Mass flow rate is reduced.

$$\underset{\text{constant}}{\text{Channel Power}} = \underset{\downarrow}{\dot{m}}\;(\overset{\uparrow}{h}_{out} - \underset{\text{constant}}{h_{in}})$$

For the equation to balance, the enthalpy of the coolant leaving the channel must rise. The only way this can occur is for the reduced coolant flow to pick up the same amount of heat, ie, channel outlet temperature rises.

Q8.4 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.

B8.5 A fuel channel is operating normally with the following conditions:

Channel outlet temperature 296°C.

Channel outlet pressure 8.47 MPa(a), corresponding saturation temperature 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 flow rate, 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 (ΔT) and reactor power is essentially zero. As the power is increased, the channel ΔT increases to a maximum at full power of 40° to 55°C, depending on the station.

There are also some significant differences in the method used to measure ΔT across the channel in different stations.

At some stations (eg, PNGS-A and -B), the average HT temperature is kept sensibly constant, rising only a few degrees centigrade over the whole power range. This minimizes shrink/swell in the HT system caused by power manoeuvres and means the HT pressurizing system does not require a pressurizer.

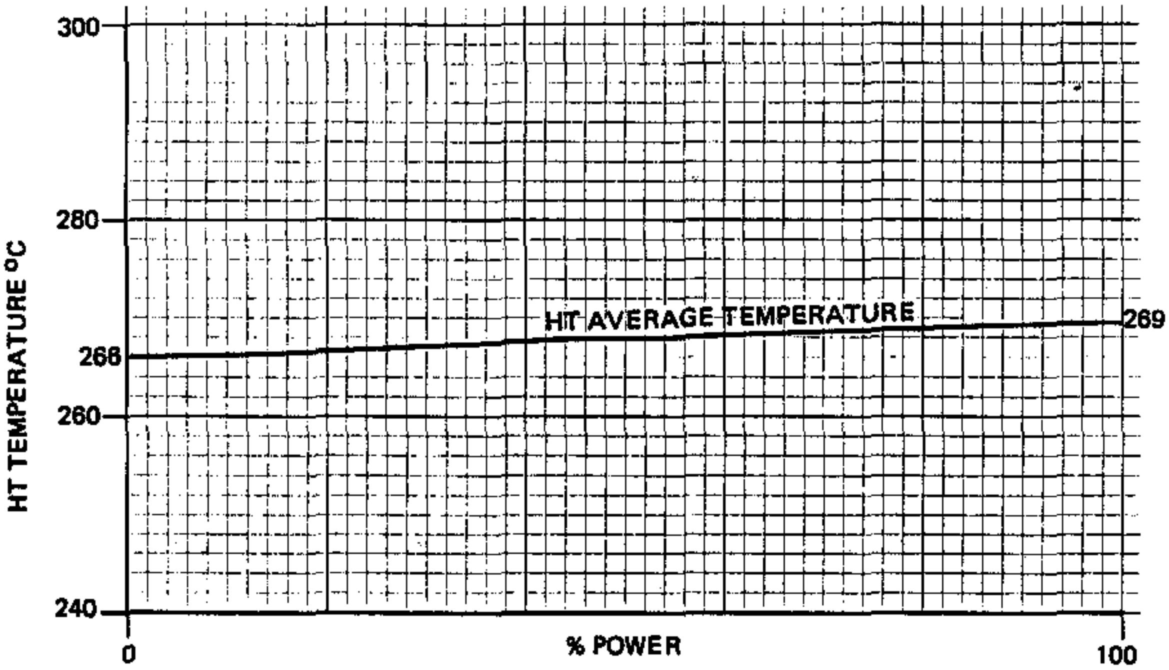


Figure 4
HT Temperature vs % Full Power

Figure 4 represents a HT system where the HT system temperature remains relatively constant over the power range.

B8.6 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 example illustrated in Figure 4?

B8.7 In order to transfer heat from the HT D_2O to the H_2O in 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% to 100% in the example illustrated in Figure 4?

Check your answers with the notes at the end of the module.

* * * * *

In other stations, eg, BNGS-A and -B, Darlington NGS, where a pressurizer is part of the HT pressurizing system the situation between the HT system and the steam generator is reversed. The pressure in the steam generator is kept relatively constant and the HT average temperature rises as reactor power increases.

B8.8 In a system with a pressurizer, the steam generator pressure is kept constant at 4.25 MPa(a). What is the heat transport average temperature when the unit is at zero power hot.

B8.9 In question Q8.8 how would you expect the heat transport average temperature to change with power? 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.

* * * * *

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 HT circuit. The 'solid' system (at PNGS 'A' and 'B') has no vapour space and the HT system pressure is very sensitive to changes in fluid volume. This design uses a feed and bleed system for controlling the pressure of the HT system, ie, inventory transfer to and from the HT system.

The second design (at Bruce and Darlington) uses a pressurizer which contains a large volume of D_2O vapour that expands when the liquid volume in the HT decreases and is compressed when liquid volume increases. This arrangement is very much less sensitive to the changes in HT fluid 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 change, is large when compared to a pressurizer system.

A high pressure in the heat transport system may cause over pressure of the heat transport circuit which will result in a reactor setback or trip to safeguard the heat transport circuit.

A high heat transport pressure may be caused by:

(a) A large thermal power mismatch in which the reactor power exceeds the power capacity of the heat sink, eg, boilers causing an increase in average temperature.

(b) A loss of, or impairment in, HT coolant flow, causing an increase in channel ΔT and hence average HT temperature.

(c) A malfunction in the pressure control system allowing an uncontrolled increase in pressure.

(d) A loss of feedwater to the steam generator (boiler).

The immediate effect of losing the feedwater is to reduce the heat transferred by approximately 17% due to the loss of sensible heat required to raise the feedwater temperature from 175°C to 250°C. As a result, the HT system temperature immediately starts to rise and the liquid volume expands, and HT pressure rises.

If power is not reduced, boiler level would fall until the tubes are uncovered and the heat transfer would be further impaired.

In this situation, the primary heat sink for the reactor is significantly reduced and the reactor must be shut down quickly and alternate heat sinks placed in service (eg, shutdown cooling, maintenance cooling).

This situation represents a large mismatch in thermal power.

<u>08.10</u> Explain the effects of losing feedwater to the steam generators.

* * * * *

A low pressure in the heat transport system may be caused by:

(a) Large mismatch in thermal power with the steam generator removing more heat than is being produced by the reactor. This causes the HT fluid to reduce its volume due to the drop in temperature.

(b) A loss of coolant from the HT circuit.

(c) A malfunction in the pressure control system allowing an uncontrolled decrease in pressure.

In all cases, the rate of volume reduction may be greater than the make-up from the pressurizing system and the HT system pressure will fall as a result. For a system with a pressurizer, the intent of the design is to handle power changes required for normal regulation, about 1%/s or less. The system will not keep up with pressure reductions equivalent to faster rates.

A low pressure in the HT system may produce the following problems:

(a) There is a minimum value of pressure for the HT pump suctions to avoid cavitation. If this pressure is reached, a reduction in coolant flow would impair fuel cooling and if it lasts long enough, pump damage could occur.

(b) As the pressure falls, the HT fluid has more heat than it needs 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 may occur.

Q8.11 State four possible causes of high HT pressure.

Q8.12 State two problems associated with a low heat transport 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 HT system. Needless to say, the systems at each station are different.

Systems Using Feed and Bleed

At PNGS-A/B, the major benefit of having the heat transport average temperature sensibly constant is that there are no great changes in HT coolant 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 HT pressure. Pressurizing pumps return the feed to the HT system, thus tending to raise the pressure. The inventory changes due to shrink and swell effects of the heat transport coolant are accommodated by the D_2O storage tank, which also provides the suction for the HT 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.

In the event of a problem with the bleed condenser that results in high pressure within the bleed condenser itself, relief valves are installed which operate and cause heat transport D_2O to be discharged to the boiler room sumps.

Systems Using a Pressurizer

At BNGS-A/B or Darlington NGS, there is a considerable rise in the average heat transport coolant temperature for the whole reactor (for example at BNGS-A, from 254°C to around 281°C). This temperature rise will result in an increase of heat transport D_2O volume of approximately 5%, approximately 17 m^3.

The changes of fluid volume that occur in the heat transport system with power are much larger than at PNGS-A/B and the technique used to control system pressure is different.

The pressure is controlled by a pressurizer which acts as a cushion on the HT system and absorbs pressure transients. It is similar to a conventional steam drum, having a steam space and a liquid level, and has sufficient capacity to keep the HT pressure and inventory within the predetermined limits for any normal reactor power manoeuvring.

In normal operation, the HT system pressure is determined by the vapour pressure that exists in the pressurizer. If the HT pressure rises, steam bleed valves open on the pressurizer to relieve the vapour pressure and thereby reduce the HT pressure. The steam from the pressurizer is directed into the bleed condenser.

In the event of a low HT 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 the heat transport system.

Q8.13 Briefly explain how the heat transport fluid volume changes, when hot, from 0% to 100% power level at PNGS-A and BNGS-A.

Q8.14 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.

* * * * *

Pressure Increase in Heat Transport System

Suppose there is a large mismatch in thermal power, with the reactor input thermal power exceeding the thermal power being removed via the boilers. This imbalance will increase the average heat transport temperature resulting in an increase in volume of the HT fluid. HT pressure would also increase, although this increase would be offset by the action of the HT pressure control system.

In a system with a pressurizer (eg, Bruce and Darlington), the D_2O level in the pressurizer will increase significantly and the reactor control system response is, on high level, to initiate a reactor setback in an attempt to restore thermal power balance.

Note that high pressurizer level does not always signify high HT pressure. Abnormally low pressure in the pressurizer, eg, relief valve stuck open (as happened at Three Mile Island), would cause it to fill with coolant even if HT system pressure were low or normal.

For feed and bleed systems, the increase in volume will result in a significant increase in bleed condenser level and the reactor control system response is to initiate a reactor setback on high bleed condenser level in an attempt to restore thermal power balance.

Q8.15 (i) Explain how the pressurizer level could increase due to a thermal power mismatch and the likely response of the reactor control system.

(ii) Explain how the bleed condenser level could increase (in a feed and bleed pressure controlled system), due to a thermal power mismatch and the likely response of the reactor control system.

Q8.16 Describe the possible consequences of a thermal power mismatch where the heat sink exceeds the reactor power.

* * * * *

Pressure Reduction in Heat Transport System

We have looked at the protection that is designed to accommodate <u>high</u> pressures in the HT system.

<u>Low</u> pressures in the HT system could be indicative of any of the following situations:

(a) The inadvertent opening of a large steam reject/discharge valve resulting in a large mismatch in thermal power between the reactor and the steam generator.

(b) A faulty control system allowing an uncontrolled decrease in pressure.

(c) LOCA

Suppose the HT system was pressurized at 8.00 MPa(a) and the HT temperature at this pressure was 270°C.

How would you show the condition on a temperature/enthalpy diagram?

Q8.17 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.

* * * * *

Now, suppose we start to reduce the heat transport pressure by bleeding off some liquid whilst the temperature remains at 270°C.

Q8.18 Explain what happens when the heat transport pressure reaches and then falls below 5.5 MPa(a) when the initial temperature of the D_2O is 270°C.

* * * * *

Producing a large quantity of vapour in the HT system, such as occurs in a LOCA, results in several problems.

In reactivity terms, the presence of steam (vapour) forms a void (no D_2O liquid) with a consequent local reduction in neutron moderation (and absorption). For all our reactors, there is a positive reactivity effect associated with voids, which will cause reactor power to increase followed by subsequent action by the reactor regulating system or if overwhelmed, by the safety shutdown systems neutronic trips.

The most serious effect is on the heat transfer mechanism that is used to cool the fuel. In the channel, the boiling or production of vapour starts where the temperature of the fluid is highest and the pressure is lowest, ie, at the outlet of the fuel channel. The highest HT fluid temperatures occur at the fuel bundle sheathing.

Remember, in Module 1 we learned that heat removal from the fuel elements was by forced convection. A small amount of controlled boiling improved heat transfer through the vigorous action created by the vapour bubbles leaving the fuel sheath surface. However, excessive boiling led to formation of a vapour film on the sheath surface (dry out) and greatly reduced heat transfer.

The effect of this reduced heat transfer causes the temperature of the fuel elements to rise. As a result, the fuel sheath temperatures become higher.

The major problem is that in this situation, the fuel sheath temperature starts to rise above the normal 350° to 400°C. The Zircaloy 4 sheath loses considerable strength as its temperature rises above normal values. In addition, the already weakened sheath has increased stress imposed by the thermal expansion of the fuel and the increased internal pressure of fission product gases in the fuel. If fuel should melt there will be additional stress due to the volumetric expansion on melting. There is also a danger of molten fuel burning through the sheath on contact as its temperature is above the sheath melting point.

Before the melting point is reached, sheath failure will occur (due to expansion of the pellet); probably in the range 800°C to 1100°C, and the release of fission products into the HT circuit will occur.

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.

Q8.19 Explain why excessive coolant boiling is undesirable in the reactor.

* * * * *

Boiling in Fuel Channels not Designed to Boil

Boiling in the fuel channel may 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 flow rate. The only indication will be a channel outlet high temperature alarm.

If boiling of all or many of 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 boiling is a falling heat transport system pressure. A low pressure alarm alerts the control room operator so that remedial action may be taken.

Boiling in Fuel Channels Designed for Limited Boiling

Nucleate boiling may be designed to occur in the final section of the fuel channels when at full power. This is normally referred to as bulk boiling. In this situation, conditions will change at the channel outlet header as the reactor power is increased.

Each channel ΔT will increase with power until the saturation temperature for the HT pressure is reached. At this point, the D_2O will start to boil, initially at the channel outlet, and the *temperature will now stay constant*. *As the channel produces further* power, the temperature will not rise but more vapour will be produced progressing towards the channel inlet. If 3% boiling was designed to occur, then the fluid leaving the channel would be a mixture of 3% vapour and 97% liquid by weight.

Therefore, once saturation temperature is reached

(a) the only change with power will be the % of vapour leaving the channel, and

(b) the mass flow rate, as a rule of thumb, will decrease (for the same power) by the % increase in vapour. This decrease is due to the increased flow resistance in the channel due to the larger volumes of vapour.

Q8.20 Briefly explain how the HT fluid temperature and fluid quality change as increasing reactor power produces bulk boiling.

* * * * *

Loss of Coolant Accident (LOCA)

In this situation, the prime concern is that the reactor should be shutdown safely. This means the provision of cooling for the fuel at all times.

Any loss of coolant which results in the pressurizing system being unable to maintain pressure is defined as a LOCA. If pressure control can be maintained in the HT systems, it is considered a leak.

Small LOCA

In this situation the pressure in the heat transport system will fall gradually until the saturation pressure is reached. At this point, boiling in the channel occurs and the pressure is now determined by the temperature of the liquid which will be relatively stable.

The problem is now that the pressure transient will stabilize and the fuel sheath will become damaged due to the impaired 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 rapidly reduce the heat production of the reactor by a reactor trip and to initiate a rapid cooldown (known as "crash-cool") to reduce the HT temperature and therefore pressure to a value which will facilitate emergency core cooling.

Major LOCA

In a loss of coolant condition where the break in the Heat Transport System pressure boundary is massive, the drop in both temperature and pressure of the coolant will be very rapid. Consequently, the system will have already been "crash-cooled" by the massive leak and Emergency Coolant Injection may begin.

The Emergency Coolant Injection System (ECIS) 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.

The initial inventory of ECI water (light water) is injected into the core by high pressure gas or high pressure pumps depending on the station. A more detailed description of the general operation of ECIS as well as the differences at the various stations can be found in Reactor Boilers and Auxiliaries, Course 233.

In all stations fuel cooling is maintained in the recovery phase by recirculating the water discharged from the break by pumping it from low level sumps.

Indications of a Loss of Coolant

The single most important parameter associated with the detection of a LOCA is by definition, Heat Transport pressure.

Evidence of low HT pressure sustained over several minutes or low HT pressure AND evidence of the presence of high energy fluid within areas surrounding the HT system are used as indication of a likely LOCA and initiating auto actions for ECIS operation.

Q8.21 Explain two conditions which would result in channel boiling.

Q8.22 Explain, in general how a LOCA is detected.

Q8.23 Explain why, in the event of a LOCA, (small or large) it is necessary to establish Emergency Coolant Injection to the core.

Q8.24 How does a massive rupture in the heat transport system affect the rationale explained in Q8.23.

Q8.25 Explain the basic emergency core injection system at your station.

* * * * *

Heat Transport Thermosyphoning

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, a thermosyphon may be established.

The hot D_2O leaves the reactor outlet headers and is physically pushed up to the steam generator where it travels up one side and returns as cooler fluid, down the other side of the tube bundle, back to the reactor via the HT pump (pump is turbining).

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 HT system.

Thermosyphoning can only exist when the steam generator is at a lower temperature than the HT circuit and there is no excessive boiling in the HT circuit which would allow vapour to collect at the top of the tubes in the steam generator.

The temperature at the reactor outlet header is used to monitor the thermosyphon. If the HT temperature is rising towards the saturation value, vapour may be produced which may impair the thermosyphon. More heat must be removed from the HT system and this is achieved by lowering the temperature of the steam generator by removing more steam and thereby lowering the pressure. To maintain the viability of thermosyphoning, pressure control must be maintained at a normal setpoint. This will prevent boiling (and possible vapour locking) which would occur on loss of pressure.

Q8.26 Briefly explain how the HT thermosyphon is established and how ROH temperature is used as a datum for the control of the thermosyphon.

* * * * *

MODULE 8 - ANSWERS

Q8.1

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 HT pump. This heat is from the HT system.

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 (or maintenance cooling).

Q8.2

Limiting the temperature rise across a non-boiling fuel channel will ensure that fuel bundles are not subjected to conditions beyond their operating limits. Since channel power and mass flow rate determine the temperature rise across the channel, there must be a maximum allowable channel outlet temperature (and therefore temperature rise) which corresponds to the channel power at which high powered bundles approach their maximum operating limits.

For a boiling fuel channel, the channel outlet temperature is not useful for monitoring that channel/bundle power limits are not exceeded because as long as there is liquid present in the channel, the outlet temperature will be the saturation temperature.

Q8.3

For channels where boiling occurs, it is most important to ensure sufficient liquid is present to provide adequate fuel cooling. We do this by monitoring the amount of steam produced by either,

(a) Comparing volumetric flow rates at channel inlet and outlet for fully instrumented channels. The flow rates will be equal for no boiling and the outlet flow rate will exceed the inlet if boiling is occurring. The difference in flow rates is used to calculate the percentage of steam present.

(b) Using flux mapping in conjunction with bulk power measurements. Flux maps are prepared with the aid of computer simulations and measurements of flux at a large number of strategic locations in the core. Bulk thermal power is determined using a combination of boiler steam and feedwater flows and boiler temperature measurements.

Q8.4

From the text, we saw that channel power was determined by the flow rate and the change of enthalpy across the channel, ie,

$$Q = \dot{m} \times \text{Change of Enthalpy}$$

where Q is the channel power, and

$\dot{m}$ is the channel mass flow rate

The channel power remains constant and the channel flow rate decreases. In this event, the change in enthalpy must increase in direct proportion with the falling flow rate.

$$Q = \underset{\downarrow}{\dot{m}} \times \text{Change } \overset{\uparrow}{\text{of}} \text{ Enthalpy}$$

The change in enthalpy is the difference between channel outlet enthalpy and channel inlet enthalpy. However, the channel inlet enthalpy remains essentially constant. Thus, the only way that the change of enthalpy across the channel can rise, is for the channel exit enthalpy to rise.

Q8.5

As explained in the previous question, the temperature of the coolant at the outlet end of the channel will start to rise until it reaches 299°C which is the saturation temperature corresponding to 8.47 MPa(a). Boiling will start at the channel outlet and gradually progress down the channel until thermal equilibrium is reached, with the outlet temperature remaining at the saturation value.

Q8.6

At zero power hot, 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.

Q8.7

As seen in problem Q8.5, the steam generator temperature will be equal to the average heat transport temperature at zero reactor power with the systems fully warmed.

To transfer thermal energy from the HT system to the steam generator, a temperature difference must exist. The only way that this can happen is for the steam generator temperature to fall below the average HT temperature as power increases.

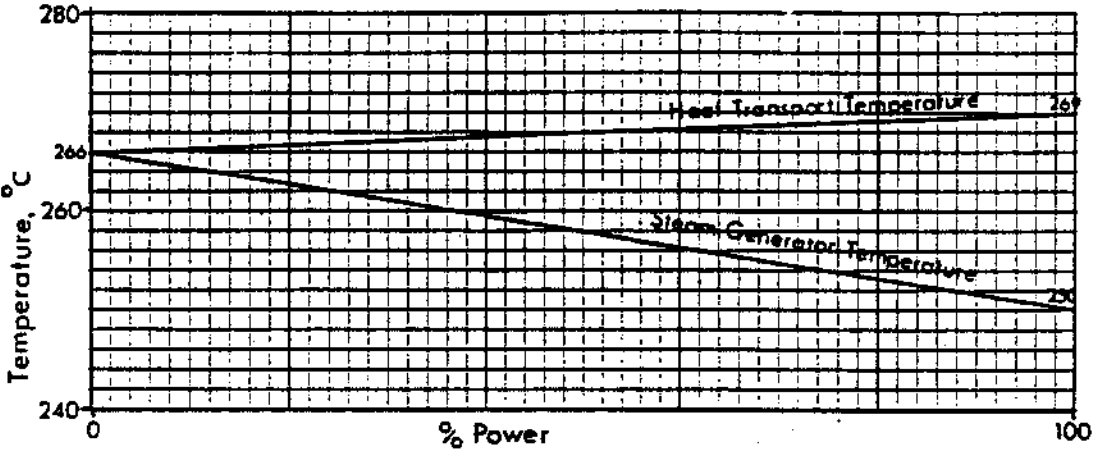


Figure 5
Temperature vs % Full Power

Q8.8

At zero power hot (fully warmed up) when the steam generator and reactor are at operating temperature, the average HT temperature and the steam generator temperature will be equal. If the steam generator pressure is 4.25 MPa(a), then the temperature is 254°C. At this condition, the average HT fluid temperature is also 254°C.

08.9

For a system with a pressurizer, 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 HT fluid and the steam generator. The average temperature of the heat transport fluid must be higher than that of the steam generator. This is shown in Figure 6 where the average HT temperature leaves the steam temperature at 254°C and rises to a higher value around 277°C.

The value of 277°C cannot be readily determined in this case because of reactor design - eg, inner and outer zones and external preheater.

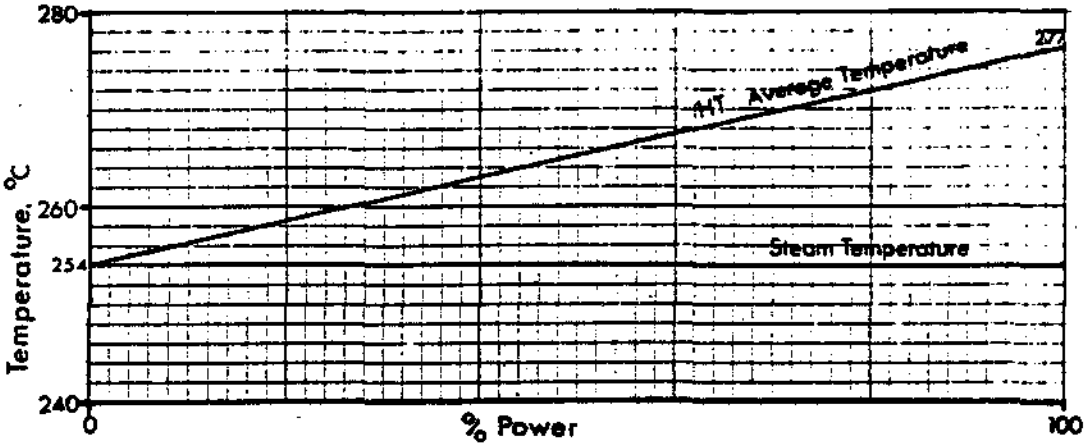


Figure 6
Temperature vs % Full Power

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 (see Figure 7).

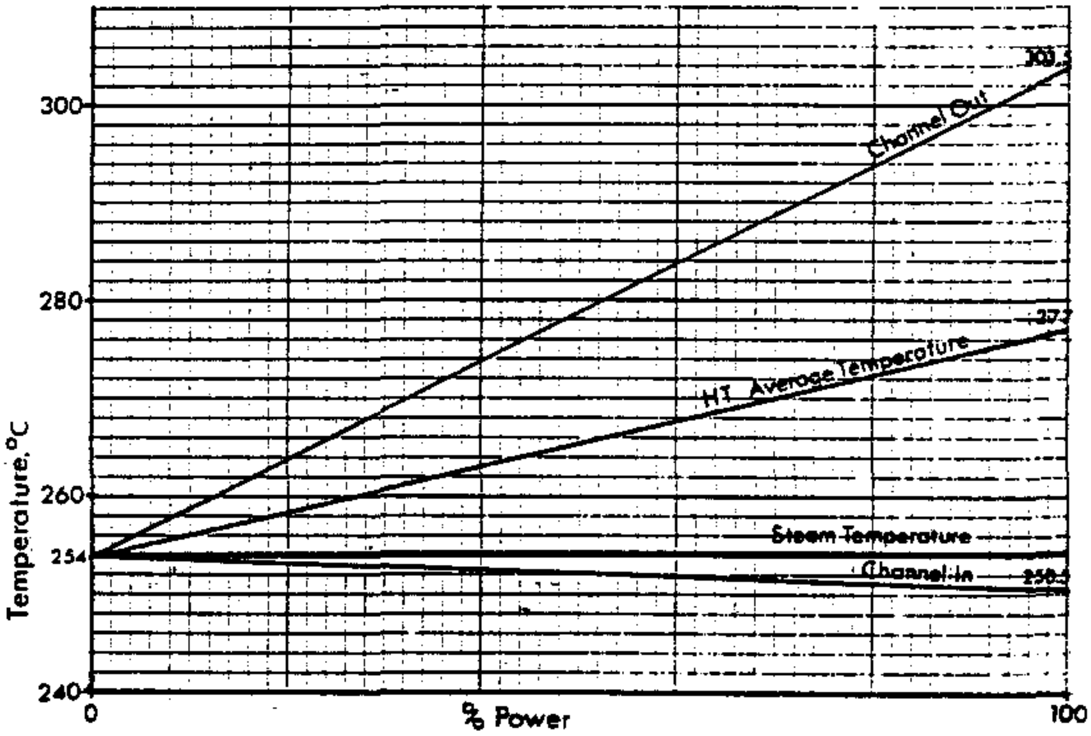


Figure 7
Temperature vs % Full Power

08.10

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, a thermal power mismatch occurs and the HT average temperature and pressure starts to rise.

If power is not reduced, boiler level will fall until tubes are uncovered and the heat transfer will be further impaired.

These conditions will both result in a massive thermal power mismatch as a result of having lost the major heat sink.

08.11

(a) Reactor power greater than available heat sink.

(b) Loss or impairment of HT coolant flow.

(c) Pressure control system malfunction allowing an uncontrolled increase in pressure

(d) Loss of feedwater supply causing an immediate loss of heat sink from the preheater section.

08.12

The two major problems of low HT pressure concern the effect vapour production within the D_2O has on the (1) Heat Transport Pumps, and the (2) Fuel in the Channel.

To avoid cavitation in the HT pumps, there is a minimum suction pressure below which pressure should not fall. This value of suction pressure depends upon the temperature of the heat transport D_2O. If cavitation persists over a sufficiently long period of time, pump damage and system damage may result. In addition to this effect, the flow through the pump will be reduced and this could result in an increase in HT temperature due to the reduction of flow through the reactor.

If the HT pressure drops to the saturation pressure corresponding to the HT temperature, vapour will be produced in the fuel channel. If large scale boiling 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 and the increase may produce fuel sheath failure and fuel damage.

08.13

At PNGS-A, the reactor design was such that the volume of the D_2O in the 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 compared to PNGS-A:

(a) The average HT temperature rises by some 27°C.

(b) Boiling is allowed to occur in some fuel channels.

As a result, there is a significant increase in HT fluid volume as the power is increased from 0% to 100%. The increase in fluid volume amounts to 17 m^3.

For the CANDU 600 the increase in fluid volume is nearly 12 m^3.

Q8.14

As we have already seen, the volumetric expansion of the HT fluid at PNGS-A and B, when at power, is not very large due to the HT average temperature being held about constant.

Control of the heat transport system pressure is effected by feeding D_2O into the HT circuit using the pressurizing pumps and by bleeding D_2O from the circuit at the HT pump suction headers. The shrink and swell of the HT system fluid is accommodated by the D_2O storage tank.

If low pressure exists in the HT 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 Bruce or Darlington, the change in HT fluid volume with power is much larger than that at PNGS-A and exceeds the rates of change which could be handled easily with a feed and bleed system alone.

The HT 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 HT 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 HT 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 HT pressure. A level control system associated with the pressurizer is used to ensure correct liquid level is maintained over the power range.

Q8.15

(a) Pressurizer System

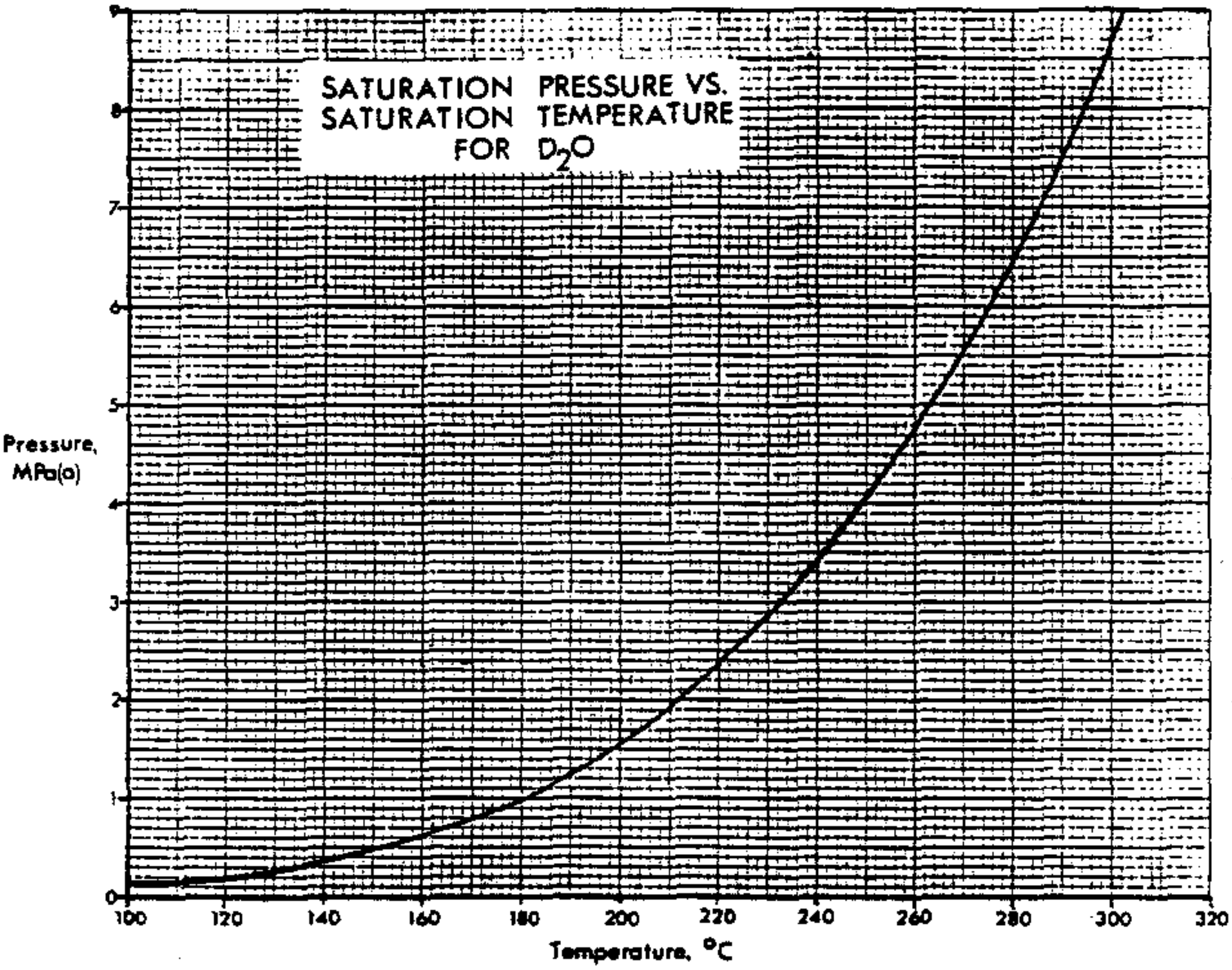
When the reactor power exceeds the available heat sink, the average HT temperature will increase, causing an increase in HT fluid volume. This will cause a sufficient increase in HT pressure to force D_2O into the pressurizer giving an increased level. On a very high level, a reactor setback is initiated to reduce reactor power in an attempt to restore thermal equilibrium.

(b) Feed and Bleed System

For a feed and bleed system, the bleed condenser level will increase due to the increased bleed initiated by the pressure control system. On a very high level, a reactor setback is initiated leading to a reduction in reactor power which may restore thermal equilibrium.

08.16

The heat-transport fluid will shrink at a greater rate than can be matched by the HT pressure control system and the temperature and pressure will fall. As soon as the pressure reaches the saturation value, the HT system will start to boil (boiling in the fuel channels.)

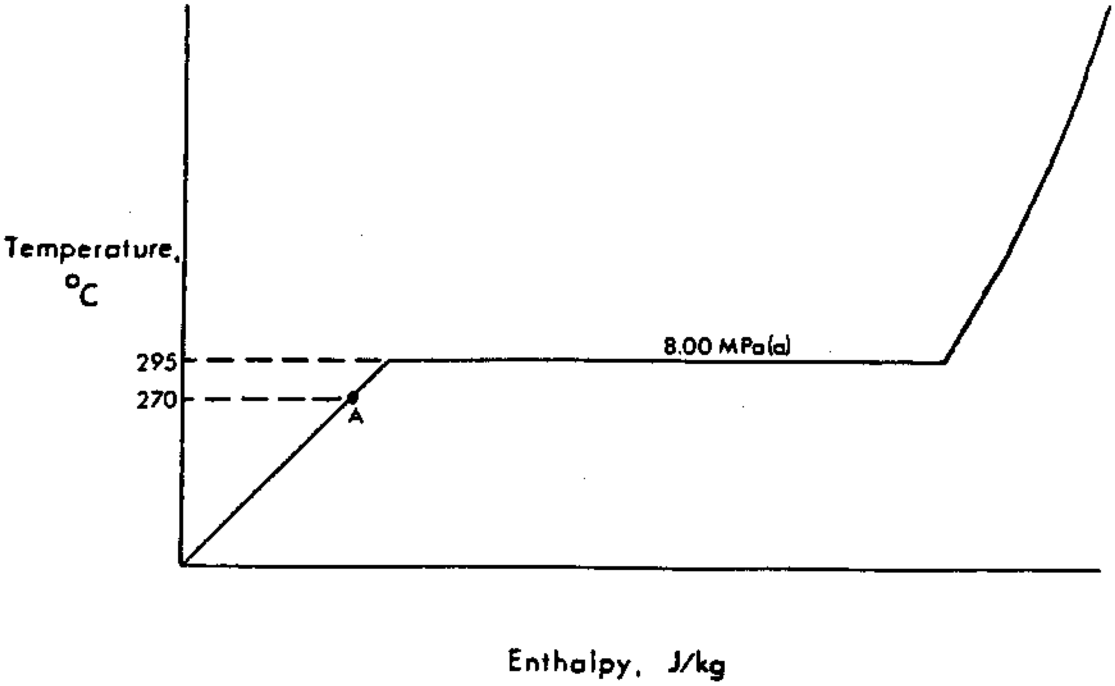


Saturation Pressure vs Saturation Temperature for D_2O
Figure 8

The graph of saturation pressure/temperature (see Figure 8) is useful to compare actual PHT pressure with the saturation pressure corresponding to the HT temperature. The actual HT pressure should always be higher than the saturation pressure.

If significant boiling does occur, heat will not be removed as effectively from the fuel and fuel temperature will rise. This in turn could lead to an increased risk of fuel failure and release of fission products into the coolant; a very undesirable outcome.

08.17

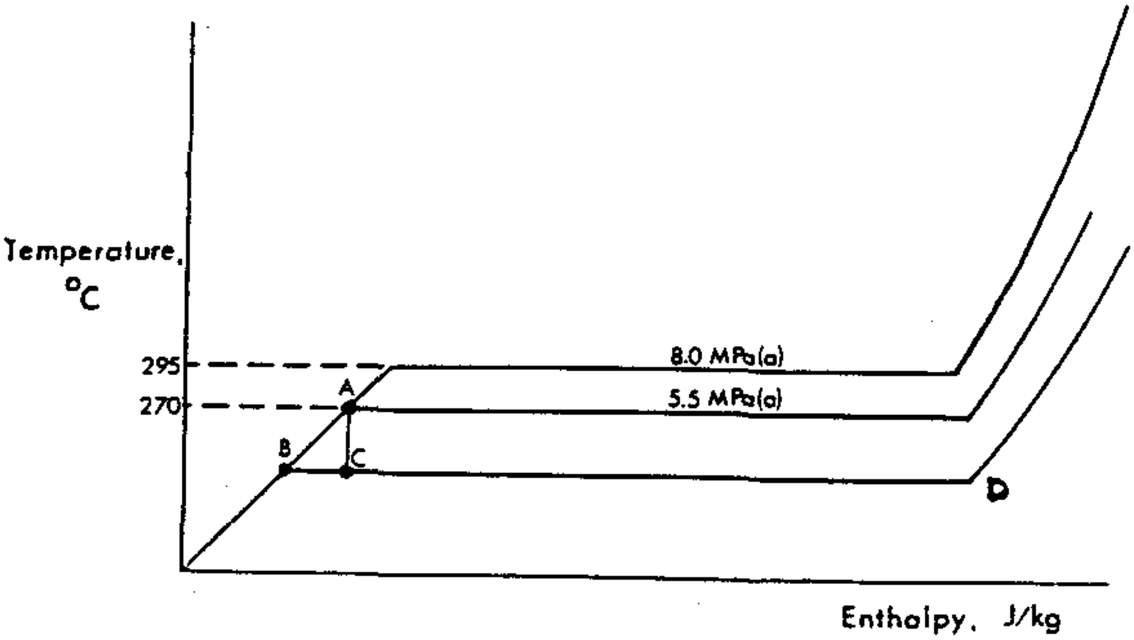


Temperature vs Enthalpy
Figure 9

At 8.1 MPa(g) (approximately) from steam tables, the saturation temperature is 295°C (see Figure 9). The actual temperature of the HT liquid is 270°C (Point A) which means that it is <u>subcooled</u> by 25°C.

08.18

When the pressure has fallen to 5.5 MPa(a), the corresponding saturation temperature is 270°C (see Figure 10, Point A). This is 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.



Temperature vs Enthalpy
Figure 10

The enthalpy of the fluid does not change. At point A, there is saturated liquid at a pressure of 5.5 MPa(g). If the pressure was to fall to a lower value, there would be a two-phase fluid. These two phases would be:

(a) Saturated liquid at point B.

(b) Vapour generated with specific enthalpy D. You can see that for saturated liquid, the specific enthalpy at B is less than that at A, as a consequence the fraction of vapour by mass is given by (B-C)/(B-D).

Q8.19

The main concern with excessive channel boiling is dry out and 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 zircaloy 4 has a melting point of around 1800°C, sheath failure is likely to occur between 800° to 1100°C.

Failure of the fuel sheath and the release of fission products into the HT system are major considerations that depend upon maintaining 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, occurring when the channel is boiling, could result in fuel melting if no action is taken.

08.20

When the liquid coolant has reached the saturation temperature and vapour is about to be produced, the indicated temperature rise will stop. From this point on, we have little idea of what is actually happening in the channel with respect to boiling.

As power is increased, more vapour is produced at a constant temperature and therefore, the channel ΔT is no longer an indication of channel power.

08.21

The two basic conditions which will result in channel boiling are:

(a) A sufficient reduction of coolant flow.

(b) A significant reduction in 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. Once vapour production starts, the indicated coolant temperature remains constant.

If the pressure falls to the saturation pressure corresponding to the temperature of the HT coolant, vapour production will again begin. 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 failures may go undetected.

08.22

(a) Low HT pressure for a prolonged period.

or

(b) Low HT pressure and evidence characteristic of hot HT coolant in areas surrounding the heat transport system.

08.23

If the loss of coolant is large enough that the HT system pressure starts to fall, then channel boiling will occur at the saturation pressure. When this happens, the rate of pressure decrease will reduce and the rate may even be zero if sufficient vapour is produced to match the leak rate.

At this point, vapour will fill the channel, boiling will occur and heat transfer from the fuel will be dramatically reduced.

The key and immediate objective is to re-establish fuel cooling as soon as possible which means that liquid must rewet the fuel bundles.

To achieve this, the reactor is crash cooled using the steam reject or boiler safety valves, depending on the station. This action significantly reduces HT system pressure and temperature in a few minutes.

As soon as HT pressure falls low enough, emergency coolant injection can commence. This provides another source of coolant if there is not enough HT D_2O left in the circuit to maintain cooling.

08.24

The basic difference between a small LOCA and a major LOCA is the time taken for the system pressure to fall. In a small LOCA with crash cooling, the time scale is in the order of minutes. With a major LOCA, the crash cooling 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 boiling of the coolant 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 degree 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 should not become unsafe due to loss of coolant.

08.26

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 HT pump, thus establishing coolant flow around the system.

The reactor outlet header temperature is monitored to ensure that it does not reach the saturation value when vapour would be produced. This 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.