PROPERTIES OF STEAM AND STEAM CYCLES

Before undertaking studies for the chiefs examination revision of work completed at 2nd Engineer level may be helpful.

(a) PHASES OF A FLUID

A substance may exist:

(i) wholly in the solid state
(ii) partly in the solid state and partly in the liquid state
(iii) wholly in the liquid state
(iv) partly in the liquid state and partly in the vapour or gaseous state
(v) wholly in the vapour or gaseous state

Thermodynamically, a substance in the solid state has no significance as a "working fluid" in a heat engine, so we are principally concerned only with the properties of liquids, vapours and gases.

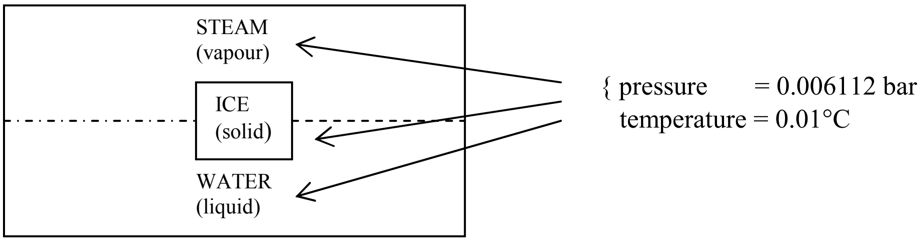
A substance will exist in the liquid state only if its temperature is below a specific value, called the "saturation temperature" or "boiling point", which depends upon the pressure to which the liquid is subjected.

It will exist as a mixture of liquid and vapour if its temperature is equal to the saturation temperature and if insufficient energy has been absorbed to effect complete evaporation of the liquid.

If the substance exists at any temperature above the saturation temperature corresponding to the pressure, it will be wholly in the gaseous state and is then referred to as a "superheated" or "unsaturated" vapour. A vapour, unlike a gas, does not exist in a free state but must be generated from its liquid state. Although it may be regarded as a fluid in the gaseous state, in practice its temperature is not usually far removed from its saturation temperature. Hence, when it is cooled, or expanded in an engine, it will probably condense (or partially condense) to the liquid state. On the other hand a fluid such as air would remain in the gaseous state even when cooled or expanded through a considerable temperature range.

The "triple point" is the only condition where the three phases, or states, of a substance (namely solid, liquid and vapour) can co-exist in equilibrium. At any other point there can only be a maximum of two phases in equilibrium.

In the particular case of ice, water and steam, the "triple point" condition is a temperature of 0.01°C and a pressure of 0.006112 bar, viz:



(b) DEFINITIONS

Saturation temperature is the temperature, at a given pressure, at which the liquid and vapour phases are in equilibrium. It corresponds to the boiling point and is, therefore, the temperature at which the evaporation of the liquid, or condensation of the vapour, occurs. It follows that the saturation temperature is also the maximum temperature at which a liquid can exist at a given pressure.

Saturation pressure is the pressure corresponding to a given saturation temperature.

A saturated liquid is a liquid which exists at the saturation temperature corresponding to a given pressure.

An unsaturated or undercooled liquid is a liquid existing at a temperature which is below the saturation temperature at a given pressure.

A wet saturated vapour is a mixture of liquid and vapour existing at the saturation temperature corresponding to a given pressure. Generally, such a mixture is more commonly referred to as a “wet vapour”.

Dry saturated vapour is vapour (no liquid present) which exists at the saturation temperature corresponding to a given pressure.

Unsaturated or superheated vapour is vapour existing at a temperature which is above its saturation temperature at a given pressure.

The degree of superheat is the difference in temperature between the temperature of a superheated vapour and the saturation temperature at a given pressure.

In order to superheat a vapour, the saturated vapour must be taken away from direct contact with the liquid from which it was generated, and must then be heated externally to the superheated state.

In the case of a wet saturated vapour, the dryness fraction (x) expresses the “quality” of the mixture i.e. the proportion of dry vapour in the mixture of dry vapour and liquid.

$$\text{i.e. dryness fraction} = x = \frac{\text{mass of dry vapour}}{\text{mass of vapour} \sim \text{liquid mixture}}$$

e.g. if wet vapour of total mass 1 kg has a dry vapour content of mass 0.9 kg then:

$$\text{dryness fraction} = x = \frac{0.9\text{ kg}}{1\text{ kg}} = 0.9$$, and the liquid content must then be

$$= (1 - x) = 0.1\text{ kg}$$

Thus, if 100 kg of wet steam has a dryness fraction of 0.85, then:

Mass of dry vapour present = $0.85 \times 100 = 85$ kg
And mass of liquid present = $(1 - 0.85) \times 100 = 15$ kg

[Ex 1]

Complete the following problem:

The mass of dry vapour in a wet vapour sample is 2.1 kg and the liquid content amounts to 0.9 kg. Estimate the dryness fraction of the wet vapour.

Mass of liquid in the mixture =

Mass of dry vapour in mixture =

∴ Total mass of wet vapour =

∴ Dryness fraction, x = ______________

= ………………… Ans

There are, of course, many substances which co-exist in both the liquid and vapour phases as they undergo processes in direct and reversed engine cycles. The most common vapour which is used as a working fluid in vapour power plants is, without doubt, steam. Mercury, as well as steam, is the working fluid which is used in some binary vapour power cycles and freon and ammonia are substances used in vapour-compression refrigeration cycles, (i.e. reversed engine cycles).

Let us now direct our study, more specifically, to the generation of steam and to the properties of steam and water.

(c) FORMATION OF SATURATED STEAM FROM DATUM CONDITIONS

In a boiler, steam is generated from water by the energy released during the combustion of fuel in the boiler furnace. Wet, dry saturated or superheated steam may be produced and continuous process of steam generation from water is essentially a flow process.

In considering the energy changes during such a flow process, it is necessary that some arbitrary datum is chosen in order that absolute energy values may be compiled and energy changes evaluated. As a consequence, the datum chosen for energy values of steam and water is the aforementioned "triple point" condition (0.01°C, 0.006112 bar). At this datum condition, the internal energy of water is deemed to be zero, i.e. $u_o = 0$.

Consider then, in the context of a flow process, the stage by stage formation of unit mass of saturated steam from unit mass of water at the triple point. (N.B. kinetic and potential energy changes are small enough to be ignored):

(i) At the datum, the water is at pressure $p_o = 0.006112$ bar, temperature $t_o = 0.01$°C and specific volume $v_o = 0.001\ m^3/kg$.

By definition, the internal energy of the water, $u_o = 0$
Since enthalpy = internal energy + flow energy

$$\begin{aligned} \text{i.e.} \quad h &= u + pV \text{ (refer to 2C (14)11)} \\ h_o &= u_o + p_o V_o \\ &= 0 + 0.006112 \times 10^2 \times 0.001 \\ &= 0 + 0.0006112 \\ &= 0.0006112 \text{ kJ/kg (negligible)} \\ \text{i.e.} \quad h_o &= 0 \end{aligned}$$

(ii) The feed pump now compresses the water from pressure p_o to final pressure p at constant volume V_o.

$$\begin{aligned} \therefore \text{ pump work transferred} &= W_{in} \\ &= (p - p_o)\, V_o \\ \therefore \quad W_{in} &= p\, V_o, \text{ since } p_o V_o = 0 \end{aligned}$$

(iii) Heat energy is now transferred to this high pressure water to raise the temperature from t_o up to saturation temperature t. In practice this <u>sensible heat</u> supply is affected partly in feed heaters and partly in the boiler itself.

Let the specific internal energy increase from u_o to u_f and let the specific volume of the water increase from V_o to V_f. Then:

$$\begin{aligned} \text{Sensible heat transfer} &= Q_{in} \\ &= \Delta u + w \\ &= (u_f - u_o) + p(V_f - V_o) \\ &= u_f + pV_f - pV_o, \text{ (since } u_o = 0) \end{aligned}$$

(N.B. u_f is referred to as "the specific internal energy of saturated water")

Thus the energy added to produce 1 kg of saturated water at pressure p, saturation temperature t, from 1 kg of water at the triple point:

$$\begin{aligned} &= \text{pump work} + \text{sensible heat transfer} \\ &= pV_o + u_f + pV_f - pV_o \end{aligned}$$

$= \quad u_f + pV_f$

$= \quad h_f$, by definition

(N.B. h_f is referred to as "the specific enthalpy of saturated water")

(iv) As heating continues in the boiler, the 1 kg of saturated water will eventually be converted into 1 kg of dry saturated steam. During this period the pressure "p" and the temperature "t" will remain constant. Assuming that evaporation is complete (i.e. the 1 kg of steam produced is dry saturated), that the relatively small specific volume of the saturated water, V_f, is considerably increased to that of dry saturated steam, Vg, and that the specific internal energy of the saturated water, u_f, is increased to that of the dry saturated steam, u_g, then:

$$\begin{aligned}
\text{Latent heat transfer} &= Q_{in} \\
&= \Delta u + W \\
&= (u_g - u_f) + p(Vg - V_f) \\
&= (u_g + pV_g) - (u_f + pV_f) \\
&= h_g - h_f \\
&= h_{fg}
\end{aligned}$$

(N.B. h_{fg} (= h_g - h_f), is referred to as "the specific enthalpy evaporation")

Thus, the energy added to produce 1 kg of dry saturated steam at pressure p, saturation temperature t, from 1 kg of water at the triple point

= (pump work + sensible heat transfer) + latent heat transfer

$= \quad h_f + h_{fg}$

$= \quad h_g$

(N.B. h_g (= h_f + h_{fg}) is referred to as "the specific enthalpy of dry saturated steam")

(v) If, however, during the conversion of 1 kg of saturated water into saturated steam, evaporation is incomplete, then the steam so-formed is said to be "wet" since there will be some unevaporated water particles remaining in suspension in the dry vapour.

If the dryness fraction of this wet steam is x, then:

Mass of dry vapour = x kg
and mass of water present = (1 – x) kg, thus only x kg of water has received latent heat transfer.

This means that the energy added to produce 1 kg of wet steam, of dryness x, at pressure p, saturation temperature t, from 1 kg of water at the triple point

= (pump work + sensible heat transfer) + latent heat transfer

$= \quad h_f + x\,h_{fg}$

= h

(N.B. h(= h_f + x h_{fg}) is referred to as “the specific enthalpy of wet steam)

Note also that, since x is always less than unit, then “h” must always be less than “h_g” .

The foregoing notes on the stage by stage formation of saturated steam from the triple point state may, perhaps, be better understood by referring to the pictorial representation depicted in Fig 1

FIGURE 1 on Page 95

(d) SPECIFIC VOLUME OF WET STEAM

Since wet steam consists of a mixture of dry vapour and water, then the specific volume of wet steam, dryness x, will be given by:

v = volume of x kg of dry vapour + volume of (1 – x) kg of saturated water

= $x v_g + (1 - x) v_f$

In very many cases the volume of the liquid part of the mixture, namely (1 – x) v_f is exceedingly small compared with the dry vapour part, x v_g, and may be neglected without incurring any appreciable error. Thus, for a wet vapour, we may write that, approximately:

$v = x v_g$

The student should note that energy symbols are given the following subscripts:

f ………………….. for a saturated liquid
e.g. v_f denotes the specific volume of saturated water

g ………………….. for a saturated vapour
e.g u_g denotes the specific internal energy of dry saturated steam

fg ………………….. for phase change from liquid to vapour or vice versa
e.g. h_{fg} denotes the specific enthalpy of evaporation

(e) STEAM TABLES

The actual values of the specific energy terms for saturated water and steam, at different saturation pressures and temperatures, dealt with fully in section © above, are conveniently tabulated in many and varied forms. The set of steam tables used in this course is “Thermodynamic and Transport Properties of Fluids”, arranged by “Mayhew and Rogers” and published by Basil Blackwell, and it is assumed that the student has a set of these tables available.

Pages 2 to 5, inclusive, show tabulated values for saturated water and steam whilst pages 6 to 8, inclusive, give values for superheated steam.

For our present level of study only pages 2 to 5, inclusive, involving properties of saturated steam and water are considered in depth and the thermodynamic property "entropy" (denoted by "S") needs to be considered. for the C/E syllabus only (see later)

By way of explanation, let us consider the bottom horizontal column on page 4 of the steam tables. This is depicted in the extract shown in Fig 2 below:

Fig 2 Saturated Water and Steam

p	t_s	V_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
1.0										
40	250.3	0.04977	1082	2602	1087	1714	2801	____	see later	_____

Reading horizontally, from left to right, and noting the meaning of the symbols which head each vertical column, we deduce that:

At an absolute pressure (p) of 40 bar:

The saturation temperature (t_s) of steam and water is	250.3°C
The specific volume (V_g) of dry saturated steam is	0.04977 m^3/kg
The specific internal energy of saturated water (u_f) is	1082 kJ/kg
The specific internal energy of dry saturated steam (u_g) is	2602 kJ/kg
The specific enthalpy of saturated water (h_f) is	1087 kJ/kg
The specific enthalpy of evaporation (h_{fg}) is	1714 kJ/kg
And the specific enthalpy of dry saturated steam (h_g) is	2801 kJ/kg

Some important points to note are as follows:

(i) when it is stated that the specific enthalpy of dry saturated steam, at an absolute pressure of 40 bar, is 2801 kJ/kg, what is meant is that 2801 kJ of energy must be supplied to 1 kg of water at the triple point (i.e. at 0.006112 bar, 0.01°C) in order to produce 1 kg of dry saturated steam at 40 bar, 250.3°C.

(ii) as "p" and "t" increase, "u_f" and "h_f" increase but "h_{fg}" decreases.

(iii) at any pressure, $h_f + h_{fg} = h_g$

(iv) although "u_{fg}" values are not tabulated, they may be determined from:

$$u_f = u_g - u_f$$

e.g. at 40 bar pressure, $u_{fg} = 2602 - 1082 = 1520$ kJ/kg

(v) on page 2, the first vertical column lists exact temperatures (t) (up to 100°C) corresponding to saturation pressures (p_s), whilst on pages 3, 4 and 5 the first vertical column gives absolute pressures (p) corresponding to saturation temperatures (t_s)

e.g. with reference to the steam tables, verify the following statements:

the specific enthalpy of saturated water (h_f) at 26°C = 108.9 kJ/kg
(thus the enthalpy of 5 kg of saturated water at 26°C = 108.9 x 5 = 544.5 kJ)
the specific enthalpy of dry saturated steam (h_g) at 2.7 bar = 2720 kJ/kg
the specific volume of dry saturated steam (V_g) at 220 bar = 0.00368 m^3/kg
and at 8°C = 121.0 m^3/kg

(thus the volume of 1000 kg of dry saturated steam at 220 bar = 3.68 m^3)
the saturation temperature (t_s) at a pressure of 180 bar = 357.0 °C
and at a pressure of 0.1 bar = 45.8 °C
and at a pressure of 0.02982 bar = 24 °C
the specific enthalpy of evaporation (h_{fg}) at 19 bar = 1901 kJ/kg
and at 19 °C = 2456 kJ/kg
the specific internal energy of evaporation (u_{fg}) at 150 bar
= $u_g - u_f$ = 2456 – 1585 = 871 kJ/kg

[Ex 2]

With reference to the steam tables, write down the following values, stating clearly the units involved:

The specific enthalpy of saturated water at 0.075 bar = h_f = ………..
The saturation pressure corresponding to a temperature of 10°C = p_s = ………..
The saturation temperature corresponding to a pressure of 0.7 bar = t_s = ………..
The specific volume of dry saturated steam at 2.5 bar = V_g = ………..
The volume of 0.5 kg of dry saturated steam at 2.5 bar = = ………..
The specific enthalpy of evaporation at 221.2 bar = h_{fg} = ………..
The specific internal energy of dry saturated steam at 13°C = u_g = ………..
The specific internal energy of saturated water at 150 bar = u_f = ………..
The internal energy of evaporation of 3 kg of steam at 1 bar = 3 x ………..
= …………

e.g. determine the enthalpy of 4 kg of saturated steam at 20 bar pressure if the steam is

(i) dry
(ii) wet, with a dryness fraction of 0.8

(i) specific enthalpy of dry saturated steam at 20 bar = h_g = 2799 kJ/kg
∴ enthalpy of 4 kg = 4 x 2799 = 11.196 kJ Ans

(ii) specific enthalpy of wet steam at 20 bar = $h_f + x\,h_{fg}$
= 909 + (0.8 x 1890)
= 909 + 1512
= 2421 kJ/kg
∴ enthalpy of 4 kg = 4 x 2421 = 9684 kJ Ans

Note that the specific enthalpy of wet steam is always less than that of dry saturated steam at the same pressure. This is because, in the case of wet steam of dryness x, only x kg of dry vapour is produced and (1 – x) kg remains unevaporated as saturated water. Note also that the specific enthalpy of the wet steam sample given above could have been determined as follows:

Since dryness of steam is 0.8, this means that 1 kg of the wet steam will consist of 0.8 kg of dry vapour and 0.2 kg of saturated water at 20 bar pressure.

Thus:

Specific enthalpy of dry vapour = $x \;X\; h_g$
= 0.8 x 2799
= 2239.2 kJ/kg
and specific enthalpy of saturated liquid = $(1 – x)$ x h_f
= 0.2 x 909
= 181.8 kJ/kg
∴ specific enthalpy of wet steam = specific enthalpy of dry vapour + specific enthalpy of saturated liquid
= 2239.2 + 181.8
= <u>2421 kJ/kg</u> (as before)

[Ex 3]

Complete the following problem:

Determine the enthalpy, internal energy and volume of 5 kg of wet steam of dryness 0.7 at a pressure of 2.2 bar. State also the temperature of this steam.

N.B. It is usually more convenient to evaluate specific values first and then multiply by the mass involved as a final step viz:

From steam tables (page 4)

Specific enthalpy = $h_f + x h_{fg}$

i.e. h =

= ………..k J/kg

∴ enthalpy of steam sample = specific enthalpy (kJ/kg) x mass (kg)

=

= ……….. kJ Ans

specific internal energy = $u_f + x u_{fg}$

or u = $(x \times u_g) + (1 - x) u_f$

=

= ……….. kJ/kg

∴ internal energy =

= ……….. kJ Ans

specific volume = $x v_g$

=

= ……….. m^3/kg

∴ volume of steam sample =

= ……….. m^3 Ans

the temperature of this saturated steam will, of course, be the saturation temperature (t_s) corresponding to a pressure of 2.2 bar

= ……….. °C Ans

(f) TRUE AND APPROXIMATE VOLUMES OF WET STEAM

Earlier in this lesson it was stated that the specific volume of wet steam, of dryness x, is given by:

$$V = x v_g + (1 - x) v_f$$

By ignoring the volume of water, we reduced the above expression to:

V = x v_g (approximately)

Let us now investigate this approximation quantitatively by considering, say, a saturated steam sample, dryness 0.85, at atmospheric pressures, namely 1.01325 bar.

Per 1 kg of wet steam

Mass of dry vapour = 0.85 kg
And mass of saturated water = 1 - 0.85 = 0.15 kg

From steam tables, page 2

Specific volume of dry vapour = v_g at 1.01325 bar (t = 100 °C)

= 1.673 m^3/kg

Now in order to find the specific volume of saturated water (v_f) we can refer to page 10 of the steam tables.

Looking down the vertical column headed "p" we notice that for the listed pressure of 1.01325 bar (t = 100 °C), the specific volume of saturated water, multiplied by 10^2, (i.e. $v_f \times 10^2$) is listed as 0.1044 m^3.

Thus, $v_f = 0.144 \times 10^{-2} = 0.001044$ m^3/kg

Hence the true volume of the 1 kg of wet steam sample given

$= x\,v_g + (1 - x)\,v_f$

$= (0.85 \times 1.673) + (0.15 \times 0.001044)$

$= 1.422 + 0.0001566$

$= 1.4221566$ m^3 Ans

If now we ignore the very small volume of water, then we may state that the approximate volume of the wet steam sample is:

$= x\,v_g$

$= 1.422$ m^3/kg Ans

Note that the percentage error incurred, in using the approximate volume instead of the actual volume, is only in the order of:

$$\frac{0.0001566}{1.4221566} \times 100\% = 0.011\%$$

Although this percentage approximation will obviously vary with pressure, temperature and dryness, nevertheless, for most practical cases, the error involved is very small and certainly for our purposes we may use the approximate expression:

Specific volume of wet steam = x v_g

[Ex 4]

Complete the following problem:

Calculate the volume of 2.5 kg of saturated steam, of dryness 0.6, at a saturation temperature of 230 °C.

(i) ignoring the volume of water
(ii) taking the volume of water into account

What percentage error is incurred in using the approximate volume?

What is the pressure of the steam?

<u>Per 1 kg of wet steam</u>

Mass of dry vapour = ... kg

∴ mass of water = ... = ... kg

Specific volume of dry vapour = v_g at 230 °C

= .... m^3/kg

Specific volume of water = v_f at 230 °C

= .... m^3/kg

∴ approximate specific volume of wet steam = ...

= .... m^3/kg

∴ approximate volume of 2.5 kg of wet steam = 2.5 x ....

= .... m^3 Ans

true specific volume of wet steam = ... + ...

= .... + ...

= .... m^3/kg

∴ true volume of 2.5 kg of wet steam = 2.5 x ....

= ……….. m^3 Ans

hence: percentage error incurred = ………..

= ……….. % Ans

Form page 4 of steam tables, for a saturation temperature of 23.0 °C, the pressure = ……….. bar Ans

(g) FORMATION OF SATURATED STEAM FROM WATER AT t°C

As we have learned in sections (c) and (e) of this lesson, if we have 1 kg of water at its datum condition (i.e. at 0.006112 bar and 0.01 °C) and we then supply heat energy to this water to produce saturated steam, then the amount of heat energy to be supplied to produce 1 kg of saturated steam (at some given pressure "p") will be:

= $h_f + x\ h_{fg}$ ……….. (if the steam produced is wet)
= h_g ………………... (if the steam produced is dry)

the values of h_f, h_{fg} and h_g being able to be read directly from the steam tables.

If however, we have 1 kg of water at some temperature above 0.01 °C (say t °C) then obviously the amount of heat energy to be supplied to produce 1 kg of saturated steam will be less by an amount equal to the enthalpy content of the water at t °C.

e.g. Estimate the amount of heat energy to be supplied to 10 kg of water in order to produce 10 kg of steam of dryness 0.9 and at a pressure of 7 bar, if the water is initially at:

(i) 0.01 °C
(ii) 130 °C
(iii) 165 °C

(i) Water initially at datum conditions (0.01 °C)

Specific enthalpy of water at 0.01 °C = h_f at 0.01 °C

= 0 (zero) kJ/kg

Specific enthalpy of the wet steam produced = $h_f + x\ h_{fg}$, at 7 bar

= 697 + (0.9 x 2067)

= 2557 kJ/kg

∴ heat energy needed to be supplied = enthalpy of steam - enthalpy of water

= 2557 - 0

= 2557 kJ/kg

= 2557 x 10 = 25570 kJ

(ii) Water initially at 130 °C

Specific enthalpy of water at 130 °C = h_f at 130 °C

= 546 kJ/kg (steam tables, page 4)

Specific enthalpy of wet steam produced = 2557 kJ/kg

∴ heat energy needed to be supplied = 2557 - 546

= 2011 kJ/kg

= 2011 x 10 = 20110 kJ

(iii) Water initially at 165 °C

Specific enthalpy of water at 165 °C = h_f at 165 °C

= 697 kJ/kg

Specific enthalpy of wet steam produced = 2557 kJ/kg

∴ heat energy needed to be supplied = 2557 - 697

= 1860 kJ/kg

= 1860 x 10 = 18600 kJ

The following points should be noted:

(1) The higher the temperature of the water, the less heat energy is needed to produce the given steam. This is one of the reasons why feed heating is employed in a steam power plant.

(2) The approximate values of specific enthalpy in the feed water may have been estimated in the following manner:

Case (ii)

Specific enthalpy of water at datum conditions (t = 0.001 °C)

= 0 (zero) kJ/kg

heat required to raise the temperature of 1 kg of water from 0 °C to 130 °C

= mass x specific heat x temp. rise

= 1 x 4.1868 x (130 - 0)

= 4.1868 x 130

= 544 kJ/kg

∴ specific enthalpy of water at 130 °C = 544 - 0

= 544 kJ/kg Ans (cf. 546 kJ/kg)

Case (ii)

Heat required to raise the temperature of 1 kg of water from 0 °C to 165 °C

= 1 x 4.1868 x (165 - 0)

= 4.1868 x 165

= 691 kJ/kg

∴ specific enthalpy of water at 130 °C = 691 kJ/kg Ans

N.B. The enthalpies determined in this manner are only approximate since it is assumed that the specific heat capacity of water, namely 4.1868 kJ/kg K, remains constant at all pressures and temperatures. In fact the specific heat capacity of water, like that of most liquids, gases and vapours, varies quite considerably as pressures and temperatures change.

Consequently, it is more accurate, more convenient and quicker to use the table values as shown (h_f) for the specific enthalpy of saturated and unsaturated water.

(3) In case (iii) it should be noted that at 7 bar pressure, the saturation temperature is 165 °C which is the quoted temperature of the water. In this case, therefore, only latent heat is being supplied to the water to produce the wet steam.

i.e. heat energy needed to be supplied = x h_{fg}, at bar pressure

= 0.9 x 2067

= 1860 kJ/kg Ans (QED)

[Ex 5]

Complete the following problem:

Calculate the heat energy required in each of the following cases:

(i) to produce 5 kg of dss at 15 bar pressure from water at 118.6 °C
(ii) to produce 8 kg of saturated steam, 15% wet, at 32 bar from saturated water at 4 bar.

(i) Specific enthalpy of dss at 15 bar = h_g at 15 bar

= ………… kJ/kg

Specific enthalpy of water at 118.6 °C = h_f at 118.6 °C

= ………… kJ/kg

∴ heat energy required = …………

= ………… kJ/kg

= …………x…………

= kJ Ans

(ii) Dryness fraction of steam 15% wet = …………

Specific enthalpy of wet steam at 32 bar = $h_f + x\,h_{fg}$, at 32 bar

= …………

= ……….. kJ/kg

Specific enthalpy of saturated water at 4 bar = h_f at 4 bar

= ………… kJ/kg

∴ heat energy required = …………-…………

= ………… kJ/kg

= …………x………

= kJ Ans

(h) INTERPOLATION

It sometimes happens that the steam pressure and/or temperature which is being considered is not listed in the steam tables. In such instances if values are to be found, interpolation must be resorted to. Interpolated values are determined by assuming a linear relationship between successive values, as illustrated in the examples shown below.

e.g. Determine the specific volume and enthalpy of dss at 72 bar. If we refer to our steam tables (page 5 in this instance) we see that specific volume (v_g) and specific enthalpy (h_g) values are given only at 70 bar and at 75 bar, viz:

at 70 bar, v_g = 0.02737 m^3/kg and h_g = 2772 kJ/kg
at 75 bar, v_g = 0.02532 m^3/kg and h_g = 2766 kJ/kg

To interpolate the values at 72 bar, the procedure is as follows:

Considering specific volume

v_g falls from 0.2737 m^3/kg to 0.02532 m^3/kg as the pressure rises form 70 bar to 75 bar.

∴ decrease in specific volume for a 5 bar increase in pressure
= 0.02737 - 0.02532
= 0.00205 m^3/kg

∴ decrease in specific volume for a 2 bar increase in pressure

= 2/5 x 0.00205
= 0.00082 m^3/kg

∴ specific volume at 72 bar = specific volume at 70 bar + specific volume change for 2 bar.

In this case, the specific volume change is negative (i.e. the specific volume decreases by 0.00082 m^3/kg as the pressure rises through 2 bar, namely form 70 bar to 72 bar).

∴ specific volume at 72 bar

= 0.02737 - 0.00082
= 0.02655 m^3/kg Ans

Considering specific enthalpy

h_g falls from 2772 to 2766 kJ/kg as the pressure rises from 70 to 75 bar.

∴ decrease in specific enthalpy = 2.722 - 2766

= 6 kJ/kg, for a 5 bar increase in pressure

= 6 x 2/5

= 2.4 kJ/kg, for a 2 bar increase in pressure

∴ specific enthalpy at 72 bar = 2772 - 2.4

= 2769.6, but to 4 significant figures

= 2770 kJ/kg Ans

In a similar manner we can interpolate if a given temperature does not coincide with a listed value in the steam tables.

e.g. Determine the specific volume and specific enthalpy dss at a saturation temperature of 73 °C.

Referring to page 2 of the steam tables and abbreviating the evaluations:

V_g at 70 °C = 5.045 m^3/kg

at 75 °C = 4.133

difference for 5 °C = 0.912

" " 1 °C = 0.182

" " 3 °C = 0.546

∴ V_g at 73 °C = 5.045 - 0.546 (volume decreasing)

= 4.499 m^3/kg

h_g at 75 °C = 2634.7 kJ/kg

at 70 °C = 2626.3

difference for 5 °C = 8.4

difference for 3 °C = 5.0

∴ h_g at 73 °C = 2626.3 + 5.0 (enthalpy increasing)

= 2631.3 kJ/kg Ans

N.B. After some practice, the student should be able to interpolate table values with relative ease and without the need for the detailed procedures indicated above. **More complex interpolation problems will be discussed in the chief's syllabus.**

e.g. Estimate the dryness fractions of the following steam samples:

(i) 1 kg steam at 8.5 bar pressure having an enthalpy of 2650 kJ
(ii) 0.2 kg steam at 0.07375 bar pressure having a volume of 3 m^3

(i) Since 8.5 is the arithmetic mean of 8 and 9, then, by interpolation we may write:

$$h_f \text{ at } 8.5 \text{ bar} = \frac{721 + 743}{2} = \frac{1464}{2} = 732.0 \text{ kJ/kg}$$

$$h_{fg} \text{ at } 8.5 \text{ bar} = \frac{2048 + 2031}{2} = \frac{4079}{2} = 2039.5 \text{ kJ/kg}$$

$$h_g \text{ at } 8.5 \text{ bar} = \frac{2769 + 2774}{2} = \frac{5543}{2} = 2771.5 \text{ kJ/kg}$$

since 2771.5 > 2650, the steam samples must be wet from:

$$h = h_f + x\, h_{fg}$$

$$\therefore 2650 = 732 + 2039.5x$$

$$\text{whence } x = \frac{2650 - 732}{2039.5} = \frac{1918}{2039.5}$$

$$= 0.9411 \quad \text{Ans}$$

(ii) At 0.07375 bar, $v_g = 19.55 \text{ m}^3/\text{kg}$

thus, the volume of 0.2 kg of dry saturated steam at 0.07375 bar pressure will be $= 19.55 \times 0.2$

$$= 3.91 \text{ m}^3$$

but the volume of the steam sample $= 3 \text{ m}^3$

hence the steam sample must be wet, and the dryness fraction, x, must be

$$= \frac{3}{3.91} = 0.7672 \quad \text{Ans}$$

Alternatively, we could write:

Specific volume of steam sample $= v = \frac{3}{0.2} = 15 \text{ m}^3/\text{kg}$

and since V_g at 0.07375 bar $= 19.55 \text{ m}^3/\text{kg}$

then, from $v = x\,v_g$

$\therefore 15 = x \times 19.55$

$\therefore x = \dfrac{15}{19.55}$

$= 0.7674$ QED

[Ex 6]

Complete the following problem:

(a) Determine the saturation temperature, volume and enthalpy of 3.5 kg of dry saturated steam at a pressure of 25 bar.

(b) What would be the amount of heat energy needed to produce this amount of steam from water at 45 °C?

Referring to page 4 of the steam tables we see that 25 bar is not a listed pressure. However, since 24 bar and 26 bar are listed pressures and assuming, as we do for purposes of interpolation, that a linear relationship exists between successive values, then properties and energy values at 25 bar may be assumed to be the <u>ARITHMETIC MEAN</u> of those at 24 bar and 26 bar.

(a) Thus, a <u>25 bar</u> pressure:

saturation temperature, $t_s = \dfrac{221.8 + 226.0}{2}$

$=$ .... °C Ans

specific volume, $v_g = \dfrac{0.08323 + 0.07689}{2}$

$=$ .... m^3/kg

$\therefore$ volume of 3.5 kg mass $=$ 3.5 X ....

$=$ .... m^3 Ans

specific enthalpy, h_g $=$ ....

$=$ .... kJ/kg

$\therefore$ enthalpy of 3.5 kg mass $=$ .... kJ Ans

(b) Referring to page 2 of the steam tables and interpolating, we get:

Specific enthalpy of water at 45 °C = h_f at 45 °C

$$= \frac{184.2 + 192.5}{2}$$

= ……….. kJ/kg (to 4 sig. figs.)

∴ heat energy needed = enthalpy of steam - enthalpy of water

= ………..

= ……….. kJ/kg

= 3.5 X ………..

= ……….. kJ Ans

(j) FORMATION OF SATURATED STEAM FROM ICE

Let us consider the changes of condition and state which may occur when heat energy is supplied, uniformly, to a block of ice which is at some temperature t °C. The events may be summarised, in order, as follows:

(i) the temperature of the ice will rise from t °C to 0 °C. Thus the heat supplied during this period is sensible heat

(ii) the ice will change its state from solid to liquid (ice to water) at the constant temperature of 0 °C, the heat supplied being the "latent heat of fusion" (335 kJ/kg) …… refer to (2C(12)6)

(iii) the substance will now be saturated water at its "triple point" temperature, namely 0 °C, and if the heating is continued in a closed vessel, saturated steam will eventually be produced, as described in section (c).

e.g. Calculate the amount of heat needed to convert 6 kg of ice at -10 °C into wet steam of dryness 0.8 at a pressure of 0.25 MN/m^2. Take the specific heat capacity of ice to be 2.04 kJ/kg K and the enthalpy of fusion to be 335 kJ/kg.

As indicated previously, it is perhaps simpler to consider unit mass of fluid and then correct for the actual mass at the end of the calculation, viz:

Heat required to raise the temperature of 1 kg of ice from -10 °C to 0 °C

= m x c x ΔT

= 1 x 2.04 x 10

= 20.4 kJ

Heat required to convert 1 kg of ice into 1 kg of saturated water at 0 °C
= 335 kJ

Heat required to produce 1 kg of wet steam, dryness 0.8, at 0.25 MN/m^3 (2.5 bar) from water at the triple point temperature.

= $h_f + h_{fg}$ ……….. at 2,5 bar pressure

= 541 + (0.8 x 2178)

= 541 + 1742.4

= 2283.4 kJ

∴ total heat required

= 20.4 + 335 + 2283.4

= <u>2638.8 kJ/kg</u>

= 2638.8 x 6

= 15832.8 kJ (i.e. for 6 kg mass) Ans

(N.B. 1 $MN/m^2 = 10^6$ N/m^2 : 1 bar = 10^5 N/m^2 ∴ 1 MN/m^2 = 10 bar)

[Ex 7]

Complete the following problem:

(i) Calculate the amount of heat required to produce 1.5 kg of dry saturated steam at 11.4 °C from ice at -40 °C. Take the specific heat of the ice and the enthalpy of fusion to be 2.1 kJ/kg K and 335 kJ/kg respectively.

(ii) What would be the pressure and volume of the steam so formed?

(i) Considering unit mass (i.e. 1 kg) of substance:

sensible heat supply to the ice = ………..

= ……….. kJ/kg

latent heat supply at 0 °C = ……….. kJ/kg

specific enthalpy of dry steam = ……….. kJ/kg (h_g at 111.4 °C from tables)

∴ total amount of heat supplied = ..…..+ …..... + ...…..

= .... kJ/kg

= 1.5 x ....

= .... kJ Ans

(ii) pressure of steam, so formed = ... bar (p at t_s = 111.4 °C)

volume of steam, so formed = ... m^3/kg (V_g at t_s = 111.4 °C)

= 1.5 x ....

= .... m^3 Ans

[Ex 8]

Complete the following problem:

A certain mass of ice at - 22°C is supplied with heat energy until it is completely converted into wet steam, dryness fraction 0.6, saturation temperature 130 °C. The resulting volume of steam formed is 3 m^3. Estimate the amount of heat supplied. Take the specific heat of ice and the enthalpy of fusion at 0 °C to be 2 kJ/kg K and 335 kJ/kg respectively.

We must, at some stage, determine the mass of substance involved. This may be done by considering the volume of wet steam formed, as follows:

Volume of wet steam formed = 3 $m^{3,}$ at 130 °C (p_s = 2.7 bar)

Specific volume of dss at 2.7 bar = ... m^3/kg (V_g at 2.7 bar)

∴ specific volume of wet steam at 2.7 bar = x V_g
= .... x ....

= .... m^3/kg

∴ volume of "m" kg of wet steam at 2.7 bar = m x .... (m^3)
= 3 (m^3)

∴ m = <u>3 kg</u>

i.e. mass of substance = ... kg

Considering <u>unit mass</u> of substance:

Heat supplied to ice = = ... kJ/kg

Heat supplied to form water from ice at 0 °C = ………… kJ/kg

Heat supplied to form wet steam from water at 0 °C = $h_f + h_{fg}$ (at 2.7 bar)

= …………

= ………… kJ/kg

∴ total amount of heat supplied = …… + …… + ……..

= ………… kJ/kg

= ………… x …………

= ………… kJ Ans

N.B. In the foregoing examples, dealing with steam generation from water (or ice), the heating processes are assumed to be FLOW PROCESSES. It follows, therefore, that the heat required to be supplied necessarily involves ENTHALPY change (refer to 2C (14) 14 and 18).

If however, the heating processes were carried out under constant volume conditions (i.e. in a closed vessel) then the heat supply would involve INTERNAL ENERGY change only, since the processes involved would be NON FLOW PROCESSES (REFER TO 2c (14) 11), VIZ:

From $Q = \Delta U + W$

And since there is no change in volume, $W = 0$, then:

$\underline{Q = \Delta U}$, for a NON-FLOW process.

Thus, to summarise:

For a FLOW PROCESS, heat supplied = $Q = \Delta H$

And for a NON-FLOW PROCESS, heat supplied = $Q = \Delta U$

Although these differences have been indicated, the student should treat all examples on steam generation as being involved with FLOW PROCESSES and changes in ENTHALPY unless specifically indicated otherwise.

NOW MOVE TO THE CHIEF ENGINEER COURSE NOTES AND WORK THROUGH THEM]

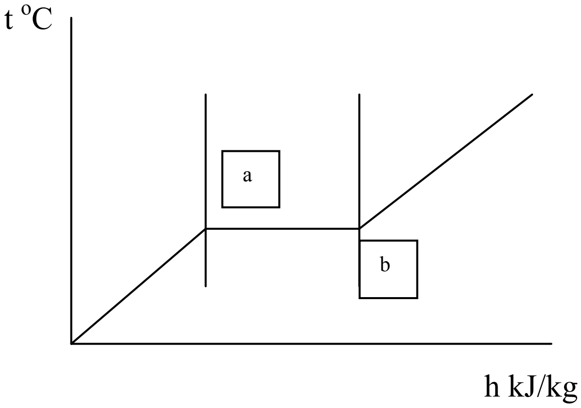
Properties of Steam and Steam Cycles

Properties of Steam

Steam is used to transport heat energy from the place of generation, the boiler, to the place of application, the turbine (or heater), where this energy is converted in to mechanical work (or to heat fuel oil or lub. oil). Steam is used in marine applications because it is convenient and effective.

As water is heated it passes through distinct ‘phases’ before is becomes steam.

Consider 1kg of water at, say 5^{o}C being heated, at atmospheric pressure until it is steam



1 ‘Sensible’ heat being passed to water raising temperature to the boiling point of 100^{o}C.

2 The transition from water to steam. The temperature stays constant during this transitional phase despite heat being added. At point *a* the entire 1kg is water at 100^{o}C and at point *b* the entire 1kg is steam at 100^{o}C. Between points *a* and *b* there is a mixture of water and steam – the proportion of water reducing as point b is approached. The temperature being constant during this phase due to the conversion of all the water into steam. The added heat is required to change the phase of the water into steam and is known as the ***enthalpy of evaporation*** (sometimes known as *latent heat*). The proportion of steam to water, during this phase, is known as the ***dryness fraction***.

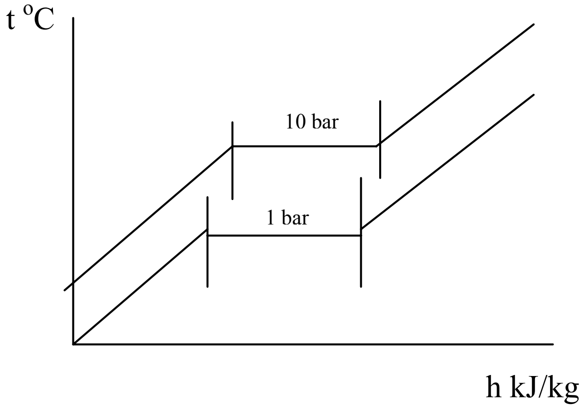
Terms such as saturated are used to describe the condition of the steam and the water when dealing with steam. When water is heated up to, what we know as, the ‘boiling point’ molecules will escape from the liquid, some will fall back into the liquid, but some will escape the liquid surface to establish equilibrium. In this condition the vapour is said to be ***saturated***. The temperature at which this occurs is said to be the ***saturation temperature*** t_s. Water that is at point *a* is said to be saturated liquid.

3 At point *b* all of the water has been changed to steam; there is no water present. In this state its condition is known as dry saturated steam. If heating continues the temperature of this steam will increase and the steam is known as

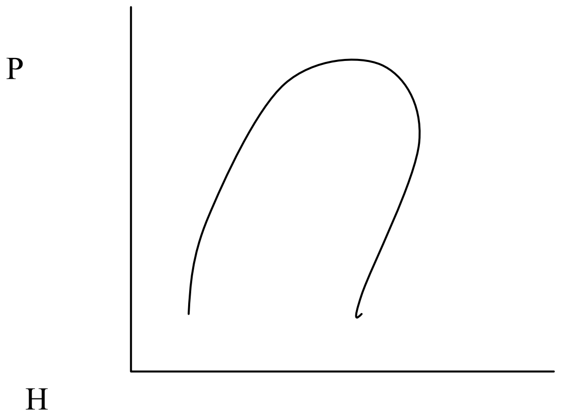
superheated steam. This means that the steam exists at above its saturation temperature.

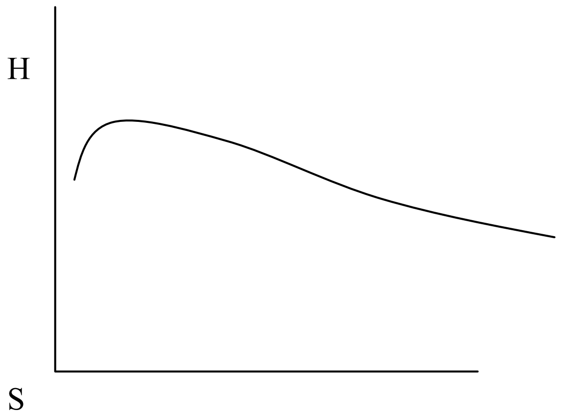
To be strictly correct we should talk in terms of liquid and vapour rather than water and steam, but in marine practice water and steam/liquid and vapour are used interchangeably.

The pressure was specified in the illustration above. This is important because pressure exerts a huge influence on the behaviour of the steam. Referring to the t ~ h graph below



Comparing the behaviour of steam at 1 bar and 10 bar the graph would look like this. In practice t ~ h graphs are not used. Pressure/enthalpy (P ~ H) and enthalpy/entropy (H ~ S) graphs can used.





In fact the behaviour of the steam is comprehensively displayed in steam tables and an extremely comprehensive graph could be built up using the information contained in them.

Navigating around Steam Tables

Referring to the page titled *Saturated Water & Steam*.

Symbols:

p	pressure in bar
t_s	saturation temperature in oC
v_g	the specific volume of dry saturated steam. m3/kg
u_f	the internal energy of the liquid. The suffix f indicates fluid. kJ/kg
u_g	the internal energy of the dry saturated steam. The suffix g indicating dry vapour. kJ/kg
h_f	the enthalpy of the liquid. kJ/kg
h_{fg}	the enthalpy required to turn 1kg of water into dry sat. steam at that pressure. The suffix fg indicating transition between liquid and steam. kJ/kg
h_g	the enthalpy of dry saturated steam. kJ/kg
s_f	the entropy of the liquid. kJ/kgK
s_{fg}	the entropy of the wet steam. kJ/kgK
s_g	the entropy of the dry saturated steam. kJ/kgK.

In general the suffixes used are:

f	for liquid phase
fg	for the transitional phase, when the steam is wet.
g	when the steam is dry saturated.

As indicated earlier, between the liquid and the dry saturated phase, there is a transitional phase when the steam is considered 'wet', that is when water and steam co-exist. The proportion of steam to water is described by the ***dryness fraction x***.

Example 1.1.

Find the enthalpy and internal energy per kg of steam at 12 bar when the steam is:

i) *dry saturated*
ii) *0.7 dry. (this is the dryness fraction)*

i) from the tables $h_g = 2784$ kJ/kg

ii) refer to 2nd eng revision notes

$$h = h_f + xh_{fg}$$
$$h = 798 + 0.7 \times 1986$$
$$h = 798 + 1390.2$$
$$h = 2188.2kJ\_/kg$$

It is sometimes necessary to interpolate the information in the steam tables. This would be necessary if you needed to find h_f at 29 bar. Interpolation in steam tables assumes a linear increment between two entries.

At 29 bar

$$h_f = \underline{991 + 1008}$$
$$= 999.5\ kJ/kg$$

where h_f at 28 bar = 991 kJ and h_f at 30 bar =1008

Example 1.2

Find the enthalpy and internal energy per kg of steam at 21 bar when the steam is:

i) *dry saturated*
ii) *0.75 dry. (this is the dryness fraction)*

The only values in the table are at 20 bar and 21 bar

i) at 20 bar $U_f = 907, U_g=2600, h_f=909, h_{fg}=1890$ and $h_g=2799$
at 22 bar $U_f = 928, U_g=2601, h_f=931, h_{fg}=1870$ and $h_g= 2801$

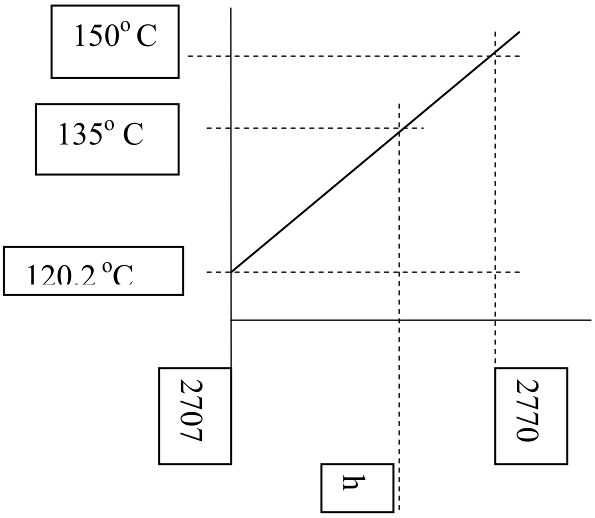
all values in kJ/kg

remember $U_{fg} = U_g - U_f$ and $h_{fg} = h_g - h_f$ 2nds revision

Sometimes there is a requirement for a more complicated interpolation – the following examples show how this can be done.

If it is required to find the enthalpy of steam at 2 bar and 135°C you will see that reference to the steam tables only gives hg and h at 150°C, we must therefore interpolate. This can be shown graphically.

hg at 2 bar is 2707 kJ/kg. t_{sat} 120.2 °C
h at 150°C is 2770 kJ/kg



Using similar triangles the difference in enthalpy between 120.2 °C and 150°C will be in the same ratio as that between 120.2 °C and 135°C.

$$\frac{(150 - 120.2)}{(2770 - 2707)} = \frac{(135 - 120.2)}{(h - 2707)}$$

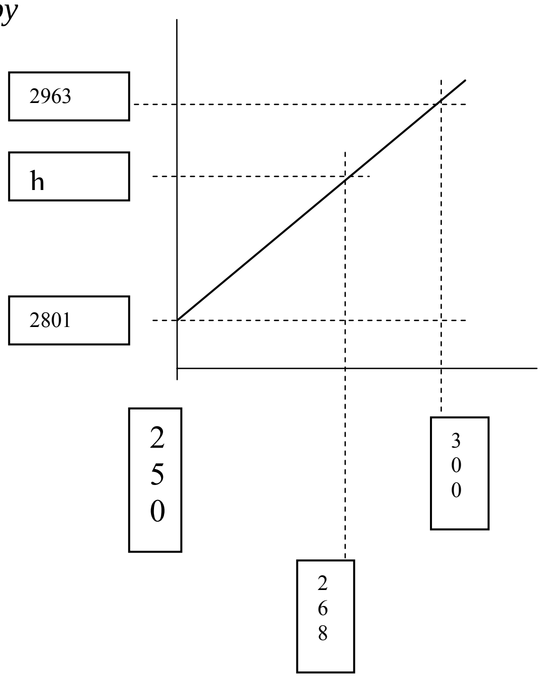
$$h = 2707 + \frac{[(2770 - 2707)x(135 - 120.2)]}{(150 - 120.2)}$$

$$h = 2738.28 \text{ kJ/kg.}$$

Ex 1.3

Find the enthalpy and entropy of steam at 40 bar and 268°C.

Enthalpy



Using similar triangles

$$\frac{300 - 250.3}{2963 - 2801} = \frac{268 - 250.3}{\mathbf{h} - 2801}$$

$$\mathbf{h} - 2801 = \frac{268 - 250.3}{300 - 250.3}(2963 - 2801)$$

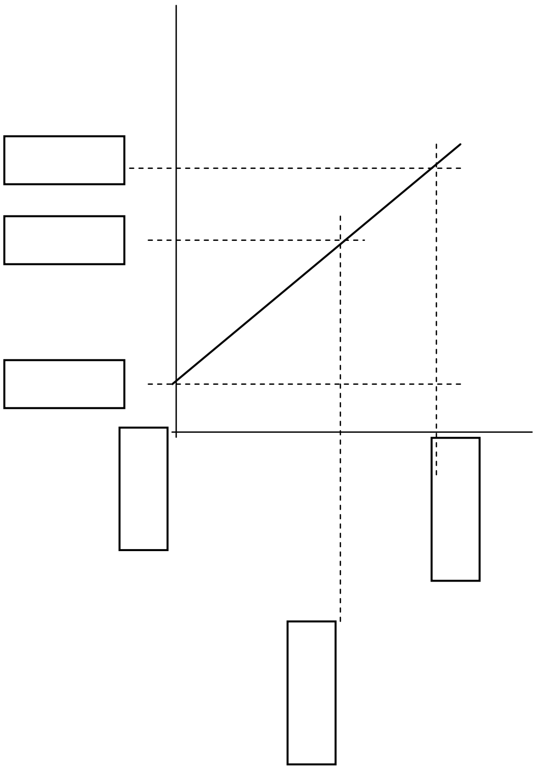
$$\mathbf{h} = 2801 + \frac{17.7}{49.7} \times 162 = 2858.7\,\mathbf{kJ/kg}$$

Try this next one yourself:

Ex 1.4

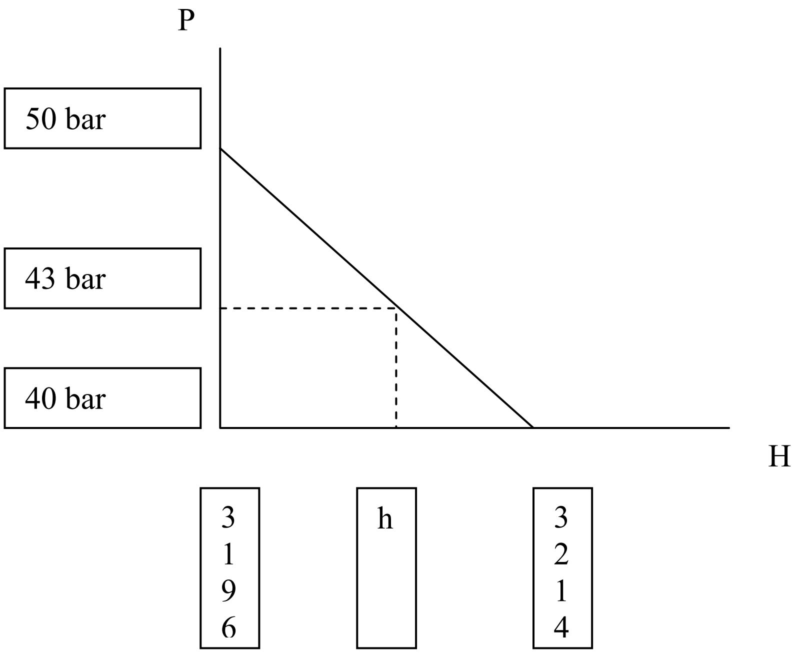
For a pressure of 20 bar determine the temperature of the steam given that the enthalpy is 3401kJ/kg

Ans 470°C



Interpolation can be carried out with any combination of two variables within the tables. Please also note that some variables decrease as the pressure or temperature changes and as such this must be taken into account

Consider the requirement to determine the enthalpy of steam at 43 bar 400°C
Note that between 40 and 50 bar the enthalpy value reduces from 3214 to3196 hence the straight-line graph will have a negative slope as shown.



by similar triangles

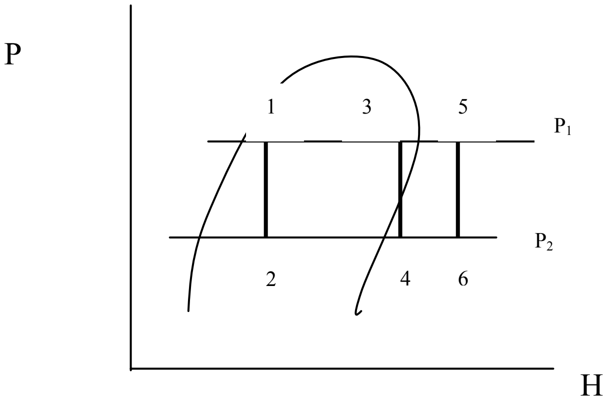
$$\frac{3214-\mathbf{h}}{3214-3196}=\frac{43-40}{50-40}=\frac{3}{10}=0.3$$

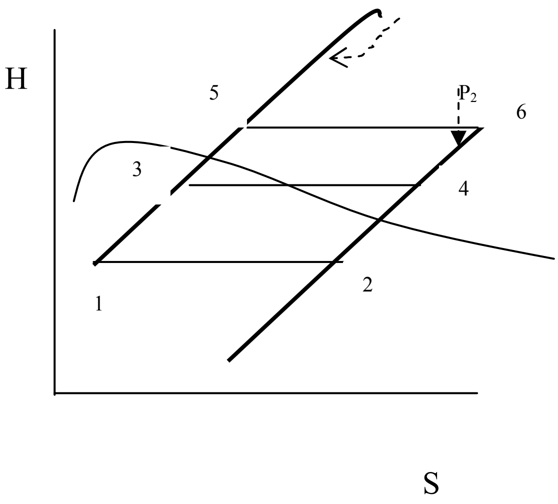
$$\mathbf{h}=3214-0.3(3214-3196)=3214-5.4=\underline{3208.6\mathbf{kJ/kg}}$$

Throttling

A common process in marine practice is to throttle steam. Throttling is essentially restricting the flow of steam through a pipe. This can be done by closing in a valve. During throttling the pressure of the steam downstream of the throttle is reduced. The saturation temperature of the steam after throttling is lower than that up stream of the throttle. Throttling can, therefore, increase the dryness of the steam or even cause wet steam to be superheated. The throttling process can be shown on P ~ H and H ~ S graphs.

P_1





Consider steam being throttled in a reducing valve in the following initial conditions.

Process 1 – 2. Steam initially wet
Process 3 – 4.Steam initially with high dryness fraction
Process 5 – 6. Steam initially superheated.

In all cases the assumption made is that enthalpy is constant during the process so that:

enthalpy before throttling = ***enthalpy after throttling***

$$H_{before} = H_{after}$$

Ex 1.5

Steam is throttled from 8 bar to 1.1 bar. If the steam is dry saturated finally, what is the condition before throttling.

$$(\text{First find the enthalpy at } 1.1\text{bar ds}) = 2680\,\mathbf{kJ/kg} = \text{enthalpy at 8 bar}$$

$$h_{8bar} \text{ is wet} = h_f + x.h_{fg}$$

$$(\mathbf{x}) = \frac{\mathbf{h}_{8bar} - \mathbf{h}_f}{\mathbf{h}_{fg}} = \frac{2680 - 721}{2048} = \frac{1929}{2048} = \underline{0.942}$$

Ex 1.6

Steam at a pressure of 7 bar is throttled to a pressure of 1.01325 bar when the temperature is found to be 125^oC. Determine the initial dryness fraction of the steam.

We must find the enthalpy of steam at 1.01325 bar This will require alittle interpolation.

Note that 125° C lies halfway between the sat temp of $100\ ^\circ$C and a superheat temp of 150° C

$$\mathbf{h}_{125} = \frac{\mathbf{h}_{\mathbf{atmos}} + \mathbf{h}_{150}}{2} = \frac{2676 + 2777}{2} = 2726.5\mathbf{kJ/kg} = \mathbf{h}_{\mathbf{7bar}}$$

$$\mathbf{h}_{\mathbf{7bar}} = \mathbf{h}_{\mathbf{f}} + \mathbf{x}\mathbf{h}_{\mathbf{fg}}$$

$$\mathbf{x} = \frac{\mathbf{h}_{\mathbf{7bar}} - \mathbf{h}_{\mathbf{f}}}{\mathbf{h}_{\mathbf{fg}}} = \frac{2726.5 - 697}{2067} = \frac{2029.5}{2067} = \underline{0.982}$$

Entropy

Entropy is an extremely difficult concept to explain. Entropy is a property of a system. It is difficult to establish the absolute magnitude of entropy, but it is possible to measure changes in entropy. In fact the change of entropy is a useful tool when describing steam expanding through a turbine nozzle. The change of entropy can be used as an indication of how close the expansion is to the perfect case of no friction or turbulence. In this perfect world situation entropy would not change during expansion and the process would be termed isentropic. However, in the real world there is friction and turbulence and the entropy would increase during expansion. The comparison between the perfect and the real worlds when expanding steam through a turbine nozzle is called the ***isentropic efficiency*** $\eta_{isentropic}$.

Isentropic efficiency can be defined in terms of enthalpy drop or temperature drop

Isentropic efficiency for an **expansion** process

$$\eta_{\mathbf{isentropic}} = \frac{\text{Actual enthalpy drop}}{\text{Isentropic enthalpy drop}} = \frac{\Delta\mathbf{h}}{\Delta\mathbf{h}_{\mathbf{s}}}$$

or

$$\eta_{\mathbf{isentropic}} = \frac{\text{Actual Temperature drop}}{\text{Isentropic Temperature drop}} = \frac{\Delta\mathbf{T}}{\Delta\mathbf{T}_{\mathbf{s}}}$$

for a **compression** process the Isentropic efficiency changes to the following

$$\eta_{\mathbf{isentropic}} = \frac{\text{Isentropic enthalpy drop}}{\text{Actual enthalpy drop}} = \frac{\Delta\mathbf{h}_{\mathbf{s}}}{\Delta\mathbf{h}}$$

or

$$\eta_{\mathbf{isentropic}} = \frac{\text{Isentropic Temp drop}}{\text{Actual Temp drop}} = \frac{\Delta\mathbf{T}_{\mathbf{s}}}{\Delta\mathbf{T}}$$

It will be more usual to use enthalpy drops for steam systems and enthalpy or temperature drops for gas systems such as gas turbines

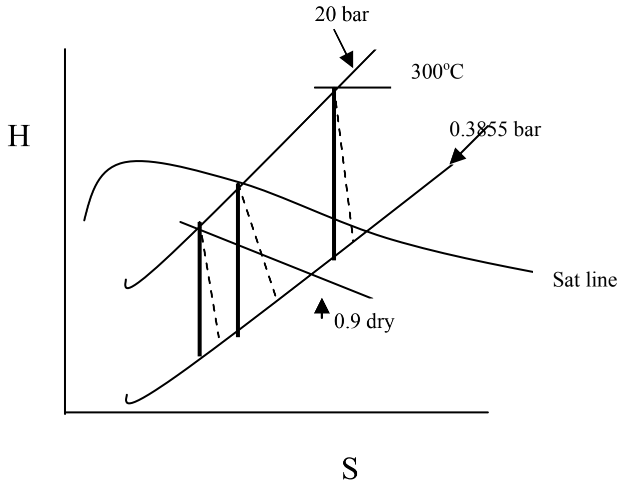
This concept can be illustrated by an example.

Ex 1.7

a) *Steam is expanded isentropically from 20 bar to 0.3855 bar. Find the dryness and enthalpy at the end of expansion and the isentropic enthalpy drop if the steam is initially:*

   i) *dry saturated*
   ii) *0.9 dry*
   iii) *300^oC*

b) *Using the same initial conditions find dryness, enthalpy at the end of expansion and enthalpy drop if the isentropic efficiency of the nozzle is 0.9.*



The diagram shows the HS chart with the isentropic expansions (shown in dark full lines) and the actual expansions (shown dotted). Note the expansions shown are only diagrammatic approximations.

Let 20 bar position be suffix (1) and 0.3855 bar position be suffix (2)

a) Isentropic expansions

Dry sat

$$\mathbf{s}_1 = \mathbf{s}_2 = \mathbf{s}_{\mathbf{20bardry}} = 6.34\mathbf{kJ/kg}$$

$$\mathbf{s_g} \text{ at } 0.3855\text{bar} = 7.681 > 6.34 \text{ hence steam is wet after expansion}$$

$$\mathbf{x} = \frac{\mathbf{s}_2 - \mathbf{s_f}}{\mathbf{s_{fg}}} = \frac{6.34 - 1.015}{6.666} = \underline{0.8\mathbf{dry}}$$

$$\mathbf{h}_2 = \mathbf{h_f} + \mathbf{x h_{fg}}$$

$$\mathbf{h}_2 = 313.9 + 0.8 \times 2320.8 = \underline{2170.5\mathbf{kJ/kg}}$$

$$\mathbf{h}_1 = \mathbf{h_g} \text{ at } 20 \text{ bar} = 2799\mathbf{kJ/kg}$$

$$\text{Isentropic Enthalpy drop } \Delta h_s = \mathbf{h}_1 - \mathbf{h}_2 = 2799 - 2170.5 = \underline{628.5}\mathbf{kJ/kg}$$

0.9dry

$$\mathbf{s}_1 = \mathbf{s}_2 = \mathbf{s}_{0.9\mathbf{dry}\,20\mathbf{bar}} = \mathbf{s_f} + \mathbf{xs_{fg}} = 2.447 + 0.9 \times 3.893 = 5.9507\,\mathbf{kJ/kg}$$

$$\mathbf{x}_{0.3855\mathbf{bar}} = \frac{\mathbf{s}_2 - \mathbf{s_f}}{\mathbf{s_{fg}}} = \frac{5.9507 - 1.015}{6.666} = 0.74$$

$$\mathbf{h}_2 = \mathbf{h_f} + \mathbf{xh_{fg}}$$

$$\mathbf{h}_2 = 313.9 + 0.74 \times 2320.8 = \underline{2032.3\,\mathbf{kJ/kg}}$$

$$\mathbf{h}_1 \text{ at 20 bar} = \mathbf{h_f} + \mathbf{xh_{fg}} = 909 + 0.9 \times 1890 = 2610\,\mathbf{kJ/kg}$$

$$\text{Isentropic Enthalpy drop } \Delta h_s = \mathbf{h}_1 - \mathbf{h}_2 = 2610 - 2032.3 = \underline{577.7\,\mathbf{kJ/kg}}$$

300°C

$$\mathbf{s}_1 = \mathbf{s}_2 = \mathbf{s}_{20\mathbf{bar}\,300\mathbf{C}} = 6.768\,\mathbf{kJ/kg}$$

$$\mathbf{s}_2 = \mathbf{s_f} + \mathbf{xs_{fg}}$$

$$\mathbf{x} = \frac{\mathbf{s}_2 - \mathbf{s_f}}{\mathbf{s_{fg}}} = \frac{6.768 - 1.015}{6.666} = 0.863$$

$$\mathbf{h}_2 = \mathbf{h_f} + \mathbf{xh_{fg}} = 313.9 + 0.863 \times 2320.8 = 2316.83\,\mathbf{kJ/kg}$$

$$\underline{\Delta \mathbf{h}_s = \mathbf{h}_1 - \mathbf{h}_2 = 3025 - 2316.83 = 708.17\,\mathbf{kJ/kg}}$$

Now consider the enthalpy drops with an isentropic efficiency of 0.9

Dry sat

$$\text{Since } \eta_{\mathbf{isen}} = \frac{\Delta \mathbf{h}}{\Delta \mathbf{h}_s}$$

$$\Delta \mathbf{h} = 0.9 \times \Delta \mathbf{h}_s = 0.9 \times 628.5 = 565.65\,\mathbf{kJ/kg}$$

hence the new $h_2^{/}$ can be found

$$\mathbf{h}_2^{/} = \mathbf{h}_1 - \Delta \mathbf{h} = 2799 - 565.65 = 2233.35\,\mathbf{kJ/kg}$$

$$\mathbf{h}_2^{/} = \mathbf{h_f} + \mathbf{xh_{fg}}$$

$$\mathbf{x} = \frac{\mathbf{h}_2^{/} - \mathbf{h_f}}{\mathbf{h_{fg}}} = \frac{2233.35 - 313.9}{2320.8} = 0.827$$

0.9dry

$$\eta_{\mathbf{isen}} = \frac{\Delta \mathbf{h}}{\Delta \mathbf{h}_{\mathbf{s}}}$$

$$\Delta \mathbf{h} = 0.9 \times \Delta \mathbf{h}_{\mathbf{s}}$$

$$\Delta \mathbf{h} = 0.9 \times 577.7 = 519.93 \mathbf{kJ/kg}$$

$$\mathbf{h}_2{}^{/} = 2610 - 519.93 = 2090 \mathbf{kJ/kg}$$

$$\mathbf{h}_2{}^{/} = \mathbf{h}_{\mathbf{f}} + \mathbf{x}\mathbf{h}_{\mathbf{fg}}$$

$$\mathbf{x} = \frac{\mathbf{h}_2{}^{/} - \mathbf{h}_{\mathbf{f}}}{\mathbf{h}_{\mathbf{fg}}} = \frac{2090 - 313.9}{2320.8} = \underline{0.765}$$

300°C

$$\Delta \mathbf{h} = 0.9 \times \Delta \mathbf{h}_{\mathbf{s}}$$

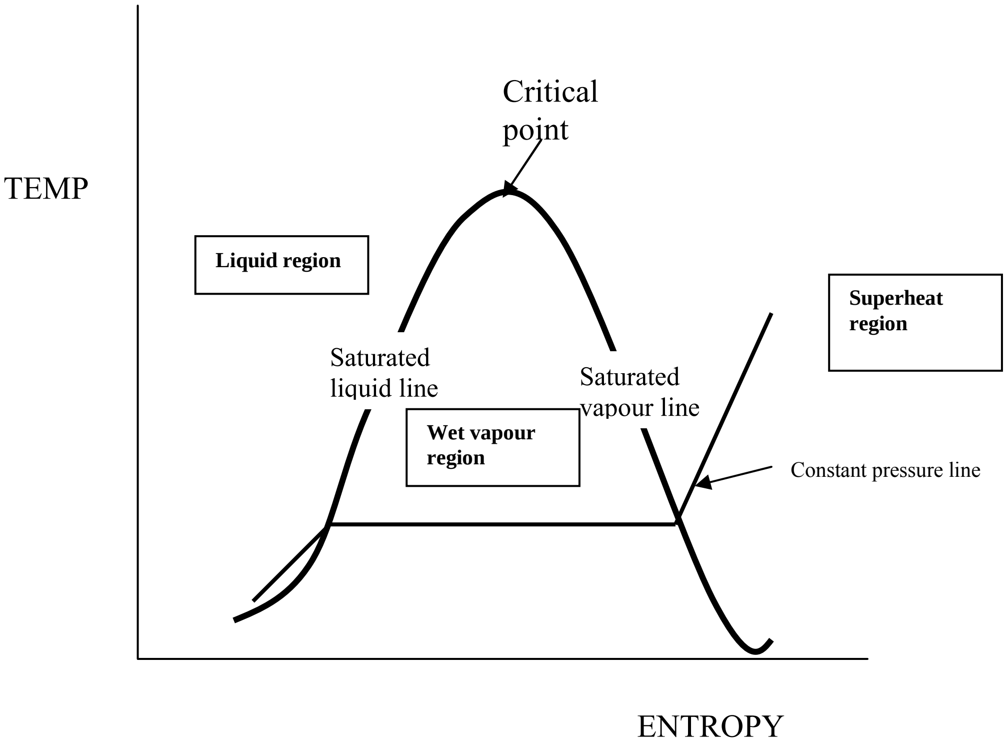
$$\Delta \mathbf{h} = 0.9 \times 708.17 = 637.35 \mathbf{kJ/kg}$$

$$\mathbf{h}_2{}^{/} = 3025 - 637.35 = 2387.65 \mathbf{kJ/kg}$$

$$\mathbf{x} = \frac{\mathbf{h}_2{}^{/} - \mathbf{h}_{\mathbf{f}}}{\mathbf{h}_{\mathbf{fg}}} = \frac{2387.65 - 313.9}{2320.8} = \underline{0.894}$$

THE TEMPERATURE ENTROPY DIAGRAM

The TS digram shown below for steam can be a useful aid to displaying a process such as that of a steam cycle. The diagram below shows the salient points of the vapour at various pressures



Many of the steam processes can be represented on this diagram and in many chief engineer applied heat examination papers the question involves the sketching of a T~S diagram.

We will consider this diagram again when we consider some typical exam type questions.

Gas and Saturated Vapour Mixtures

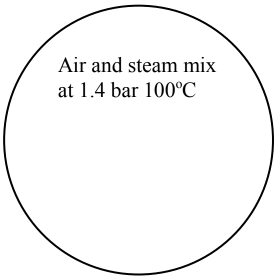
If a vessel is filled with a gas at low pressure and a liquid vapour mixture is introduced into the vessel the gas will have a negligible effect on the final state of equilibrium between the liquid and its vapour. The presence of the gas molecules will have a retarding effect on the establishment of equilibrium but eventually the vapour will exert the saturation vapour pressure, corresponding to the temperature of the mixture.

This saturation pressure is the partial pressure of the vapour in the mixture and the total pressure in the vessel is the sum of the partial pressure of the vapour and the partial pressure of the gas.

The liquid is subjected to the vapour and gas pressure so that it, is strictly speaking, a compressed liquid. However the properties of a compressed liquid are nearly the same as a saturated liquid at the same temperature. Thus for practical purposes both the liquid and vapour can be considered saturated.

Ex 1.8

A closed vessel contains a mixture of air and dry saturated steam at a temp of 100°C. The total pressure of the vessel is 1.4 bar. Determine the mass of air/kg of vapour given that 1 kg of air at 0 °C at a pressure of 1.01325 bar occupies 0.775 m^3.



Sat pressure of steam = p_s at 100°C =1.01325 bar this is the partial pressure of the steam

Hence the partial pressure of the air = 1.4 – 1.01325 = 0.38675 bar

from

$$\frac{\mathbf{p}_1\mathbf{v}_1}{\mathbf{T}_1} = \frac{\mathbf{p}_2\mathbf{v}_2}{\mathbf{T}_2}$$

we can find the specific volume of the air at the partial pressure and at 100° **C**

$$\frac{1.01325 \times 0.775}{273} = \frac{0.38675 \times \mathbf{v}_2}{373}$$

$$\mathbf{v}_2 = 2.774 \mathbf{m}^3 / \mathbf{kg}$$

This is the volume occupied by the steam at a partial pressure of 1.01325 bar

v_g at this pressure is 1.673 m^3 / **kg**

hence mass of steam/kg of air $= \frac{2.774}{1.673} = 1.658\mathbf{kg}/\mathbf{kg}$

hence

mass of air/kg of steam $= \frac{1}{1.658} = 0.603\mathbf{kg}/\mathbf{kg}$

Ex 1.9

A mixture of air and steam having a dryness of 0.6 is at a temperature of 95 °C. Total pressure is 3 bar. Determine the mass of air present per kg of wet steam. $R_{air} = 0.287$ *kJ/kgK*

Partial pressure of vapour = p_s at 95° **C** = 0.8453**bar**

Partial pressure of air = 3 - 0.8453 = 2.1547**bar**

For one kg of wet vapour $\mathbf{vol} = \mathbf{xv_g} = 0.6 \times 1.982 = 1.1892\mathbf{m}^3$

This is the volume that the air would occupy if it existed at the partial pressure.

From

$\mathbf{pv} = \mathbf{mRT}$ for air

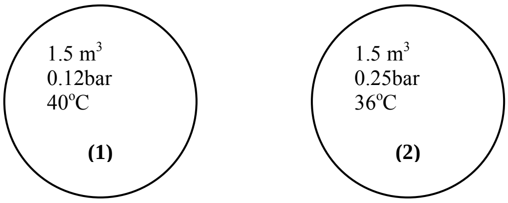
$$\mathbf{m} = \frac{\mathbf{pv}}{\mathbf{RT}} = \frac{2.1547 \times 10^2 \times 1.1892}{0.287 \times 368} = \underline{2.426 \text{ kg of air/kg of steam}}$$

Air Leakage into a Condenser

The condenser is an important component of a modern steam plant. The condenser operates at very low pressures, almost a vacuum. At these low pressures air and other gases find their way into the condenser. If these incondensibles were not removed then the pressure in the condenser would rise to the detriment of plant efficiency.

Example1.10

A closed vessel of 1.5 m^3 *capacity contains saturated water vapour and air at 40°C and 0.12 bar. Due to air leakage into the vessel, the pressure rises to 0.25 bar and the temperature falls to 36°C. Calculate the mass of air that has leaked into the vessel.*
R = 0.287 kJ/kgK.



Consider state (1)

Partial pressure of vapour $= p_s = 0.07375\,\mathbf{bar}$

$\mathbf{p}_{\mathbf{1air}} = 0.12 - 0.07375 = 0.04625\,\mathbf{bar}$

$$\mathbf{m}_{\mathbf{1air}} = \frac{\mathbf{pv}}{\mathbf{RT}} = \frac{0.04625 \times 10^2 \times 1.5}{0.287 \times 313} = 0.07723\,\mathbf{kg}$$

Consider state (2)

Partial pressure of vapour $= p_{s@36C} = 0.0594\,\mathbf{bar}$

$\mathbf{p}_{\mathbf{2air}} = 0.25 - 0.0594 = 0.1906\,\mathbf{bar}$

$$\mathbf{m}_{\mathbf{2air}} = \frac{\mathbf{pv}}{\mathbf{RT}} = \frac{0.1906 \times 10^2 \times 1.5}{0.287 \times 309} = 0.32238\,\mathbf{kg}$$

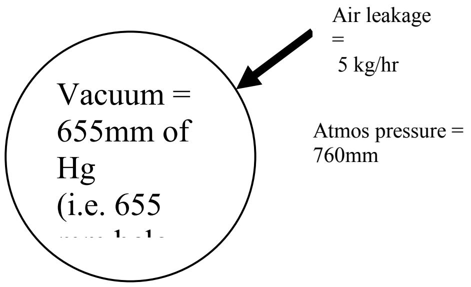
$\mathbf{Leakage} = \mathbf{m}_{\mathbf{2air}} - \mathbf{m}_{\mathbf{1air}} = 0.32238 - 0.07723 = \underline{0.245\,\mathbf{kg}}$

Ex 1.11

The rate of air leakage into a condenser is 5 kg/hr. The vacuum at the air pump suction 655 mm Hg when the barometer reading is 760 mm Hg. Estimate the volume of air to be extracted/minute when the temperature at the air pump suction is:

- *i)* $48\,^oC$
- *ii)* $44\,^oC$

Take $R_{air} = 0.287$ *kJ/kgK*



Note the pressure in the condenser is measured as a vacuum and is thus measured with reference to the atmospheric pressure i.e. a gauge pressure of zero

Absolute pressure within the condenser = 760 – 655 = 105mm hg.

Since 1bar = 750 mm then:

$$\text{Cond. press.} = \frac{105 \times 1}{750} = 0.14\,\mathbf{bar}$$

$$\text{When the temp is } 48^oC \quad p_s = 0.1116\,\mathbf{bar}$$

hence

$$\mathbf{p_{air}} = 0.14 - 0.1116 = 0.0284\,\mathbf{bar}$$

$$\mathbf{v} = \frac{\mathbf{mRT}}{\mathbf{p}} = \frac{5 \times 0.287 \times 321}{60 \times 0.0284 \times 10^2} = \underline{2.7\,\mathbf{m}^3 / \min}$$

$$\text{When the temp is } 44^oC \quad p_s = 0.091\,\mathbf{bar}$$

hence

$$\mathbf{p_{air}} = 0.14 - 0.091 = 0.049\,\mathbf{bar}$$

$$\mathbf{v} = \frac{\mathbf{mRT}}{\mathbf{p}} = \frac{5 \times 0.287 \times 317}{60 \times 0.048 \times 10^2} = \underline{1.58\,\mathbf{m}^3 / \min}$$

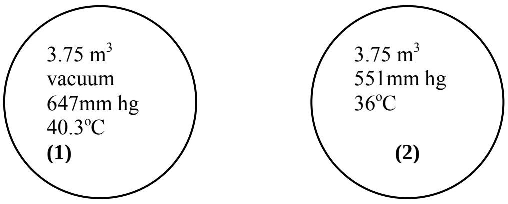
Ex 1.12 (Typical exam standard question)

A condenser has a volume of 3.75 m^3 and contains air saturated with water vapour at a temperature of 40.3 ^oC and a vacuum pressure of 647 mm Hg. The vacuum falls to 551 mm Hg and the temperature to 29 ^oC. The barometer reading is 755 mm Hg throughout.

Calculate:

- *i) the mass of air that has leaked into the vessel.*
- *ii) the amount of vapour condensed.*

Take $R_{air} = 0.287$ kJ/.   750 mm Hg = 1 kgK bar.



Consider condition (1)

$$\text{Cond pressure} = 755 - 647 = 108\text{mm hg} = \frac{108}{750} = 0.144\mathbf{bar}$$

$$\mathbf{p}_{1\mathbf{s}} = 0.075\mathbf{bar}$$

$$\mathbf{p}_{1\mathbf{air}} = 0.144 - 0.075 = 0.069\mathbf{bar}$$

$$\mathbf{m}_{1\mathbf{air}} = \frac{\mathbf{pv}}{\mathbf{RT}} = \frac{0.069 \times 10^2 \times 3.75}{0.287 \times 313.3} = 0.2878\mathbf{kg}$$

Vacuum now falls to 551 mm hg

$$\text{Cond. press} = \frac{755 - 551}{750} = 0.272\mathbf{bar}$$

$$\mathbf{p}_{2\mathbf{s}} = 0.04004\mathbf{bar}$$

$$\mathbf{p}_{2\mathbf{air}} = 0.272 - 0.04004 = 0.232\mathbf{bar}$$

$$\mathbf{m}_{2\mathbf{air}} = \frac{\mathbf{pv}}{\mathbf{RT}} = \frac{0.232 \times 10^2 \times 3.75}{0.287 \times 302} = 1.0\mathbf{kg}$$

$$\text{air leakage} = m_2 - m_1 = 1.0 - 0.2878 = 0.712kg$$

$$\text{At a temp of } 40.3^{\circ}\text{C} \quad v_g = 19.24m^3$$

$$m_s = \frac{V}{v_g} = \frac{3.75}{19.24} = 0.1949kg$$

Mass of vapour in the cond. is constant hence the specific volume of the vapour at (2) = $19.24m^3$

v_g at 29C is $34.77m^3$ hence the vapour is wet

$v = xv_g$

hence

$$x = \frac{19.24}{34.77} = 0.5533dry$$

wetness fraction = 1 - 0.5533 = 0.4467

mass of vapour condensed = wet fraction x mass of vapour

mass vapour condensed = $0.4467 \times 0.1949 = \underline{0.087\text{kg}}$

Non Flow Processes with Steam

Like the perfect gas, steam is also involved in processes that compress and expand, where heat and work transfer takes place. It follows that the non-flow energy equation will also apply to steam:

$$q = \Delta u + w$$

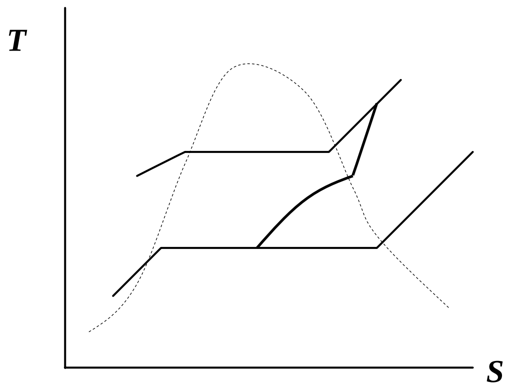
The constant volume process (Isochoric)

Since there is no change in volume there is no external work transfer, hence $w = 0$.

$$q = \Delta u$$

$$q = (u_2 - u_1)$$

On a T ~ S diagram a process where superheated steam is cooled at constant volume would be represented as follows:

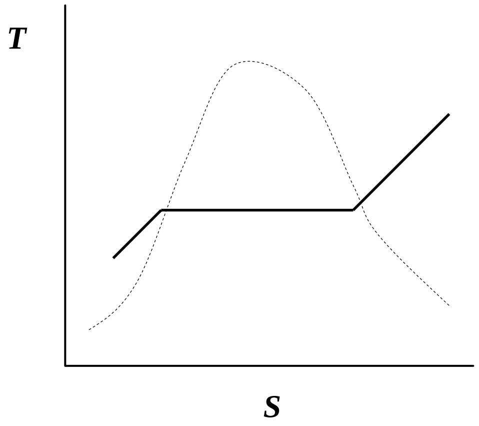


The constant pressure process (Isobaric)

In previous work the heat supplied to a kg of water to raise it to superheater outlet temperature is simply

$$q = (h_2 - h_1) = (u_2 - u_1) - P(v_2 - v_1)$$

On a T ~ S diagram the constant pressure process is represented:



The hyperbolic process, *PV = C*

Here steam is assumed to be expanded or compressed according to the law *PV = C*.

$$\text{Since } PV = C, \text{ then } P_1V_1 = P_2V_2$$

$$w = Pv \ln \frac{v_2}{v_1}$$

from the non flow energy equation :

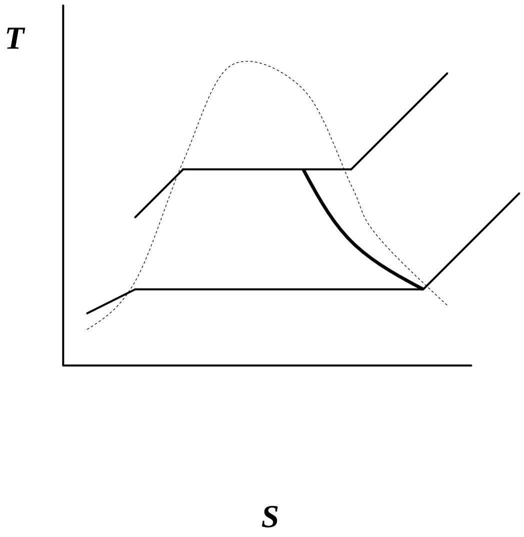
$$q = \Delta u + w$$

$$q = (u_2 - u_1) + Pv \ln \frac{v_2}{v_1}$$

$$q = (h_2 - P_2v_2) - (h_1 - P_1v_1) + Pv \ln \frac{v_2}{v_1}$$

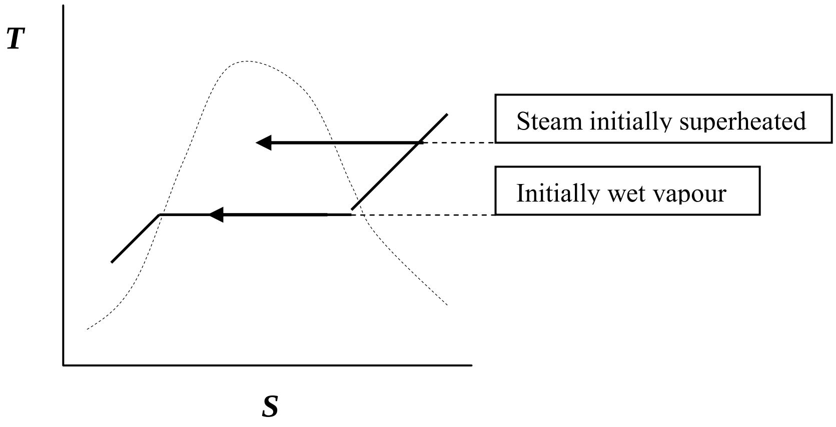
$$q = (h_2 - h_1) + Pv \ln \frac{v_2}{v_1}$$

On a T ~ S diagram a hyperbolic expansion would be represented:



The isothermal process

The evaporation of liquid to vapour is carried out at constant temperature – the saturation temperature t_{sat}. Since an isothermal process is defined as a constant temperature process it follows that the evaporation of boiler water (and condensation in condenser) is an isothermal process. In examination questions however, steam is sometimes initially superheated. The isothermal process can be shown on a T ~ S diagram.



The adiabatic process

In this case $PV^n = C$
There is no heat transfer in an adiabatic process, that is, $Q = 0$.

$$0 = \Delta u + w$$

$$w = -\Delta u$$

Since work done $w = \frac{(P_1v_1 - P_2v_2)}{n-1}$

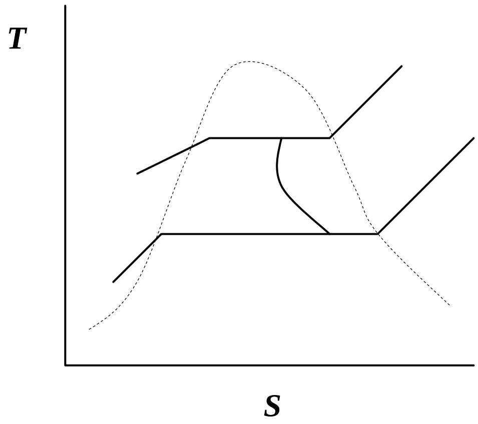
and $-\Delta u = -(u_2 - u_1)$

then $\frac{(P_1v_1 - P_2v_2)}{n-1} = -(u_2 - u_1)$

The approximate values for n for adiabatic compression or expansion of steam are given as:

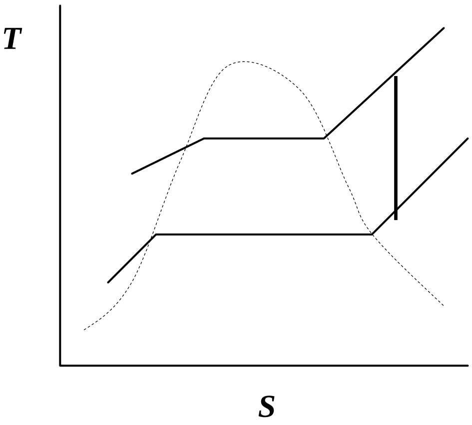
$n = 1.13$ *for wet steam*

$n = 1.3$ *for superheated steam.*



Isentropic process

In this case $s_1 = s_2$ and can be shown on a T ~ S diagram:



Ex 1.13

Steam initially 11 bar dry saturated expands in an engine to 0.3855 bar, 0.9 dry, according to the law PV = C.

- *i) What amount of heat is received/kg of steam during the expansion?*
- *ii) Show the process on a T~S diagram.*

$$q = \Delta u + w$$

$$q = (u_2 - u_1) + Pv \ln \frac{v_2}{v_1}$$

$$q = (h_2 - P_2 v_2) - (h_1 - P_1 v_1) + Pv \ln \frac{v_2}{v_1}$$

$$q = (h_2 - h_1) + Pv \ln \frac{v_2}{v_1}$$

from the steam tables

$h_1 = 2781 \text{kJ/kg}$

$h_2 = h_f + x h_{fg} = 313.9 + 0.9 \times 2320.8 = 2402.62 \text{kJ/kg}$

$v_1 = v_g$ at 11 bar $= 0.1774 \text{ m}^3/\text{kg}$

$v_2 = x\, v_g$ at 0.3855bar $= 0.9 \times 4.133 = 3.72 \text{m}^3/\text{kg}$

$\therefore q = 2402.62 - 2781 + (11 \times 10^2 \times 0.1774 \times \ln 3.72/0.1774) = \underline{\mathbf{215.44\ kJ/kg}}$

Ex 1.14

Steam initially at155.5°C and1 bar, is compressed reversibly and isothermally to a state where the specific volume is 0.28m³/kg.
Find:

- a) *the condition of the steam in the final condition.*
- b) *the change of internal energy,*
- c) *the change of entropy*
- d) *the heat transferred.*
- e) *the Work done/kg of steam.*

HAVE A GO AT THIS ONE YOURSELF

AND THEN TRY THESE STEAM EXAMPLES

POSSIBLE SOLUTIONS AT THE END OF THE CHAPTER

STEAM EXAMPLES

1. 0.12 kg of dry saturated steam at a pressure of 10 bar, expands reversibly and polytropically to a pressure and volume of 1 bar $0.17m^3$ respectively

   a) sketch the Temperature – Entropy diagram
   b) Calculate

      i) the index of expansion
      ii) the heat transferred
      iii) the change in entropy

2. A vessel containing steam at a pressure and temperature of 15 bar and 250°C respectively, has a volume of 0.6 m^3. Steam is blown off until the pressure falls to 4 bar, the expansion of the steam in the vessel being isentropic during the blow off. The vessel is then cooled until the pressure is 3 bar.

   a) Sketch the Temperature – Entopy diagram

   b) Calculate

      i) the mass of steam blown off
      ii) the final dryness fraction of the steam
      iii) the heat transferred during cooling

3. Steam of specific volume 0.12m^3/kg at 14 bar is throttled to 7 bar and then expanded hyperbolically and reversibly to 1.1bar.

   a) Sketch the process on a Temperature~Entropy diagram showing all of the temperatures

   b) Calculate:

      i) the change in entropy across each process
      ii) the total entropy change

4. Steam at 20 bar 250^{o}C is expanded isntropically to 2 bar before being throttled to 1 bar and then heated at constant pressure to the original specific enthalpy.

   a) Sketch the process on a T~S diagram
   b) Using the tables provided calculate

      i) the final steam condition
      ii) the change in entropy during the heating

5. A 10 m^3 vessel contains steam at 2 bar 0.9 dry. Steam at 9 bar 350^{o}C is admitted into the vessel until the final conditions are 6 bar 250^{o}C.

   a) Calculate the total heat transfer during the process
   b) State the direction of the heat transfer during the process

6. One kg of steam is throttled from 14 bar dry saturated to 10 bar, then expanded isentropically to 1.4 bar and finally heated at constant pressure to 200^{o}C.

   a) Sketch the process on a TS diagram
   b) Using the tables provided:

      i) Calculate for each of the three processes

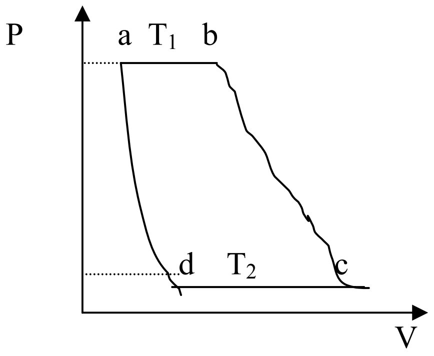
         (1) the final steam condition
         (2) the change in enthalpy

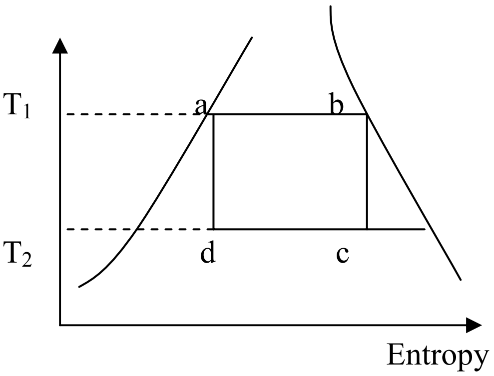
      ii) Calculate the overall change in entropy

Ideal Steam Plant Cycles

The Carnot Cycle is the ideal cycle to attain since it has the highest possible efficiency between any two given limits of temperature. However, it is limited in application because of practical consideration. To utilise the concepts of Carnot's theory, the cycle must be modified to produce the Rankine Cycle.

Carnot Cycle





For both diagrams

a – b evaporation of saturated water to dry saturated vapour at P_1, constant temp T.

b – c isentropic expansion of vapour

c – d incomplete condensation at pressure P_2 and constant temp T_2

d – a isentropic compression of wet vapour back to saturated liquid

The Carnot cycle is an ideal cycle but is impracticable. Compression of a wet vapour is undesirable and is replaced in the Rankine cycle by a process of complete condensation followed by raising of the pressure and temperature of the water.

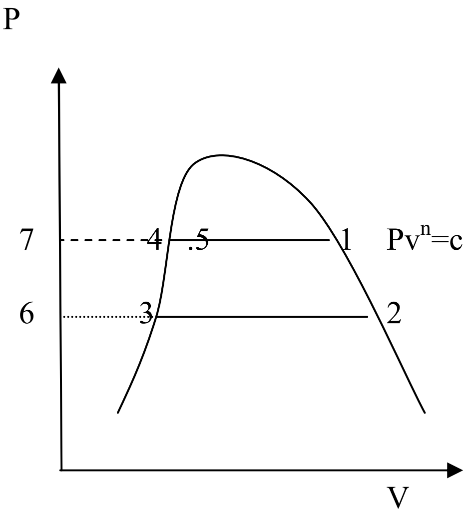
The Carnot cycle is purely used for comparison.

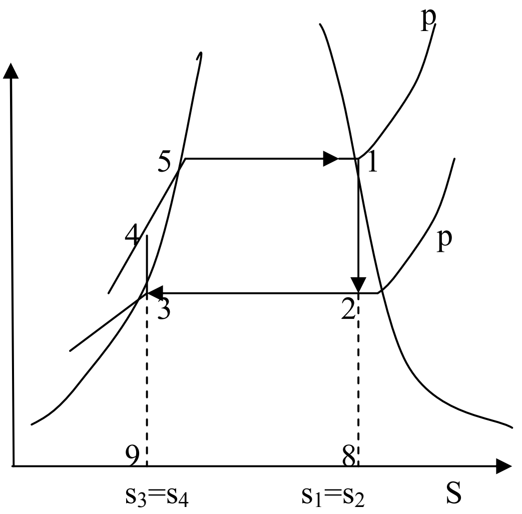
Limitations

In general the isothermal process in the boiler a-b and the isentropic expansion in the turbine b-c is a reasonable proposition. The impractical part is the partial condensation in the condenser and the compression of the wet steam in the feed pump. Modifications must be made to make the cycle in any way practical, although the modifications do reduce the cycle efficiency.

The Rankine Cycle.

(basic cycle for steam turbines and steam reciprocating engines).





Assume dry vapour at commencement of expansion.

From the p ~ v diagram

Expansion work ≡ area 67126 = $\frac{n}{n-1}$ $(P_1 V_1 - P_2 V_2)$

(flow work)

Compression work ≡ area 67436 ≈ $(P_1 - P_2) V_3$
(flow work)

∴ net cycle work (W) ≡ area 345123 = area 67126 – area 67456

$$= \frac{n}{n-1} (P_1V_1 - P_2V_2) - (P_1 - P_2)V_s$$

from the (T – S) diagram

cycle heat received = q in ≡ area 9451289

$= h_1 - h_4$

cycle heat rejected = q out ≡ area 93289
$= h_2 - h_3$

∴net cycle work (W) = q in – q out = area 9451289 - 93289 ≡ cycle area 345123

$= (h_1 - h_4) - (h_2 - h_3)$

$= (h_1 - h_2) - (h_4 - h_3)$

= W out – W in

where $h_1 - h_2 = W\ out = \frac{n}{n-1}(P_1V_1 - P_2V_2)$

$h_4 - h_3 = W\ in = (P_1 - P_2)V_3$

hence cycle $\eta = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)} = \frac{\text{net work}}{\text{heat received}}$

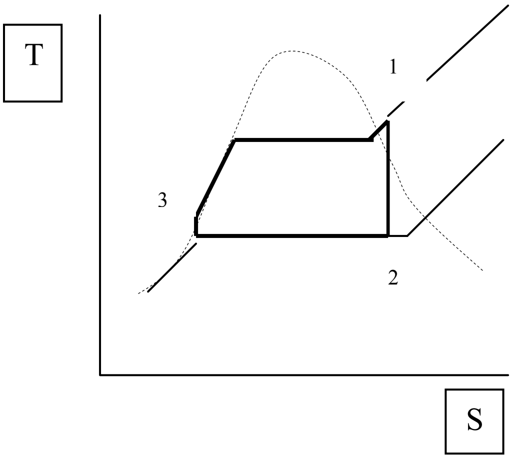
Rankine Cycle

Note: if compression (feed pump) work is neglected then the parts 3 & 4 on the diagram will become co-incident since $h_4 = h_3$ then the above expression would reduce to the following

Cycle $\eta = \frac{h_1 - h_2}{h_1 - h_4}$

The modification made to produce the Rankine Cycle is instead of only partially condensing the steam; condensation is completed in the condenser at point 3 on the T~S diagram. At this point there is all water. This water can be fed into the feed pump where the pressure is raised to boiler pressure. The feed pump process is shown by process 3-4. This is the feed pump work and since it is small is often (but not always) ignored.

When superheated steam is used in the cycle the T-S diagram is as shown below.



It is common to utilise numbers for suffix when completing problems

Work done = $h_1 - h_2$

Heat supplied = $h_1 - h_3$

Feed pump work = $(p_1 - p_2)v_3$ *(usually neglected but not always)*

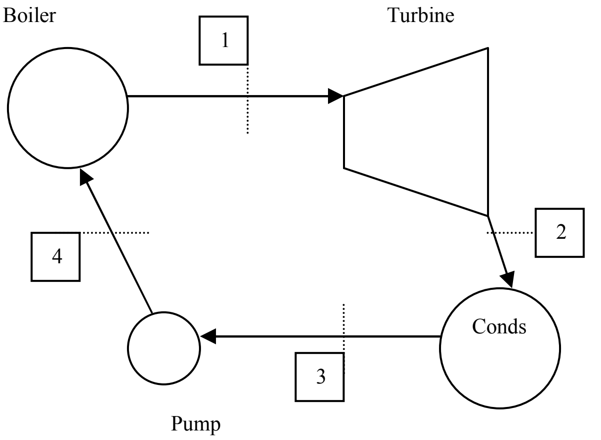
Where $v_3 = v_f$ *at boiler pressure*

$$\eta_{Rankine} = \frac{h_1 - h_2}{h_1 - h_3}$$

Ex 1.15

Steam at a pressure of 14 bar and a temperature of 260°C is supplied to an engine, which operates on the Rankine Cycle. The exhaust pressure is 0.07 bar. Determine:

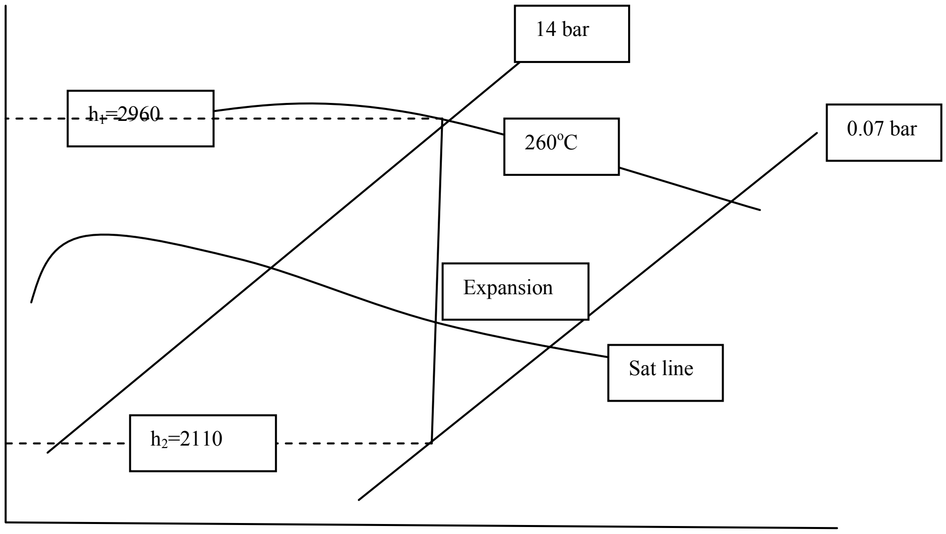
i) the work output per kilogram of steam
ii) the thermal efficiency of the plant.



Consider one kg of steam flowing through the system.

Determine the enthalpy values at various stages.

The simplest way to determine the enthalpy values at the various stages will be to represent the process of expansion in the turbine on an Enthalpy ~ Entropy chart.



$$h_1 \approx 2960 kJ/kg$$

$$h_2 \approx 2110 kJ/kg$$

$$w_{out} = h_1 - h_2 = 2960 - 2110 = \underline{850 kJ/kg}$$

$w_{feedpump} = v_f \times \Delta p$ where v_f is at sat temp of $39^\circ C$ which is the sat temp of0.07bar

Closest value in tables is v_f at $40^\circ C = 0.10018 \times 10^{-2} m^3/kg$

$$w_{feedpump} = v_f \times \Delta p = 0.10018 \times 10^{-2} \times (14 - 0.07) \times 10^2 = 1.4 kJ/kg$$

$$h_3 = h_f at 0.07 bar = 163 kJ/kg$$

$$h_4 = 163 + 1.4 = 164.4 kJ/kg$$

$$\eta = \frac{w_{net}}{Q_{in}} = \frac{w_{out} - w_{feedpump}}{h_1 - h_4} = \frac{850 - 1.4}{2960 - 164.4} = 0.3035 = \underline{30.35\%}$$

BY CALCULATION THE PROBLEM BECOMES MORE DIFFICULT SINCE COMPLEX INTERPOLATION IS REQUIRED.

Interpolation is both directions of the tables is required ie for pressure and also for temperature

$$h_{10\text{bar }250^\circ\text{C}} = 2944\text{kJ/kg}$$

$$h_{15\text{bar }250^\circ\text{C}} = 2925\text{kJ/kg}$$

$$h_{14\text{bar }250^\circ\text{C}} = 2944 - \frac{4}{5}(2944 - 2925) = 2928.8\text{kJ/kg}$$

$$h_{10\text{bar }300^\circ\text{C}} = 3052\text{kJ/kg}$$

$$h_{15\text{bar }300^\circ\text{C}} = 3039$$

$$h_{14\text{bar }300^\circ\text{C}} = 3052 - \frac{4}{5}(3052 - 3039) = 3041.6\text{kJ/kg}$$

$$h_{14\text{bar }260^\circ\text{C}} = 2928.8 + \frac{260-250}{300-250}(3041.6 - 2928.8) = 2951.4\text{kJ/kg} = h_1$$

This value compares favourably to that taken from the chart

entopy at (1) = entropy at (2)

To find s_1 we need to interpolate again

$$s_{10\text{bar }250^\circ\text{C}} = 6.926\text{kJ/kgK}$$

$$s_{15\text{bar }250^\circ\text{C}} = 6.711\text{kJ/kgK}$$

$$s_{14\text{bar }250^\circ\text{C}} = 6.926 - \frac{4}{5}(6.926 - 6.711) = 6.754\text{kJ/kgK}$$

$$s_{10\text{bar}300^\circ\text{C}} = 7.124\text{kJ/kgK}$$

$$s_{15\text{bar}300^\circ\text{C}} = 6.919\text{kJ/kgK}$$

$$s_{14\text{bar}300^\circ\text{C}} = 7.124 - \frac{4}{5}(7.124 - 6.919) = 6.96\text{kJ/kgK}$$

$$s_{14\text{bar}260^\circ\text{C}} = 6.754 + \frac{10}{50}(6.96 - 6.754) = 6.7952 = s_1 = s_2$$

$$s_2 = s_f + x \times s_{fg} \text{ at } 0.07 \text{ bar}$$

$$x = \frac{s_2 - s_f}{s_{fg}} = \frac{6.7952 - 0.559}{7.715} = 0.808$$

$$h_3 = h_f + xh_{fg} = 163 + 0.808(2409) = 2109.5\text{kJ/kg}$$

$$\text{work } w = h_1 - h_2 = 2951.4 - 2109.5 = \underline{841.9\text{kJ/kg}}$$

$$w_{\text{feedpump}} = 1.4\text{kJ/kg}$$

$$w_{\text{net}} = 841.9 - 1.4 = 840.5\text{kJ/kg}$$

$$Q_{\text{in}} = 2951.4 - 164.4 = 2787\text{kj/kg}$$

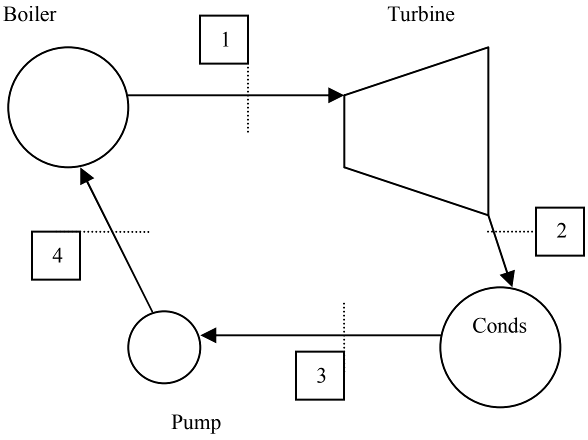
$$\eta_{\text{cycle}} = \frac{840.5}{2787} = 0.3016 = \underline{30.16\%}$$

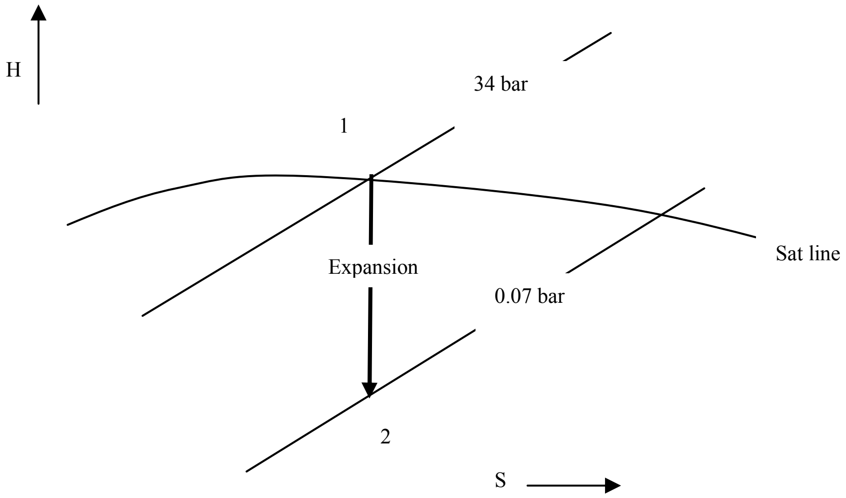
YOU CAN DECIDE WHICH IS THE EASIEST METHOD BUT REMEMBER IF THE EXAM QUESTION STATES CALCULATE THEN THE LATTER METHOD IS THE ONLY WAY TO APPROACH THE QUESTION

Ex 1.17

A steam engine operates on the Rankine Cycle between the pressure limits of 34 bar and 0.07 bar. The steam is dry saturated at the beginning of isentropic expansion. Determine:

- *i)* *the work transfer per kg of steam.*
- *ii)* *the heat transfer to the steam/kg of steam.*
- *iii)* *the heat transfer from the steam in the condenser/kg of steam.*
- *iv)* *the thermal efficiency of the engine.*





Probably more accurate to calculate using tables since values after the expansion are off the chart.

$h_1 = h_g$ at 34 bar = 2803 kJ/kg, $s_1 = s_2 = 6.136$kJ/kgK

$$s_2 = s_f + xs_{fg}$$

$$x = \frac{6.136 - 0.559}{7.715} = 0.723$$

$$h_2 = h_f + xh_{fg}$$

$$= 163 + 0.723(2409) = 1904.4kJ/kg$$

$$h_3 = 163kJ/kg$$

$$w_{feedpump} = vdp = 0.10075 \times 10^{-2} \times (34 - 0.07) \times 10^2 = 3.42kW$$

$$h_4 = 163 + 3.42 = 166.42kJ/kg$$

$$Work\ \mathrm{w} = \mathrm{h}_1 - h_2 = 2803 - 1904.4 = \underline{898.6kJ/kg}$$

$$W_{net} = 898.6 - 3.42 = 895.2kJ/kg$$

$$Q_{in} = h_1 - h_4 = 2803 - 166.42 = \underline{2536.6kJ/kg}$$

$$\eta = \frac{w_{net}}{Q_{in}} = \frac{859.2}{2636.6} = 0.3395 = \underline{33.95\%}$$

TRY THIS NEXT QUESTION YOURSELF THE ANSWERS ARE IN BRACKETS

Ex 1.18

Steam at a pressure of 30 bar and temperature of 250^oC is fed to a steam turbine from a boiler. In the turbine the steam is expanded isentropically to a pressure of 1 bar. The steam is then exhausted into a condenser but not undercooled. The condensate is then pumped back to the boiler. Determine:

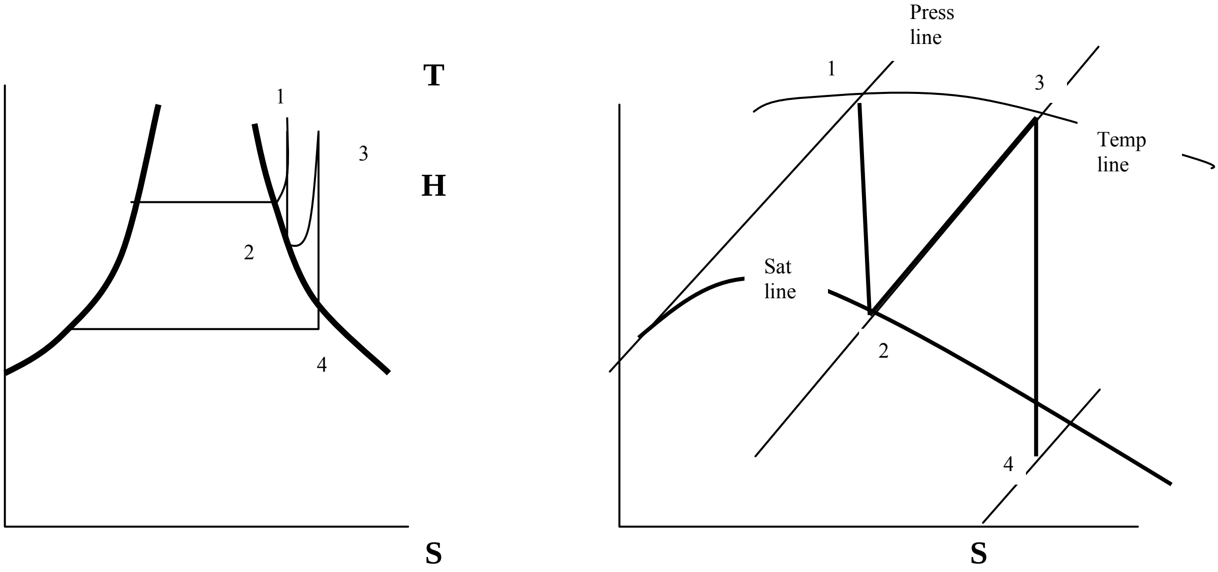
i)	*the dryness fraction of the steam after expansion.*	*(0.823)*
ii)	*The Rankine efficiency.*	*(23.88%)*

If the isentropic efficiency of the expansion of the steam is 0.8, determine the condition of the steam at the end of the expansion.(0.875)

Reheat

In modern steam plant the boiler pressures tend to be high which would lead to very large pressure ratios through the turbine. This may result in the steam becoming wet during expansion leading to erosion of turbine blades. To overcome this superheated steam after partial expansion is piped back to the boiler for reheating at constant pressure before being passed back to the turbine. The expansion, which follows, will be dry and superheated, largely eliminating the problems of erosion. Reheating is not common in marine practice largely because marine propulsion plant operates over a large power range and at lower powers precautions must be made to protect the reheater when no steam is passing through. This involves the use of gas by pass arrangements, which add to the complexity and cost of the plant.

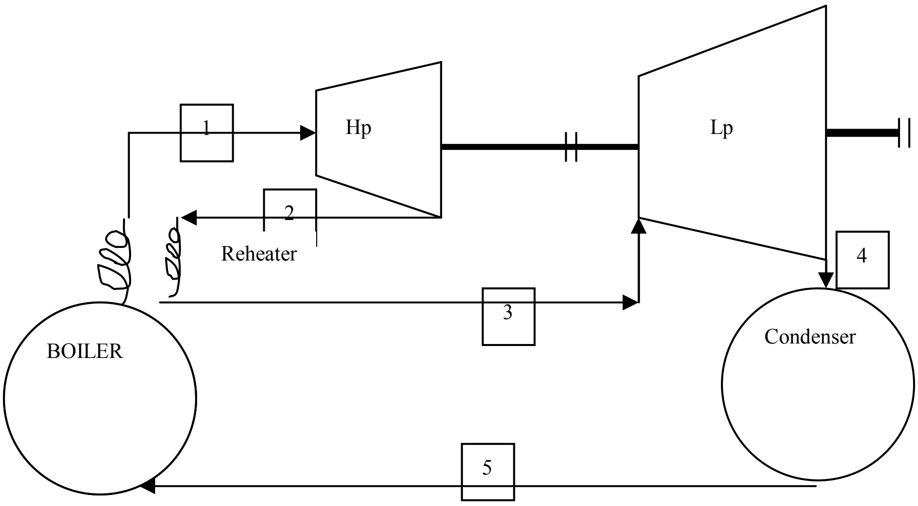
The reheat cycle can be shown on T-S and H-S diagrams.

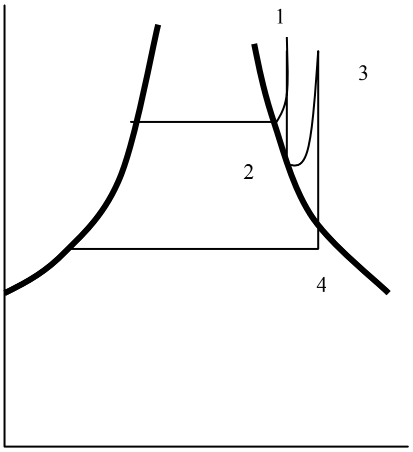


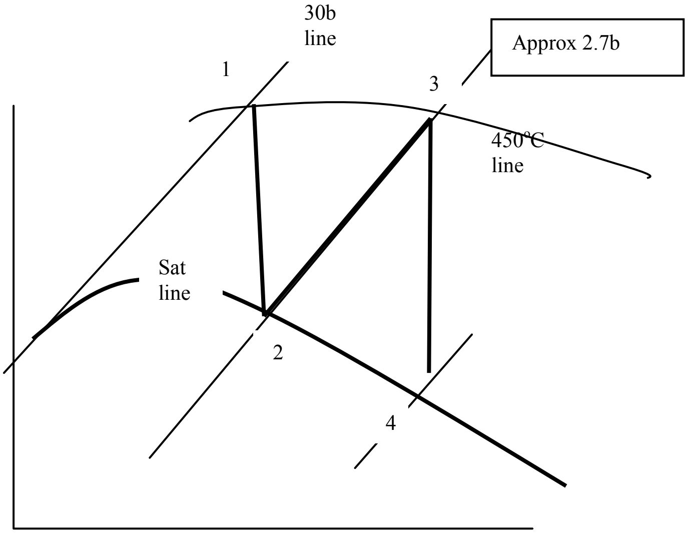
1-2 expansion in high pressure turbine
2-3 reheating at constant pressure to initial superheat temperature
3-4 expansion in next turbine stage.

Ex 1.19

Find the ideal cycle efficiency and specific steam consumption of a reheat cycle operating between pressures of 30 bar and 0.04 bar, with a superheat temperature of 450^{o}*C. Assume the first expansion is carried out to the point where steam is dry saturated and the steam is reheated to the original superheat temperature. Feed pump work may be neglected.*



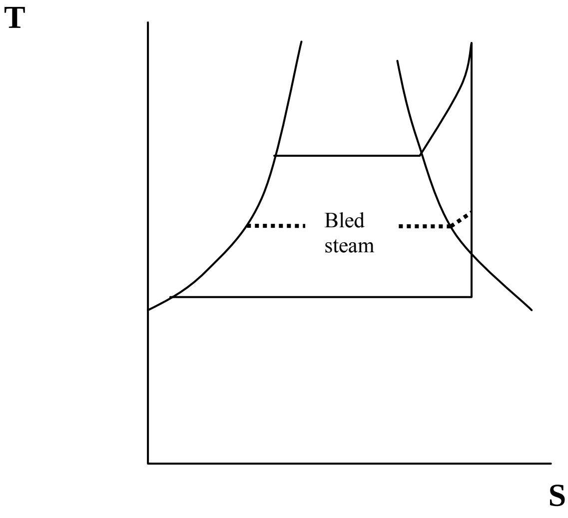


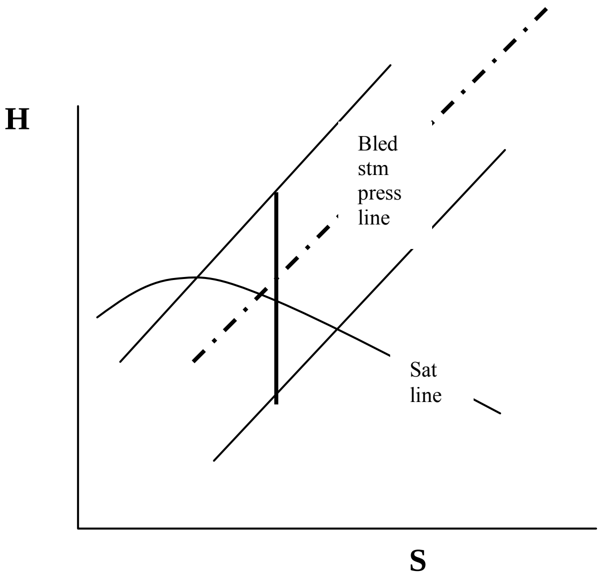


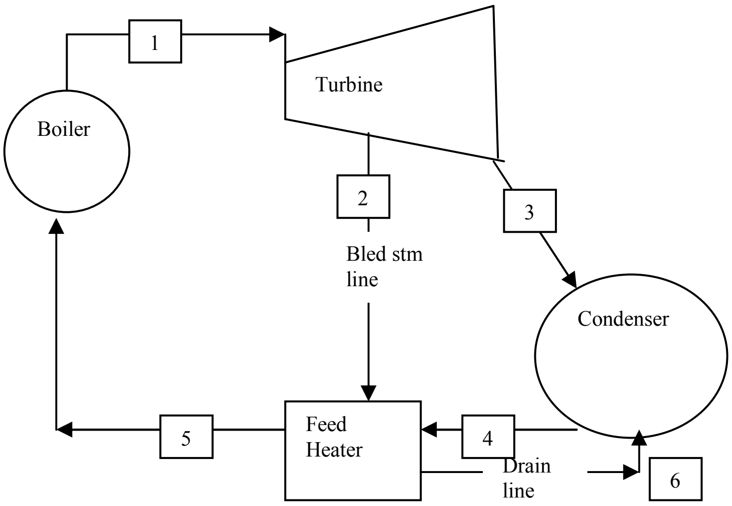
THIS QUESTION BEST WORKED OUT BY USING THE H~S CHART ;YOU WILL NEED A FULL SIZE CHART;CHECK THE VALUES YOURSELF

Feed Heating. (Regenerative Feed Heating)

The efficiency of the cycle can be improved by the use of feed heaters. At a suitable point in the turbine some steam is extracted (known as bled steam) and used to heat the feed water on its way to the boiler. The number of extraction points (bleed points) as well as the pressures and mass of steam extracted vary with each plant. A plant with one feed heater is shown.





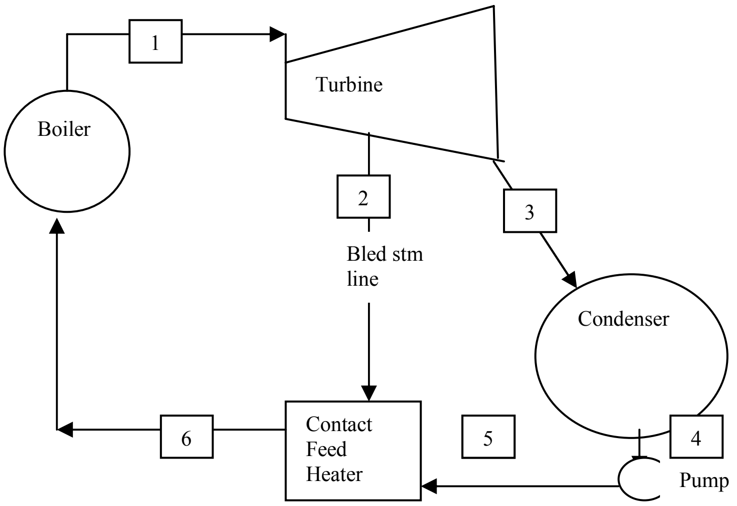


Simple Steam System showing bled steam to feed heater

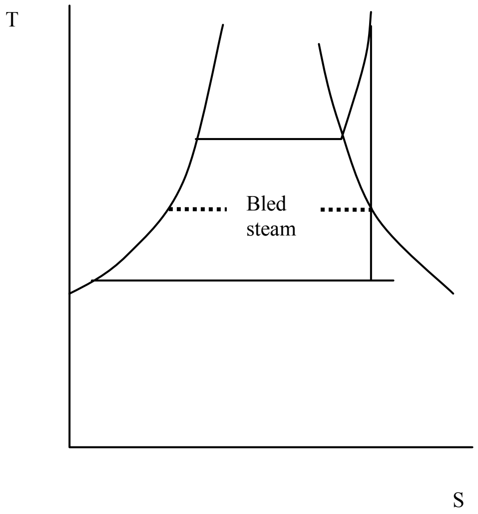
Ex 1.20 (Typical exam question)

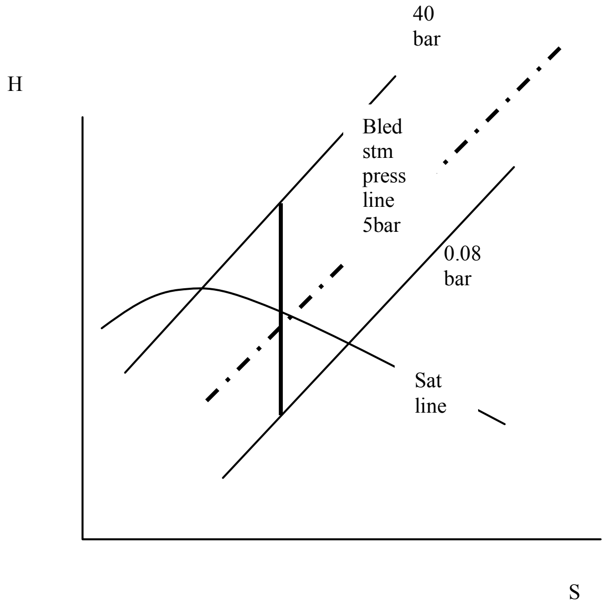
*A steam turbine installation has inlet conditions of 40 bar and 400^{o}C. The steam is expanded isentropically to a pressure of 5 bar. At this point some of the steam is bled off to a direct contact feed heater and the rest of the steam is expanded isentropically to a pressure of 0.08 bar. in the condenser. No undercooling takes place in the condenser, the feed water is heated to the saturation temperature of the bled steam and the feed pump work **CANNOT** be neglected.*

- *i) Sketch the temperature-entropy diagram for the cycle.*
- *ii) Determine the mass of bled steam/kg of steam flow.*
- *iii) Determine the efficiency of the cycle.*



Simple Steam System showing bled steam to contactfeed heater





Using the chart

$h_1 = 3220 kJ/kg$

$h_2 = 2725 kJ/kg$

$h_3 = 2120 kJ/kg$

from the tables

$h_4 = h_f @ 0.08 \text{ bar} = 392 \text{kJ/kg}$

$w_{\text{feedpump}} = v_f \times \Delta p = 0.01 \times 10^{-2} \times (40 - 0.08) \times 10^2 = 4 kJ/kg$

$h_5 = 392 + 4 = 396 kJ/kg$

$h_6 = 640 kJ/kg$

Let m = the mass flow of steam to the heater

Energy balance

Energy into heater = Enegy out of heater

$(m \times h_2) + (1 - m) \times h_5 = 1 \times h_6$

$2725m + 396 - 396m = 640$

$m = \underline{0.1048 kg/kg}$

$w_{out} = (h_1 - h_2) + (1 - m)(h_2 - h_3)$

$= (3220 - 2725) + 0.8952(2725 - 2120)$

$= 495 + 541.62 = 1036.62 kJ/kg$

$w_{net} = 1036.62 - 4 = 1032.62 kJ/kg$

$Q_{in} = h_1 - h_6 = 3220 - 640 = 2580 kJ/kg$

$$\eta = \frac{w_{net}}{Q_{in}} = \frac{1032.62}{2580} = 0.4 = \underline{40\%}$$

NOW TRY THE FOLLOWING VAPOUR POWER CYCLE EXAMPLES POSSIBLE SOLUTIONS ARE SHOWN AT THE END OF THE CHAPTER

Vapour Power Cycles Questions

1. A Rankine cycle (i.e. with no superheat) operates between 30 bar and 0.04 bar and uses 3.6 tonne/hour of steam.

   Calculate, using the tables provided:

   a) the feed pump work per second
   b) the cycle efficiency, including feed pump work;
   c) the work ratio
   d) the specific steam consumption

   Note:

   $$\textit{Work ratio} = \frac{\textit{net work output}}{\textit{work output}}$$

2. A steam turbine expands steam in two stages, from a pressure and temperature of 50 bar and 350^{o}C respectively to a condenser pressure of 0.05 bar the first stage is carried out to the point where the steam is dry saturated and the entropy increases by 4.8%. At this point some steam is bled away to a direct contact feed heater where it raises the feed water to a temperature 7^{o} below the bled steam saturation temperature. The remainder of the steam expands during the second stage to 0.05 bar and a dryness fraction of 0.92. The steam leaves the condenser at a temperature of 25^{o}C

3 In a steam plant using reheat , the turbine receives the steam at a pressure and temperature of 40 bar and 350^{o}C respectively. The steam expands in the first stage to a pressure of 10 bar with an isentropic efficiency of 0.8. It is then reheated at constant pressure to 350^{o}C. In the second stage the steam is expanded to a condenser pressure of 0.04 bar wuth an isentropic efficiency of 0.75. The feed pump work is negligible and there is no undercooling in the condenser. The steam flow is 5 tonne per hour.

a) Sketch the Temperature- Entropy diagram for the cycle
b) Determine

i) the cycle efficiency
ii) the power output
iii) the dryness fraction of the steam entering the condenser

POSSIBLE SOLUTIONS TO STEAM EXAMPLES

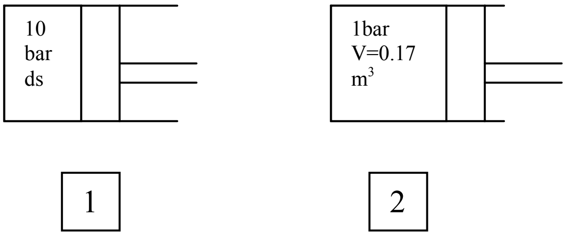
1. 0.12 kg of dry saturated steam at a pressure of 10 bar, expands reversibly and polytropically to a pressure and volume of 1 bar 0.17m^3 respectively

a) sketch the Temperature – Entropy diagram

b) Calculate

i) the index of expansion
ii) the heat transferred
iii) the change in entropy

a) It may be better to calculate some of the steam conditions before we attempt to draw the T~S diagram
b)



Mass of steam 0.12 kg

To find the index of expansion we must assume that the expansion follows the gas law of $PV^n = C$

We know the pressures at the 2 stages thus we must find the volumes at the initial stage

The volume v_1 can be found by determining v_g from the steam tables

At 10 bar ds the specific volume v_g =0.1944 m^3/kg

$$\begin{aligned}\mathbf{v}_1 &= \mathbf{m}\times\mathbf{v_g}\\ &= 0.12\times 0.1944\\ &= 0.023328\mathbf{m}^3\end{aligned}$$

from

$$\begin{aligned}&\mathbf{p}_1\mathbf{v}_1^{\mathbf{n}} = \mathbf{p}_2\mathbf{v}_2^{\mathbf{n}}\\ &10\times 0.023328^{\mathbf{n}} = 1\times 0.17^{\mathbf{n}}\\ &\mathbf{take}..\log\mathbf{s}..\mathbf{to}..\mathbf{base}10\\ &\log 10+\mathbf{n}\log 0.023328 = \mathbf{n}\log 0.17\\ &\therefore 1+(-1.6321\mathbf{n}) = (-0.769\mathbf{n})\\ &\therefore 1 = 0.8625\mathbf{n}\\ &\underline{\mathbf{n} = 1.159}\end{aligned}$$

To find the heat transferred utilise the Non flow energy equation

Ie

$$\mathbf{Q} = \Delta\mathbf{u}+\mathbf{w}$$

We will need to determine internal energies and work transfer

To calculate the internal energy at the 2 states we will need to determine the condition of the steam at state 2

Specific volume at 2 $\mathbf{v}_{\mathbf{s}_2} = \dfrac{\mathbf{v}_2}{\mathbf{mass}}$

$$= \frac{0.17}{0.12} = 1.41667\mathbf{m}^3/\mathbf{kg}$$

now v_g at 1 bar is 1.694m^3/kg and since this is greater than the actual specific volume of 1.41667m^3/kg then the steam must be wet. We can determine the dryness fraction (x) from:

$$\mathbf{v = xv_g}$$

$$\mathbf{x = \frac{v}{v_g}}$$

$$\mathbf{x} = \frac{1.41667}{1.694} = \underline{0.8363}$$

$$\mathbf{u_2 = u_f + x.u_{fg} ...(specific - values - at -} 1\mathbf{bar})$$

$$\mathbf{remember..u_{fg} = (u_g - u_f)}$$

$$\mathbf{u_2} = 417 + 0.8363(2506 - 417)$$

$$\mathbf{u_2} = 2164\mathbf{kJ/kg}$$

$$\mathbf{Total - Internal - energyU_2 = m \times u_2}$$

$$\underline{\mathbf{U_2}} = 0.12 \times 2164 = 259.7\mathbf{kJ}$$

From tables determine **u1 (specific values)**

$$\mathbf{u_1} = 2584\mathbf{kJ/kg}$$

$$\mathbf{U_1 = m \times u_1}$$

$$\mathbf{U_1} = 0.12 \times 2584 = 310.1\mathbf{kJ}$$

We must now find the work transfer

$$\mathbf{W = \frac{(p_1v_1 - p_2v_2}{n - 1}}$$

$$\mathbf{W} = \frac{[(10 \times 0.023328) - (1 \times 0.17)] \times 10^2}{1.159 - 1}$$

$$\mathbf{W} = 39.8\mathbf{kJ}$$

Using the Non Flow energy equation will allow the determination of the heat transferred

$$\mathbf{Q = \Delta U + W}$$

$$\mathbf{Q = (U_2 - U_1) + W}$$

$$\mathbf{Q} = (259.7 - 310.1) + 39.8$$

$$\mathbf{Q} = \underline{-10.6\mathbf{kJ}}$$

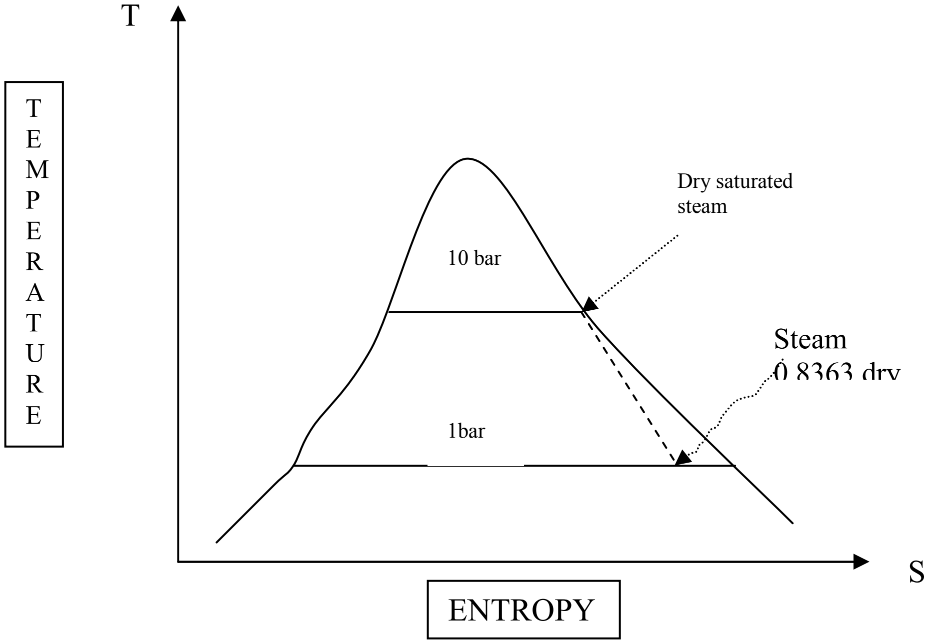
The change in entropy can be determined by taking the entropy values at the 2 stages from the steam tables

$$\mathbf{S}_1 = \mathbf{m} \times \mathbf{s}_1$$
$$\mathbf{S}_1 = 0.12 \times 6.686$$
$$\mathbf{S}_1 = 0.79\mathbf{kJ/K}$$

$$\mathbf{S}_2 = \mathbf{m} \times (\mathbf{s_f} + \mathbf{xs_{fg}})$$
$$\mathbf{S}_2 = 0.12(1.303 + 0.8363 \times 6.056)$$
$$\mathbf{S}_2 = 0.76412\mathbf{kJ/K}$$

$$\mathbf{Entropy..change} = \Delta\mathbf{S} = \mathbf{S}_2 - \mathbf{S}_1$$
$$\Delta\mathbf{S} = 0.76412 - 0.79 = \underline{-0.026\mathbf{kJ/K}}$$

i)

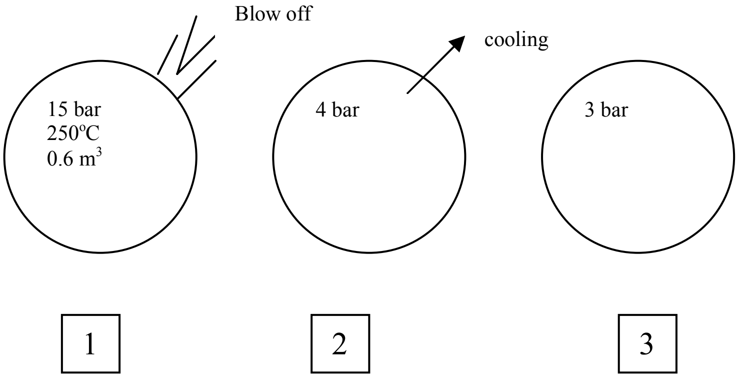

T
TEMPERATURE
10 bar
Dry saturated steam
Steam
0.8363 dry
1bar
S
ENTROPY

2. A vessel containing steam at a pressure and temperature of 15 bar and 250°C respectively, has a volume of 0.6 m^3. Steam is blown off until the pressure falls to 4 bar, the expansion of the steam in the vessel being isentropic during the blow off. The vessel is then cooled until the pressure is 3 bar.

   a) Sketch the Temperature – Entopy diagram

   b) Calculate

      i) the mass of steam blown off
      ii) the final dryness fraction of the steam
      iii) the heat transferred during cooling



Find the initial mass steam in the vessel i.e. m_3

$V_{1(secific)}$ from the tables at 15 bar 250°C = 0.152 m^3/kg

$$\mathbf{m}_1 = \frac{\mathbf{V}}{\mathbf{v}_{\mathbf{1sp}}} = \frac{0.6}{0.152} = 3.947\mathbf{kg}$$

We must now find the condition of the steam after blow off
We can use the fact that the process is isentropic
Hence $S_1 = S_2 = 6.711$ kJ/kgK
S_g at 4 bar is 6.897kJ/kgK > S_2 hence the steam is wet
From

$$\mathbf{s}_2 = \mathbf{s_f} + \mathbf{x.s_{fg}}$$
$$6.711 = 1.776 + \mathbf{x}5.121$$
$$\therefore \mathbf{x} = 0.964$$

Volume at 2 $V_2 = 0.6m^3$

$$\mathbf{v}_{\mathbf{2sp}} = \mathbf{x.v_g} = 0.964 \times 0.4623 = 0.4455\mathbf{m}^3 / \mathbf{kg}$$

$$\mathbf{V}_2 = \mathbf{m}_2 \times \mathbf{v}_{2sp}$$

$$\mathbf{m}_2 = \frac{0.6}{0.4455} = 1.3468\mathbf{kg}$$

mass of steam blown off = $m_1 - m_2 = 3.947 - 1.3468 =$ **<u>2.6 kg</u>**

At the final condition of 3 barm_3 =1.3468 kg and V_3=0.6m^3

$$\mathbf{v}_{3sp} = \frac{\mathbf{V}_3}{\mathbf{m}_3} = \frac{0.6}{1.3} = 0.446\mathbf{m}^3/\mathbf{kg}$$

$$\mathbf{v}_{3sp} = \mathbf{x}.\mathbf{v}_{\mathbf{g}} \therefore \mathbf{x} = \frac{\mathbf{v}_{3sp}}{\mathbf{v}_{\mathbf{g}}} = \frac{0.446}{0.6057} = 0.736$$

from the N.F.E.E

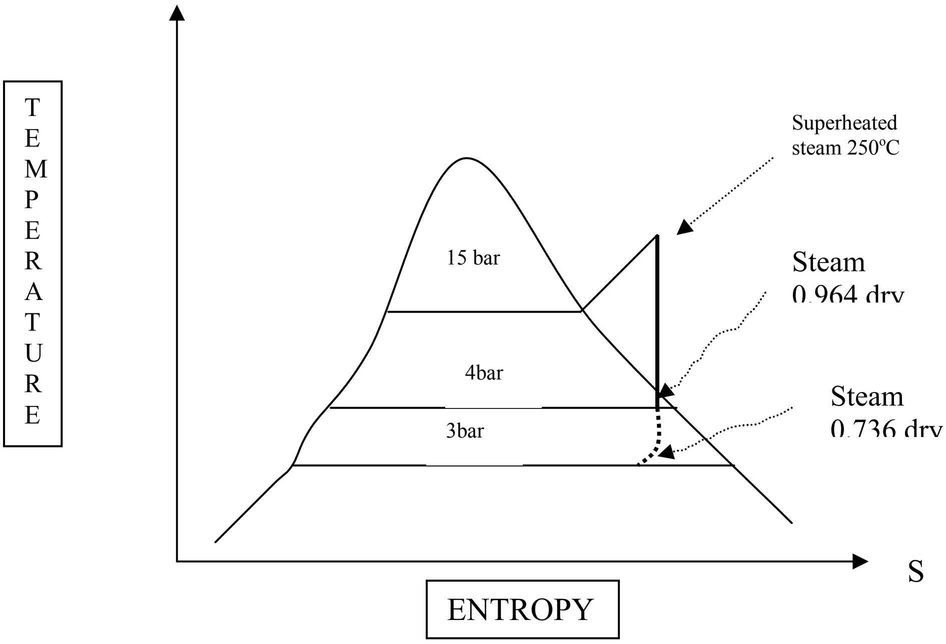
$$\mathbf{Q} = \Delta\mathbf{U} + \mathbf{W}$$
$$\mathbf{W} = 0$$
$$\therefore \mathbf{Q} = \Delta\mathbf{U} = (\mathbf{u}_3 - \mathbf{u}_2) \times \mathbf{m}_3$$

$$\mathbf{u}_{2sp} = \mathbf{u}_{\mathbf{f}} + \mathbf{x}.\mathbf{u}_{\mathbf{fg}}$$
$$\mathbf{u}_{2sp} = 605 + 0.964(2554 - 605)$$
$$\mathbf{u}_{2sp} = 2483.84\mathbf{kJ}/\mathbf{kg}$$

$$\mathbf{u}_{3sp} = \mathbf{u}_{\mathbf{f}} + \mathbf{x}.\mathbf{u}_{\mathbf{fg}}$$
$$\mathbf{u}_{3sp} = 561 + 0.736(2544 - 561)$$
$$\mathbf{u}_{3sp} = 2020.5\mathbf{kJ}/\mathbf{kg}$$

$$\mathbf{Q} = \Delta\mathbf{U} = (\mathbf{u}_3 - \mathbf{u}_2) \times \mathbf{m}_3$$
$$\mathbf{Q} = (2020.5 - 2483.84) \times 1.3468$$
$$\mathbf{Q} = \underline{-624\mathbf{kJ}}$$

Heat lost during cooling = 624kJ

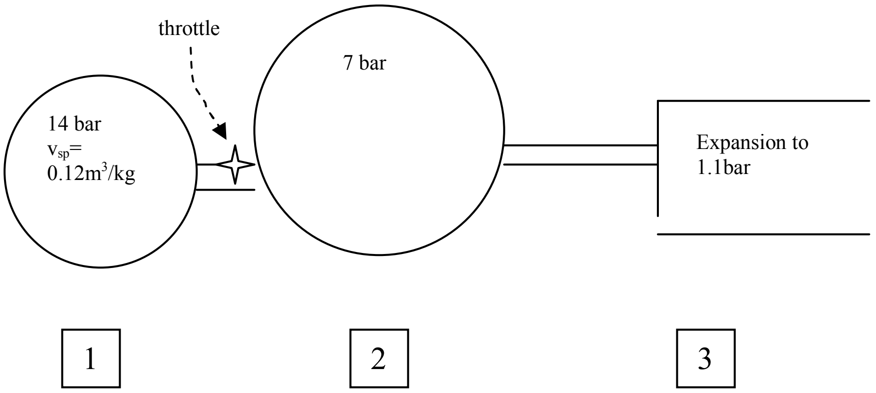


3. Steam of specific volume $0.12 m^3/kg$ at 14 bar is throttled to 7 bar and then expanded hyperbolically and reversibly to 1.1bar.

   a) Sketch the process on a Temperature Entropy diagram showing all of the temperatures

   b) Calculate:

      i) the change in entropy across each process
      ii) the total entropy change



b) i) Find the condition of the steam at state (1)

v_g at 14 bar is $0.1408 m^3/kg > 0.12 m^3/kg$ hence the steam is wet from

$$\mathbf{v} = \mathbf{x}.\mathbf{v_g}$$
$$\mathbf{x} = \frac{0.12}{0.1408} = 0.8523$$

Since we are throttling steam between (1) and (2) then the enthalpy at (1) is equal to the enthalpy at 2

$$\mathbf{h}_1 = \mathbf{h_f} + \mathbf{xh_{fg}} = 830 + 0.8253 \times 1960 = 2500\mathbf{kJ/kg}$$
$$\mathbf{h}_1 = \mathbf{h}_2 = 2500\mathbf{kJ/kg}$$

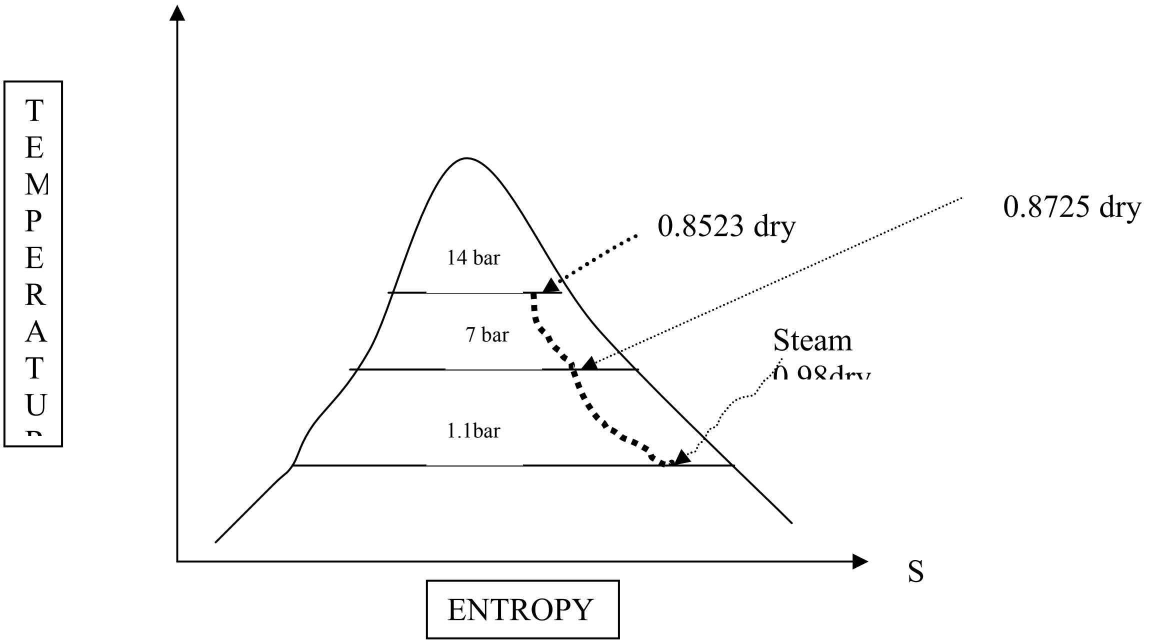
h_g at 7 bar =2764 >2500 hence steam is still wet

at 7 bar

$$\mathbf{h}_2 = \mathbf{h_f} + \mathbf{xh_{fg}}$$
$$\mathbf{hence}$$
$$\mathbf{x} = \frac{2500 - 697}{2067} = 0.8725$$
$$\mathbf{v}_2 = \mathbf{xv_g} = 0.8725 \times 0.2728 = 0.238$$

Expansion from 2 to 3 is hyperbolic hence

$$\mathbf{p}_2\mathbf{v}_2 = \mathbf{p}_3\mathbf{v}_3$$
$$7 \times 0.238 = 1.4 \times \mathbf{v}_3$$
$$\mathbf{v}_3 = 1.51466\mathbf{m}^3$$
$$\mathbf{v_g} = 1.549\mathbf{m}^3$$
$$\mathbf{steam - is - wet}$$
$$\mathbf{x} = \frac{\mathbf{v}}{\mathbf{v_g}} = \frac{1.51466}{1.549} = 0.98$$



Change of entropy from 1 to 2 = s_2 - s_1

$$\mathbf{s}_1 = \mathbf{s_f} + \mathbf{s_{fg}} = 2.254 + 0.8523 \times 4.185 = 5.851$$

$$\mathbf{s}_2 = 1.992 + 0.8725 \times 4.717 = 6.1076\,\mathbf{kJ/kgK}$$

$$\Delta\mathbf{s} = \mathbf{s}_2 - \mathbf{s}_1 = 6.1076 - 5.851 = 0.2565\,\mathbf{kJ/kgK}$$

$$\Delta\mathbf{s}_{\mathbf{evap}} = \mathbf{s}_3 - \mathbf{s}_2$$

$$\mathbf{s}_3 = 1.333 + 0.98 \times 5.994 = 7.207\,\mathbf{kJ/kgK}$$

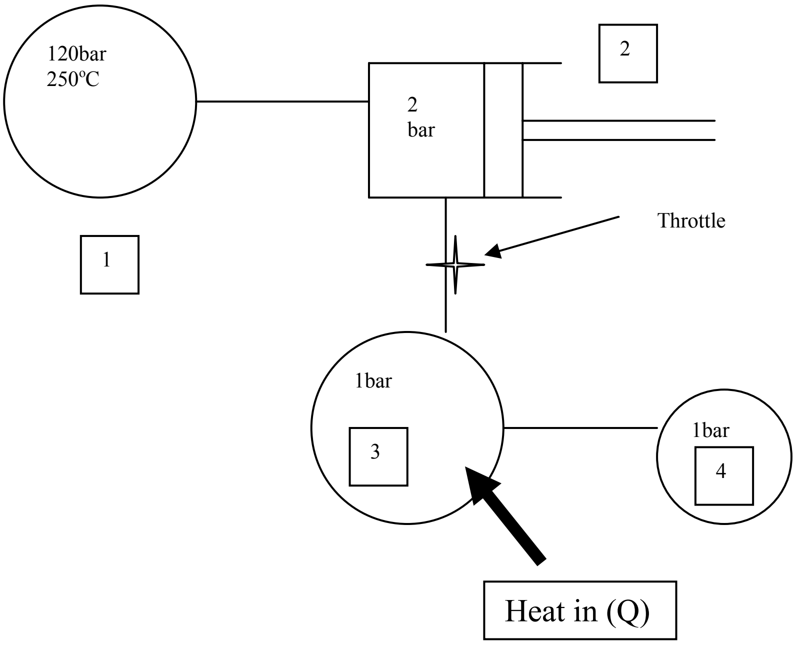
$$\Delta\mathbf{s}_{\mathbf{evap}} = 7.207 - 6.1076 = 1.0995\,\mathbf{kJ/kgK}$$

$$\mathbf{Total} - \Delta\mathbf{s} = \Delta\mathbf{s}_{1-2} + \Delta\mathbf{s}_{2-3} = \underline{1.356\,\mathbf{kJ/kgK}}$$

4. Steam at 20 bar 250°C is expanded isntropically to 2 bar before being throttled to 1 bar and then heated at constant pressure to the original specific enthalpy.

   c) Sketch the process on a TS diagram
   d) Using the tables provided calculate

      iii) the final steam condition
      iv) the change in entropy during the heating



a) Before we can make a reasonable sketch of the T~S diagram we ned to determine the quality of the steam at the various locations

b) .

   i) At (1) $h_1 = 2904$ kJ/kg $s_1 = 6.547$ kJ/kgK

   At (2) $s_2 = s_1 = 6.547$ kJ/kgK

   S_g at 2 bar =7.127kJ/kgK

   Hence the steam is wet

$$s_2 = \mathbf{s}_f + \mathbf{s}_{fg}$$

$$\mathbf{x}_2 = \frac{\mathbf{s}_2 - \mathbf{s}_f}{\mathbf{s}_{fg}} = \frac{6.547 - 1.53}{5.597} = 0.8964$$

also

$$\mathbf{h}_2 = \mathbf{h}_3 = \mathbf{h}_f + \mathbf{x}\mathbf{h}_{fg} = 505 + 0.8964 \times 2202 = 2478.9\,\mathbf{kJ/kg}$$

h_g at 1 bar = 2675 kJ/kg hence the sream is still wet

$$\mathbf{x}_3 = \frac{\mathbf{h}_3 - \mathbf{h}_f}{\mathbf{h}_{fg}} = \frac{2478.9 - 417}{2258} = 0.913$$

$$s_3 = \mathbf{s}_f + \mathbf{s}_{fg} = 1.303 + 0.913(6.056) = 6.853\,\mathbf{kJ/kgK}$$

$$\mathbf{h}_4 = \mathbf{h}_1 = 2909\,\mathbf{kJ/kg}$$

however

h_g at1 bar = 2675 < 2909 hence the steam must be superheated

and the final temperature must lie between $200^\circ\mathbf{C}$ and $250^\circ\mathbf{C}$

Interpolation is required to find the superheat temperature

$$\mathbf{t}_4 = \mathbf{t}_{200} + \frac{\mathbf{h}_4 - \mathbf{h}_{200}}{\mathbf{h}_{250} - \mathbf{h}_{200}}(\mathbf{t}_{250} - \mathbf{t}_{200})$$

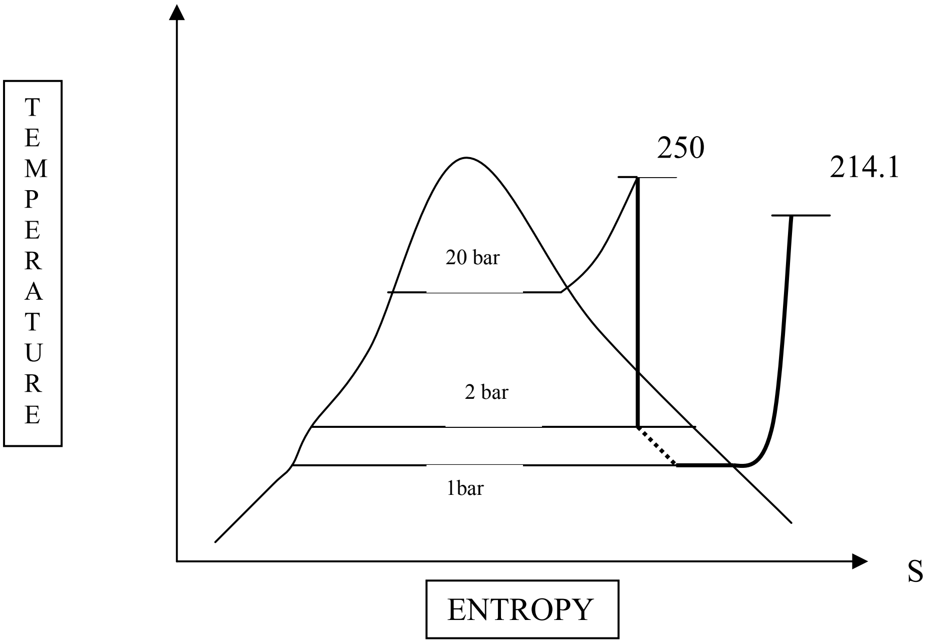
$$\mathbf{t}_4 = 200 + \frac{2904 - 2876}{2975 - 2876}(250 - 200) = \underline{214.1^\circ\mathbf{C}}$$

similarly

$$\mathbf{s}_4 = 7.834 + \frac{2904 - 2876}{2975 - 2876}(8.033 - 7.834) = 7.89\,\mathbf{kJ/kgK}$$

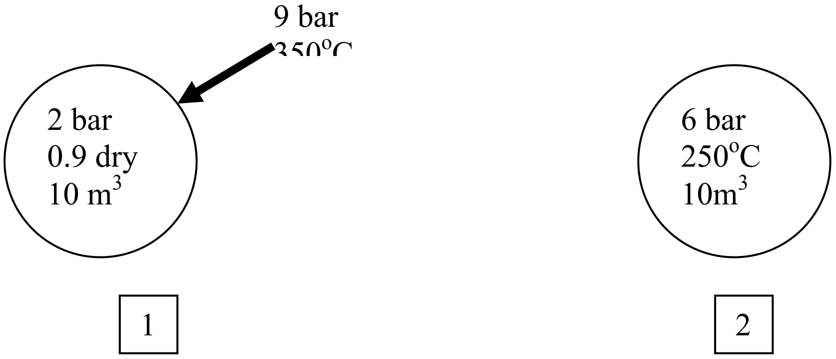
hence

$$\Delta\mathbf{s} = \mathbf{s}_4 - \mathbf{s}_3 = 7.89 - 6.853 = 1.037\,\mathbf{kJ/kgK}$$



5. A 10 m^3 vessel contains steam at 2 bar 0.9 dry. Steam at 9 bar 350^{o}C is admitted into the vessel until the final conditions are 6 bar 250^{o}C.

a) Calculate the total heat transfer during the process
b) State the direction of the heat transfer during the process



At condition (1)

$$v_{specific} \text{ at 2 bar 0.9 dry} = xv_g = 0.9 \times 0.8856 = 0.797\mathbf{m}^3/\mathbf{kg}$$

$$\text{mass of steam in container} = \frac{V_{container}}{v_{specific}} = \frac{10}{0.797} = 12.546\mathbf{kg}$$

$$\text{At condition (2) 6 bar } 200^\circ\mathbf{C}$$

$$\mathbf{v}_2 = 0.394$$

$$\mathbf{m}_2 = \frac{10}{0.394} = 25.38\mathbf{kg}$$

$$\text{mass of steam added} = 25.38 - 12.546 = 12.835\text{kg}$$

We must now consider the energy equation

The initial energy + the energy added = the final energy

The initial energy is internal energy

The energy added is internal energy +flow work i.e. enthalpy

The final energy is internal energy

Initial energy

$$(\mathbf{m_s} \times \mathbf{U})_{\mathbf{at}\,2\mathbf{bar}} + \mathbf{m}_{\mathbf{added}} \times \mathbf{H}_{\mathbf{at}\,9\mathbf{bar}\,350}$$

$$\{12.546 \times (505 + 0.9(2530 - 505))\} + 12.835 \times 3160 = 69759.42\,\mathbf{kJ}$$

Final energy

$$\mathbf{m}_{\mathbf{total}} \times \mathbf{U}_{6\mathbf{bar}\,250} = 25.38 \times 2722 = 69084.36$$

Final energy < initial hence heat is lost from the system

Heat lost = 69759.42 – 69084.36 = <u>675 kJ</u>

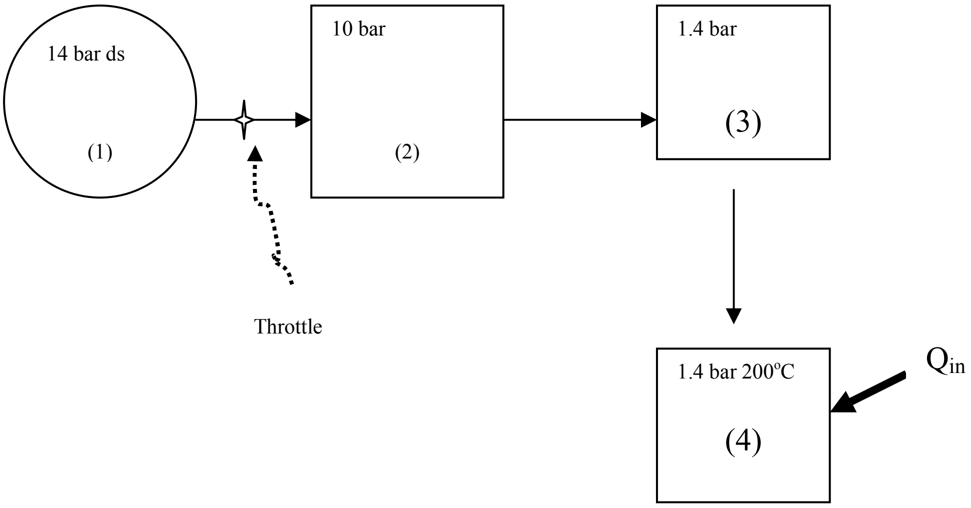
6. One kg of steam is throttled from 14 bar dry saturated to 10 bar, then expanded isentropically to 1.4 bar and finally heated at constant pressure to 200°C.

a) Sketch the process on a T~S diagram

b) Using the tables provided:

i) Calculate for each of the three processes
   1) the final steam condition
   2) the change in enthalpy

ii) Calculate the overall change in entropy



a) Complete the T~S diagram when more information on steam condition at the various points is known

b)

$$\mathbf{h}_1 = \mathbf{h}_2 = 2790\,\mathbf{kJ/kg}$$

h_g at 10 bar $= 2778 < 2790$ hence the steam is superheared . The S/H condition lies between sat temp and 200° C. Interpolation is required

$$\mathbf{t}_2 = \mathbf{t}_s + \frac{\mathbf{h}_{200} - \mathbf{h}_2}{\mathbf{h}_{200} - \mathbf{h}_g}(\mathbf{t}_{200} - \mathbf{t}_{sat})$$

$$\mathbf{t}_2 = 179.9 + \frac{2790 - 2778}{2828 - 2778}(200 - 179.9)$$

$$\mathbf{t}_2 = 179.9 + \frac{12}{51}(20.1)$$

$$\mathbf{t}_2 = \underline{184.6^{\circ}}\mathbf{C}$$

by interpolation

$$\mathbf{s}_2 = 6.586 \times \frac{12}{51}(6.695 - 6.586)$$

$$\mathbf{s}_2 = 6.6117\mathbf{kJ/kgK} = \mathbf{s}_3$$

now s_g at 1.4 bar = 7.246 kJ/kgK this is greater than s_2 hence steam is wet at point 3

$$\mathbf{s} = \mathbf{sf} + \mathbf{x.s_{fg}}$$

$$\mathbf{s}_3 = 6.6117 = 1.411 + \mathbf{x}5.835$$

$$\mathbf{x} = \frac{6.6117 - 1.411}{5.835} = \underline{0.8913}$$

$$\mathbf{h}_3 = \mathbf{h_f} + \mathbf{xh_{fg}}$$

$$\mathbf{h}_3 = 458 + 0.8913 \times 2232 = 2447.35\mathbf{kJ}$$

$$\mathbf{h}_4 = \mathbf{h_{1bar}} - (\frac{1.4-1}{1.5-1})(\mathbf{h}_{1..5\mathbf{bar}} - \mathbf{h_{1bar}}) \text{ all at } 200^\circ \text{C}$$

$$\mathbf{h}_4 = \frac{0.4}{0.5}(2876 - 2873) = 2873.6\mathbf{kJ/kg}$$

Enthalpy change 1-2 = $\underline{0}$

“ “ 2-3 = $\underline{2790 - 2447.35 = 342.65 \text{ kJ/kg}}$

“ “ 3-4 = $\underline{2447.35 - 2873.6 = 426.25 \text{ kJ/kg}}$

$$\mathbf{s}_4 = 7.834 - \frac{0.4}{0.5}(7.828 - 7.643)$$

$$\mathbf{s}_4 = 7.686\mathbf{kJ/kgK}$$

from the steam tables $\mathbf{s}_1 = 6.469\mathbf{kJ/kgK}$

$\therefore$

$$\Delta\mathbf{s} = \mathbf{s}_4 - \mathbf{s}_1 = \underline{1.217\mathbf{kJ/kgK}}$$

POSSIBLE SOLUTIONS TO VAPOUR POWER CYCLES

1. A Rankine cycle (i.e. with no superheat) operates between 30 bar and 0.04 bar and uses 3.6 tonne/hour of steam.

Calculate, using the tables provided;

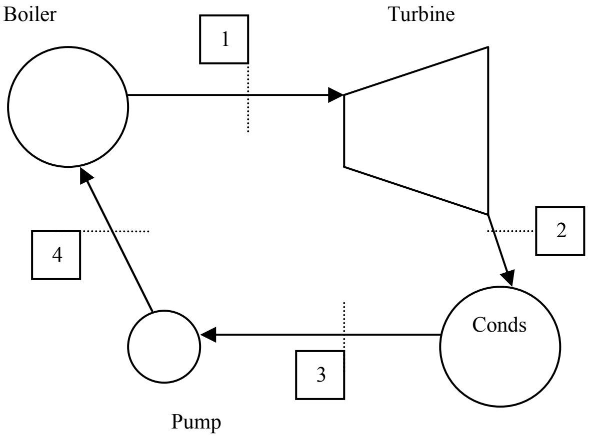
a. the feed pump work per second
b. the cycle efficiency, including feed pump work;
c. the work ratio
d. the specific steam consumption

Note:

Work ratio = $\dfrac{\textit{net work output}}{\textit{work output}}$

Since the question states that we must use tables then we cannot resort to the use of an H~S chart. As a general rule if the question asks you to calculate then use steam tables; if the question asks you to determine then use of a chart/steam tables would be appropriate.

A simple sketch of the system may be useful



Feed pump work $= \mathrm{v_f} \times dp$

where $\mathrm{v_f}$ = specific volume at 0.04 bar and

dp = difference in pressure between boiler and condenser (units $\mathrm{N/m^2}$ or $\mathrm{kN/m^2}$)

$\mathrm{v_f} = 0.1004 \times 10^{-2}\ \mathrm{m^3/kg}$ (from stm tables)

$\mathrm{dp} = (30 - 0.04) \times 10^2\ \mathrm{kN/m^2}$

Specific feed pump work $= 0.1004 \times 10^{-2} \times (30 - 0.04) \times 10^2 = 3kJ/kg$

Feed pump work done per sec = mass flow rate of feed × specific work done

$$= \frac{3.6 \times 10^3 \times 3}{3600} = \underline{3kW}$$

To determine the cycle efficiency we need to determine enthalpy values at the salient points of (1),(2),(3) & (4)

From the tables $\mathrm{h_1} = 2803$ kJ/kg

The steam at point (2) will be wet hence determination of the dryness fraction necessary

This dryness fraction can be determined from entropy values since for a rankine cycle

$\mathrm{s_1} = s_2 = 6.186\mathrm{kJ/kgK}$ and $\mathrm{s_2} = s_f + xs_{fg}$ where $\mathrm{s_f}$ and $\mathrm{s_{fg}}$ are at a pressure of 0.04 bar

$$x = \frac{\mathrm{s_2 - s_f}}{\mathrm{s_{fg}}} = \frac{6.186 - 0.422}{8.051} = 0.716$$

hence $\mathrm{h_2} = h_f + xh_{fg}$ where $\mathrm{h_f}$ and $\mathrm{h_{fg}}$ are at a pressure of 0.04 bar

$h_2 = 121 + 0.716 \times 2433 = 1863kJ/kg$

Turbine Work $= \mathrm{h_1 - h_2} = 2803 - 1863 = 940$ kJ/kg

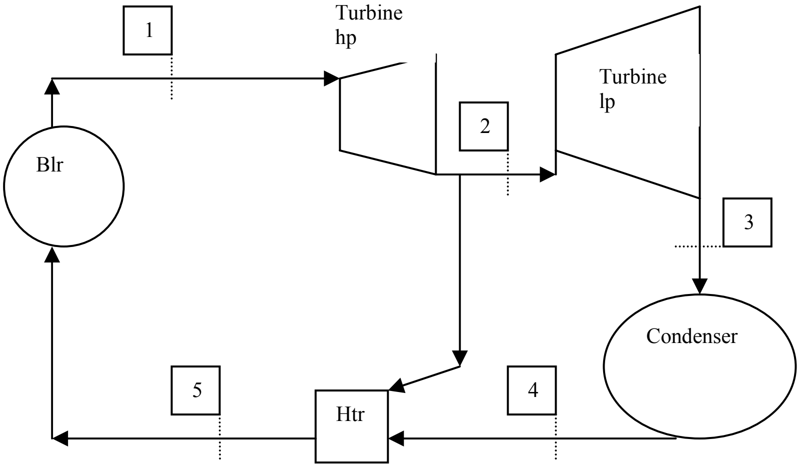
Qin $= \mathrm{h_1 - h_4}$ where $\mathrm{h_4 = h_f}$ at $0.04\mathrm{b} + 3 = 112 + 3 = 115$kJ/kg

$$\eta_{\mathrm{cycle}} = \frac{w_{net}}{Q_{in}} = \frac{940 - 3}{2803 - 115} = \underline{34.9\%}$$

$$\text{work ratio} = \frac{\mathrm{w_{net}}}{\mathrm{w_{turbine}}} = \frac{940 - 3}{940} = \underline{0.9968}$$

$$\text{Specific steam consumption} = \frac{3600}{\mathrm{w_{turbine}}} = \frac{3600}{940} = \underline{3.829kg/kWh}$$

2. A steam turbine expands steam in two stages, from a pressure and temperature of 50 bar and 350°C respectively to a condenser pressure of 0.05 bar the first stage is carried out to the point where the steam is dry saturated and the entropy increases by 4.8%. At this point some steam is bled away to a direct contact feed heater where it raises the feed water to a temperature 7° below the bled steam saturation temperature. The remainder of the steam expands during the second stage to 0.05 bar and a dryness fraction of 0.92. The steam leaves the condenser at a temperature of 25°C



a) Before we attempt to sketch the T~S diagram it may be advisable to determine some of the steam conditions throughout the cycle.

b) Since this part of the question only asks us to determine then we can utilise a combination of H~S chart and steam tables

$$\text{From steam tables } h_1 = 3070 \text{ kJ/kg}$$

$$s_1 = 6.451 \text{ kJ/kgK}$$

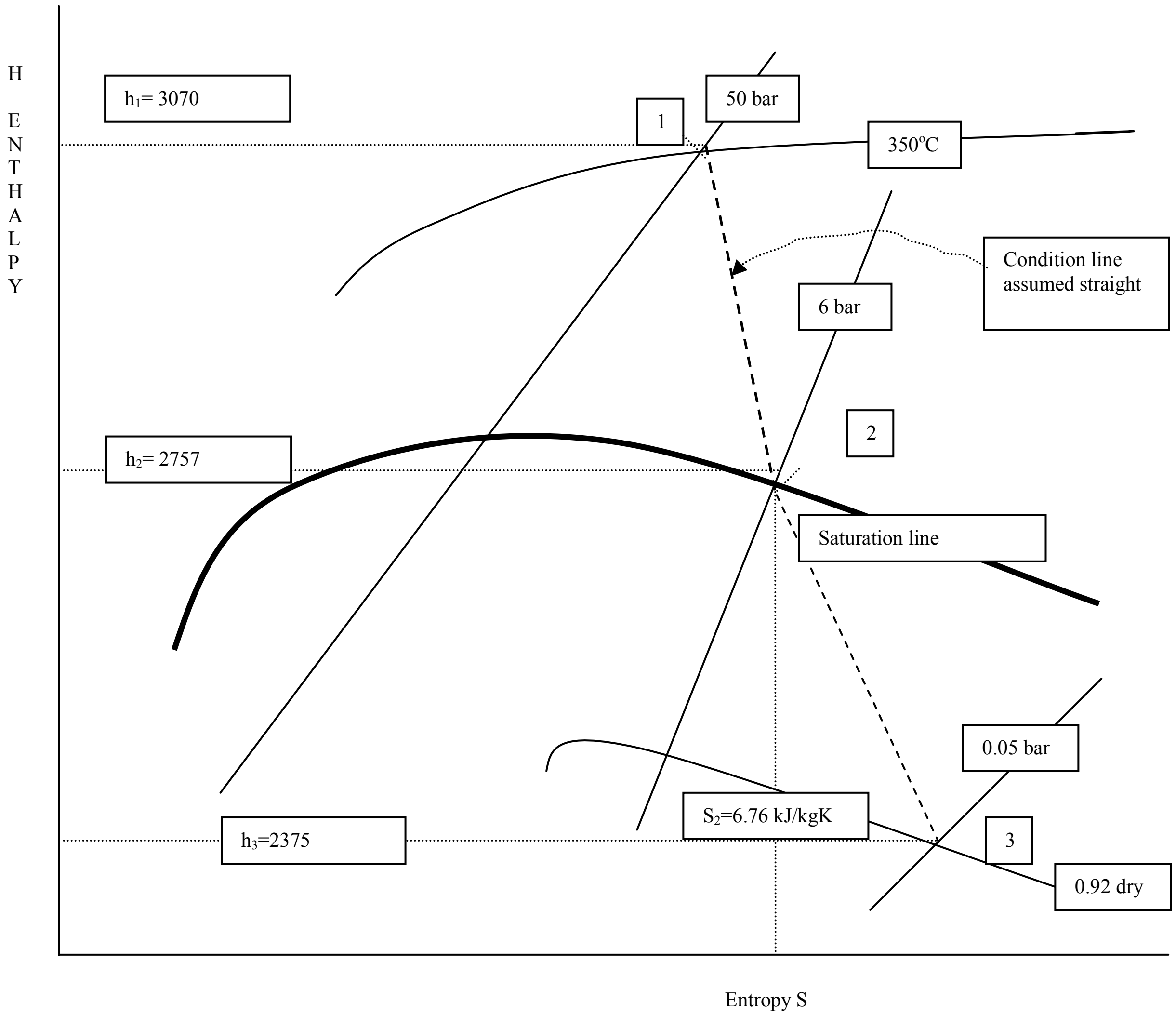
$$s_2 = 6.451 \times 1.048 = 6.76 \text{ kJ/kgK}$$

$$\text{also } h_4 = h_f \text{ at } 25^\circ\text{C} = 104.8 \text{ kJ/kgK}$$

On the h~s chart locate point (1) ie the intersection of the 50 bar pressure line and the 350°C constant temperature line

To locate point (2) find the position for s_2 = 6.76kJ/kgK entropy on the horizontal axis and project this line upwards until it intersects the saturation line (ie the thicker black line) You will note that this corresponds to a pressure of 6 bar

See a sketch of the hs chart below

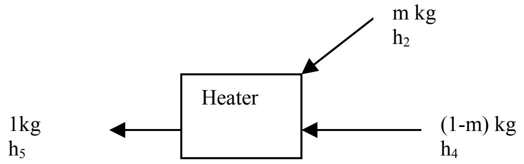


Determine point (3) at the intersection of the 0.05 bar pressure line and the 0.92 dryness line from which we can locate h_3=2375 kJ/kg

We can now determine h_5 from the tables since we know that it is 7 K below the sat temp of 6 bar pressure = 158.8°C hence feed temperature is 158.8 -7 = 151.8°C

Determine h_5 by locating h_f at 151.8°C = 640 kJ/kg

We now need to determine the mass flow of steam bled from the system to supply the heater. This mass flow rate can be determined by considering an energy balance around the heater. Let m = mass flow rate of steam to the feed heater



The general rule for this energy balance is: **ENERGY IN = ENERGY OUT**
Neglecting kinetic and potential energy and only considering total enthalpies

Hence

$$(m \times h_2) + ((1-m) \times h_4) = (1 \times h_5)$$

$$m \times 2757) + ((1-m) \times 104.8) = (1 \times 640)$$

$$2757m + 104.8 - 104.8m = 640$$

$$2757m - 104.8m = 640 - 104.8$$

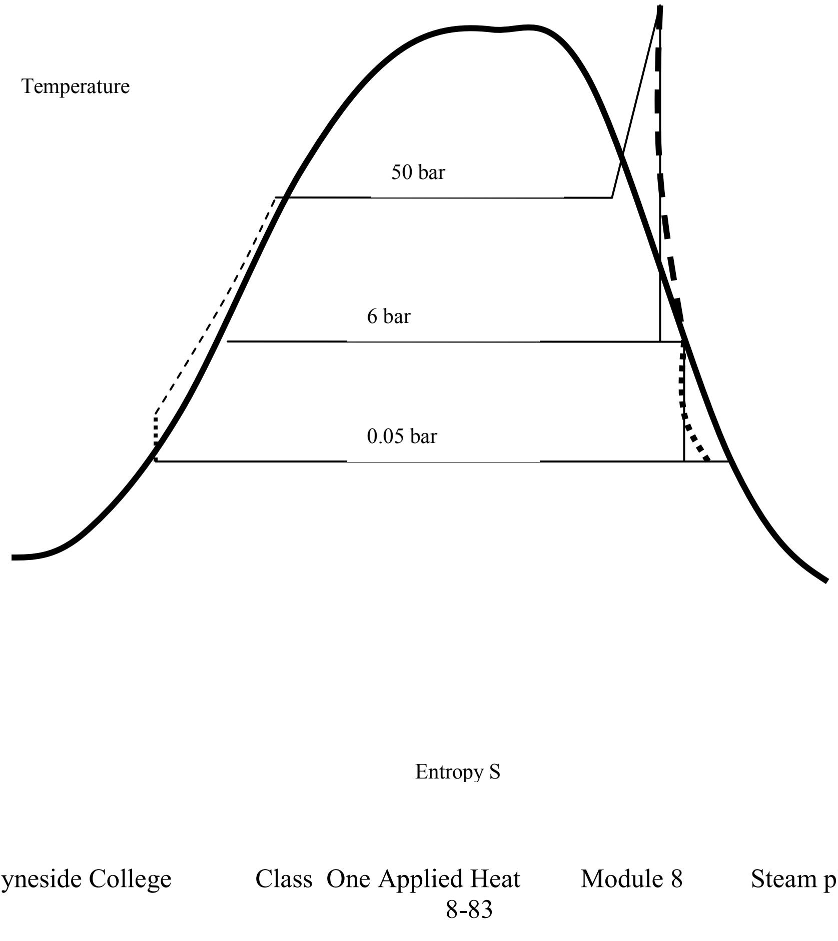
$$2652.2m = 535.2$$

$$m = \frac{535.2}{2652.2} = \underline{0.2018 \text{ kg/kg of steam supplied from the boiler}}$$

$$\eta_{thermal} = \frac{w}{Q_{in}} = \frac{(h_1 - h_2) + (1-m)(h_2 - h_3)}{h_1 - h_5}$$

$$= \frac{(3070 - 2757) + (1 - 0.2018)(2757 - 2375)}{3070 - 640} = \underline{0.257} = \underline{25.7\%}$$

b) TS diagram



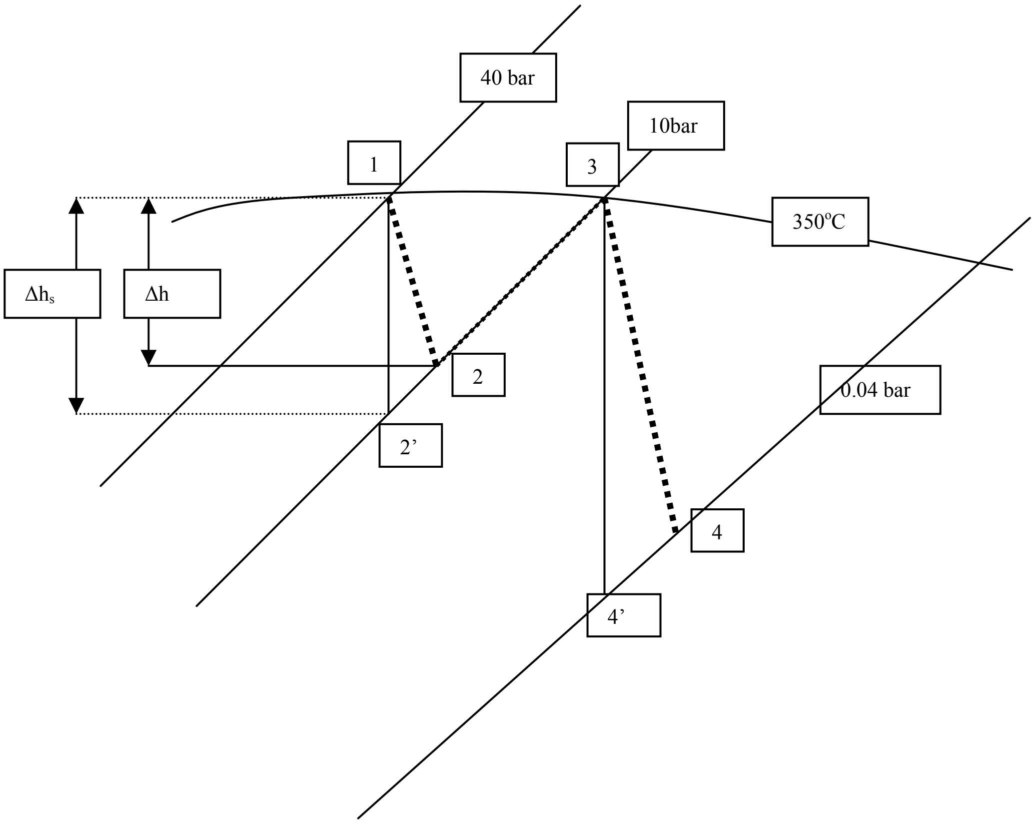
3 In a steam plant using reheat , the turbine receives the steam at a pressure and temperature of 40 bar and 350°C respectively. The steam expands in the first stage to a pressure of 10 bar with an isentropic efficiency of 0.8. It is then reheated at constant pressure to 350°C. In the second stage the steam is expanded to a condenser pressure of 0.04 bar wuth an isentropic efficiency of 0.75. The feed pump work is negligible and there is no undercooling in the condenser. The steam flow is 5 tonne per hour.

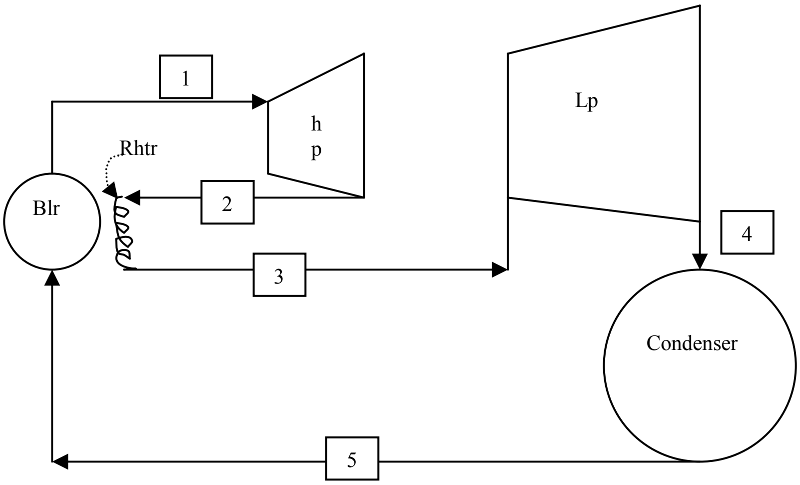
a) Sketch the Temperature- Entropy diagram for the cycle.

b) Determine

   i) the cycle efficiency
   ii) the power output
   iii) the dryness fraction of the steam entering the condenser

c) Consider the enthalpy values determined from steam tables and hs chart. A sketch of the hs chart is shown below.

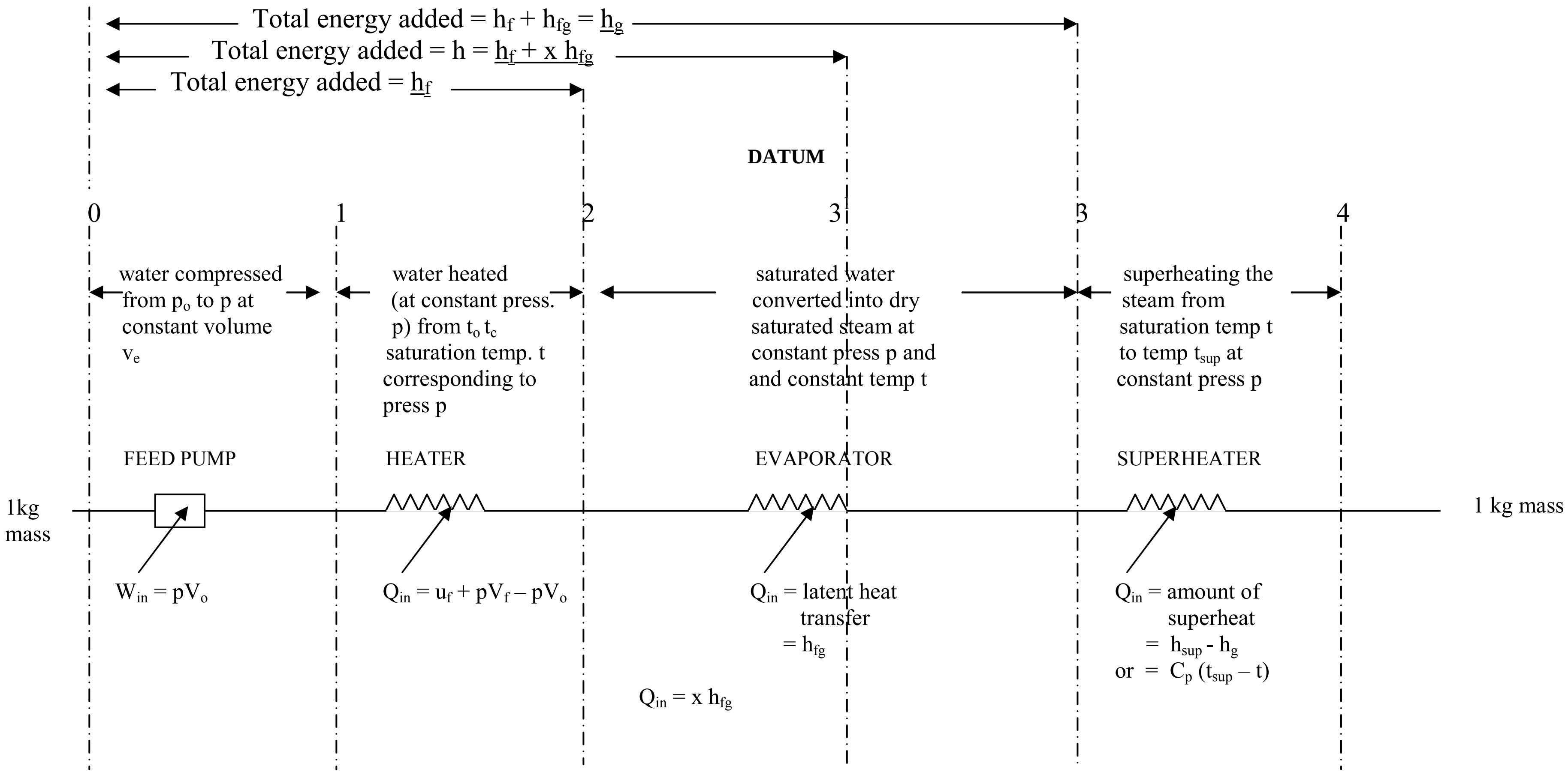




$$h_1 = 3094kJ/kg$$
$$h_{2'} = 2778kJ/kg$$
$$\Delta h_s = 3094 - 2778 = 316kJ/kg$$
$$\Delta h_{hp} = 316 \times 0.8 = 252.8kJ/kg$$
$$h_2 = 3094 - 252.8 = 2841.2kJ/kg$$
$$h_3 = 3158kJ/kg$$
$$h_{4'} = 2200kJ/kg$$
$$\Delta h_{slp} = 3158 - 2200 = 958kJ/kg$$
$$\Delta h_{lp} = 958 \times 0.75 = 718.5kJ/kg$$
$$h_4 = 3158 - 718.5 = 2439.5kJ/kg$$
$$h_5 = h_f at 0.04bar = 121kJ/kg$$
$$\eta = \frac{w}{Q_{in}} = \frac{w_{hp} + w_{lp}}{(h_1 - h_5) + (h_3 - h_2)} = \frac{971.3}{2973 + 316.8} = \underline{29.5\%}$$
$$Power = w \times massflow = 971.3 \times \frac{5 \times 10^3}{3600} = \underline{1349kW}$$

Dryness fraction can be read from the chart or calculated from :

$$h_4 = h_f + xh_{fg}$$
$$x = \frac{2439.5 - 121}{2433} = 0.953$$



	0	1	2	3^1	3	4
1 kg of water	**TRIPLE POINT CONDITION** $P_o = 0.006112$ bar $t_o = 0.01$°C $V_o = 0.001\ m^3/kg$ $u_o = 0$ $h_o = 0$	p t_o V_o u_o	1 kg of saturated water p t V_f u_f h_f	1 kg of wet steam of dryness x p t V u	1 kg of dry saturated steam p t V_g u_g h_g	1 kg of superheated steam p t_{sup} V_{sup} u_{sup} h_{sup}