125

HEAT & THERMODYNAMICS

MODULE B.6

BASICS

Heat & Thermodynamics

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BASICS

Course Objectives

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

   (a) Temperature.
   (b) Heat.

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

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

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

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

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

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

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

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

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

Enabling Objectives

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

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

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

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

BASICS

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

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

Temperature

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

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

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

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

HEAT

Heat is a Form of Energy

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

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

The Measurement of Heat

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

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

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

Specific Heat

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

Thus the units are:

kiloJoules per kilogram per degree Celsius.

Symbol - kJ/kg°C.

The symbol for specific heat is 'C'.

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

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

$$\text{kJ} = \text{kg} \times \text{kJ/kg°C} \times \text{°C}.$$

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

Example

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

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

kg x kJ/kg°C x °C

$= 14 \times 4.18 \times 34$

$= 1989.7$ kJ.

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

B.6.1

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

Enthalpy

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

The symbol for enthalpy is h.

The units are in kiloJoules/kilogram.

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

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

Temperature
Heat

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

WATER

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

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

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

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

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

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

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

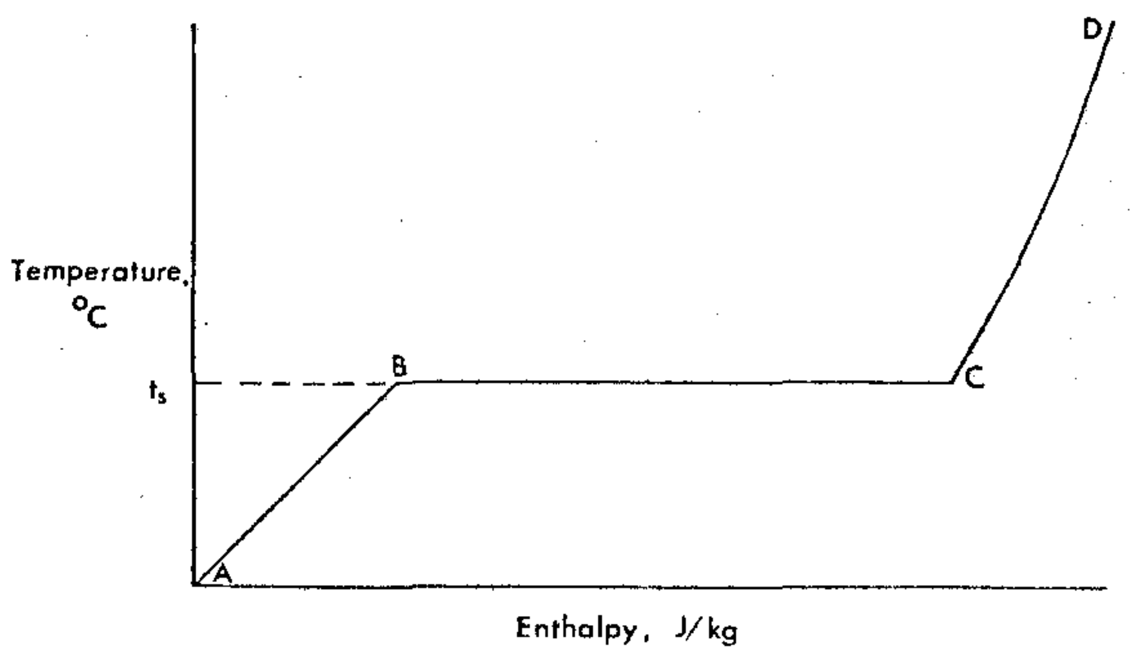

Fig. 6.1

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

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

Saturation Temperature

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

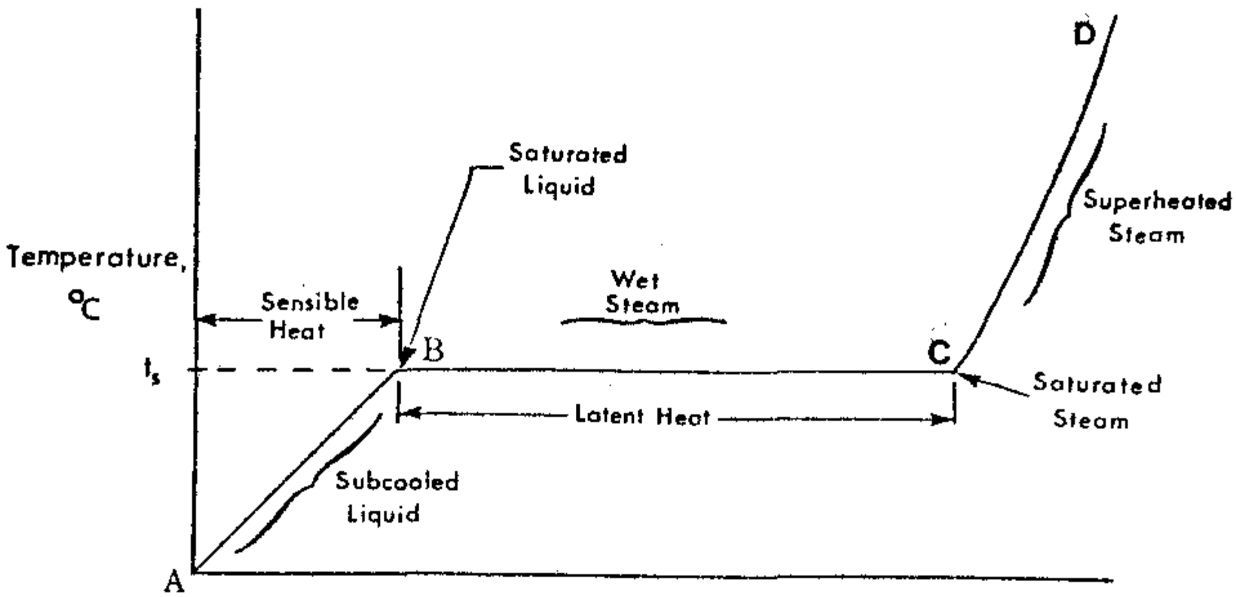

Fig. 6.2

Sensible Heat - Points A to B

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

Subcooled Liquid

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

Saturated Liquid - Point B

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

Saturated Steam - Point C

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

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

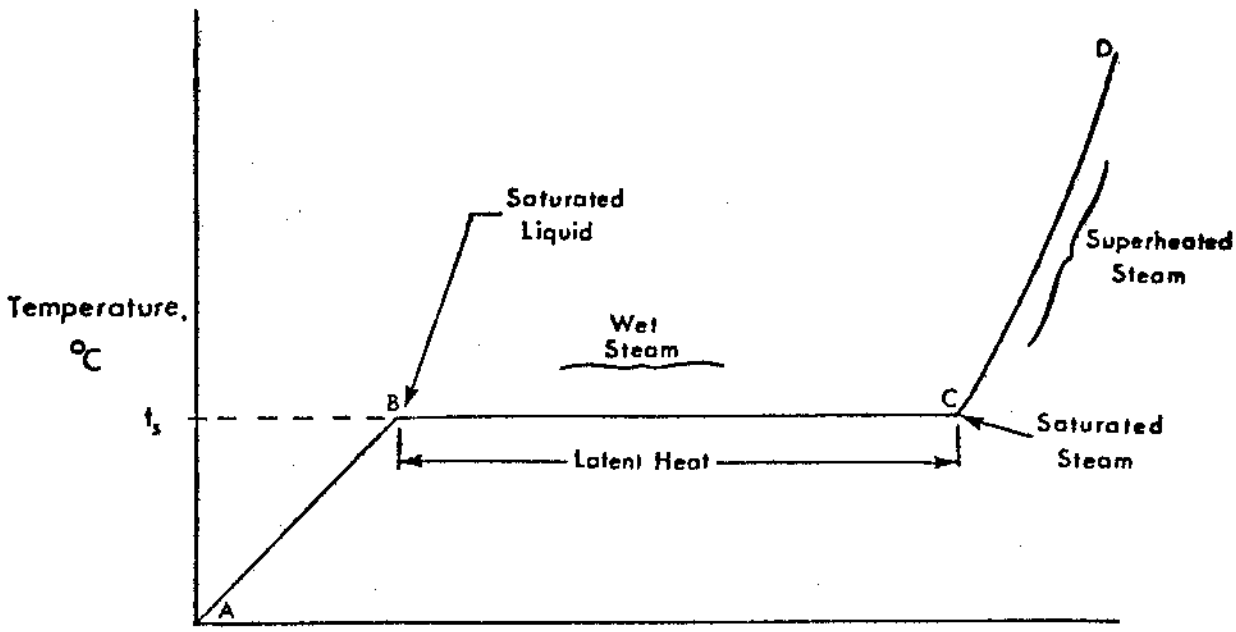

Fig. 6.3

Wet Steam - Between Points B and C

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

Superheated Steam - Between Points C and D

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

Heat Transfer Mechanisms

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

Conduction

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

Convection

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

There are two types of convection:

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

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

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

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

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B.6.2

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

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

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

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

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

B.6.3

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

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

Compressed Gas

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

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

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

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

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

B.6.4

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

B.6.5

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

Check your answers at the end of the course.

* * * * *

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

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

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

Storage of Gases

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

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

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

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

B.6.6

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

B.6.7

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

B.6.8

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

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

(a) progress to the next module, or

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

Answers

MODULE B.6

BASICS

B.6.1

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

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

Substituting the given values,

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

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

$$\Delta T = 11°\text{C.}$$

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

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

B.6.2

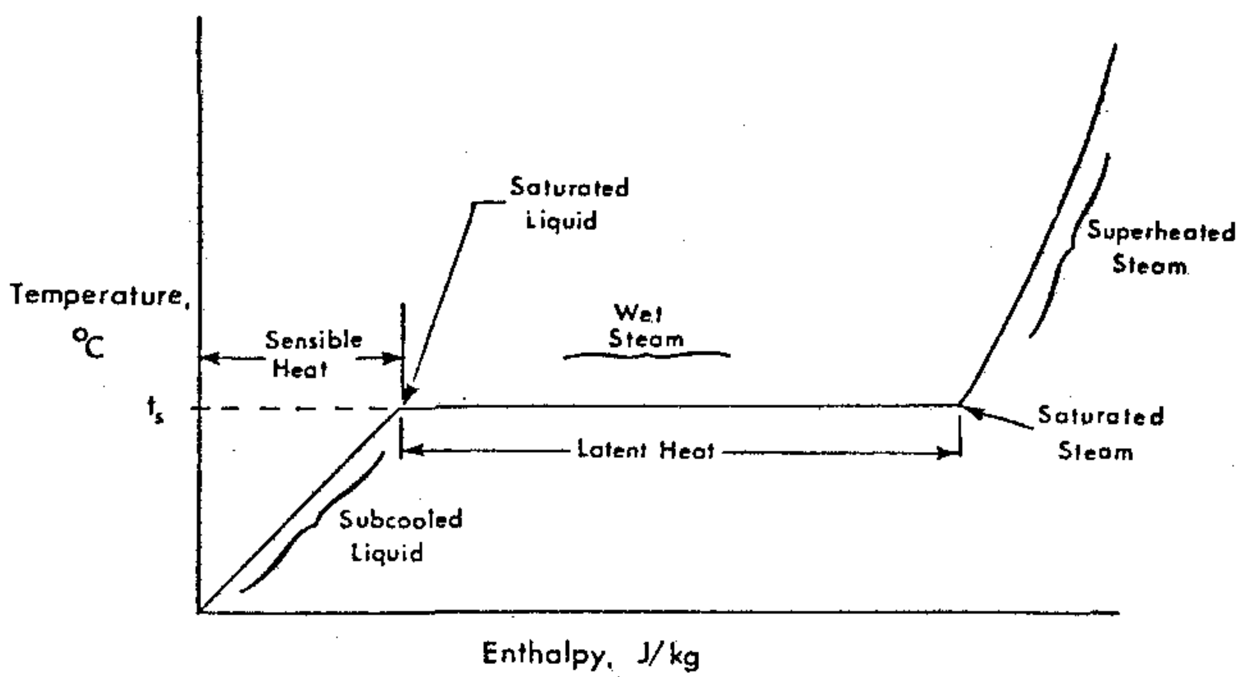

Fig. 6.2

B.6.3

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

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

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

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

B.6.4

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

B.6.5

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

B.6.6

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

B.6.7

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

B.6.8

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

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

* * * * *

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