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HEAT & THERMODYNAMICS

MODULE B.5

STEAM TABLES

Heat & Thermodynamics

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STEAM TABLES

Course Objectives

1. Given values for temperature, pressure, enthalpy and a set of steam tables, you will be able to identify the state of water as one of the following:
  - (a) Subcooled Water.
  - (b) Saturated Water.
  - (c) Wet Steam.
  - (d) Saturated Steam.
  - (e) Superheated Steam.
  
2. Given the initial and final state of water and two out of three of the following parameters: pressure, temperature, enthalpy, you will be able to perform simple calculations to determine the third quantity.
  
3. Briefly describe the process of "steam hammer" and explain why it is a problem and how it may be avoided.
  
4. Given a constant volume system with provision for adding or removing water, stated initial conditions, and one or more final condition, you will be able to state whether the remaining final conditions increase, decrease, or stay constant. You will be able to explain your statement and determine the amount of any changes that result.

Enabling Objectives

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

STEAM TABLES

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

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

TABLE 1 - SATURATION LINE (TEMPERATURE)

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

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

Temperature

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

TABLE 1 - SATURATION LINE (TEMPERATURE)

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

Pressure

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

TABLE 1 - SATURATION LINE (TEMPERATURE)

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

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

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

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

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

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

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

### B.5.1

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

### B.5.2

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

### B.5.3

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

### Sensible Heat

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

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

### Examples

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

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

Try these examples:

#### B.5.4

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

#### B.5.5

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

#### B.5.6

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

#### B.5.7

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

#### Latent Heat of Vapourization

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

Example

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

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

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm <sup>3</sup> /kg			Temp. °C
		$h_f$	$h_{fg}$	$h_g$	$s_f$	$s_{fg}$	$s_g$	$v_f$	$v_{fg}$	$v_g$	
$t_s$	$p_s$										$t_s$
140.0	3.614	589.1	2144.0	2733.1	1.7390	5.1894	6.9284	1.0801	507.41	508.49	140.0
140.5	3.665	591.3	2142.5	2733.7	1.7442	5.1795	6.9237	1.0806	500.71	501.79	140.5
141.0	3.717	593.4	2140.9	2734.3	1.7493	5.1696	6.9190	1.0811	494.11	495.19	141.0
141.5	3.770	595.5	2139.4	2735.0	1.7545	5.1597	6.9142	1.0816	487.61	488.69	141.5
142.0	3.823	597.7	2137.9	2735.6	1.7597	5.1499	6.9095	1.0821	481.22	482.30	142.0

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

B.5.8

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

B.5.9

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

Enthalpy of Saturated Steam

This is the total amount of heat that the saturated steam possesses when measured from 0°C. This quantity is shown under the column labelled 'h<sub>g</sub>' - total heat in the 'gas'. A closer inspection will show that h<sub>g</sub> is the sum of h<sub>f</sub> and h<sub>fg</sub>.

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm <sup>3</sup> /kg			Temp. °C	
		t <sub>s</sub>	p <sub>s</sub>	h <sub>f</sub>	h <sub>fg</sub>	h <sub>g</sub>	s <sub>f</sub>	s <sub>fg</sub>	s <sub>g</sub>	v <sub>f</sub>		v <sub>fg</sub>
210.0	19.077		897.7	1898.5	2796.2	2.4247	3.9293	6.3539	1.1726	103.07	104.24	210.0
211.0	19.462		902.3	1894.3	2796.6	2.4340	3.9126	6.3466	1.1743	101.05	102.23	211.0
212.0	19.852		906.9	1890.2	2797.1	2.4434	3.8960	6.3394	1.1760	99.09	100.26	212.0
213.0	20.249		911.5	1886.0	2797.5	2.4527	3.8794	6.3321	1.1777	97.162	98.340	213.0
214.0	20.651		916.0	1881.8	2797.9	2.4620	3.8629	6.3249	1.1794	95.282	96.462	214.0

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

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

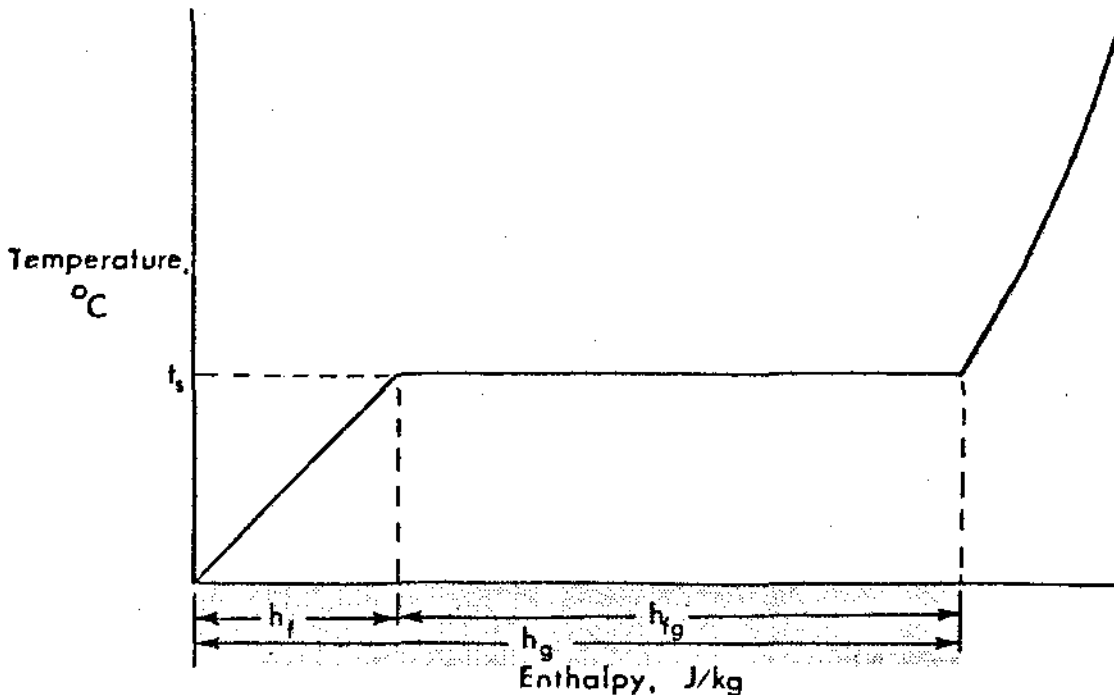


Fig. 5.1



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

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

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

### Temperature

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

### Saturated Liquid

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

### Latent Heat

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

### Enthalpy of Saturated Steam

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

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

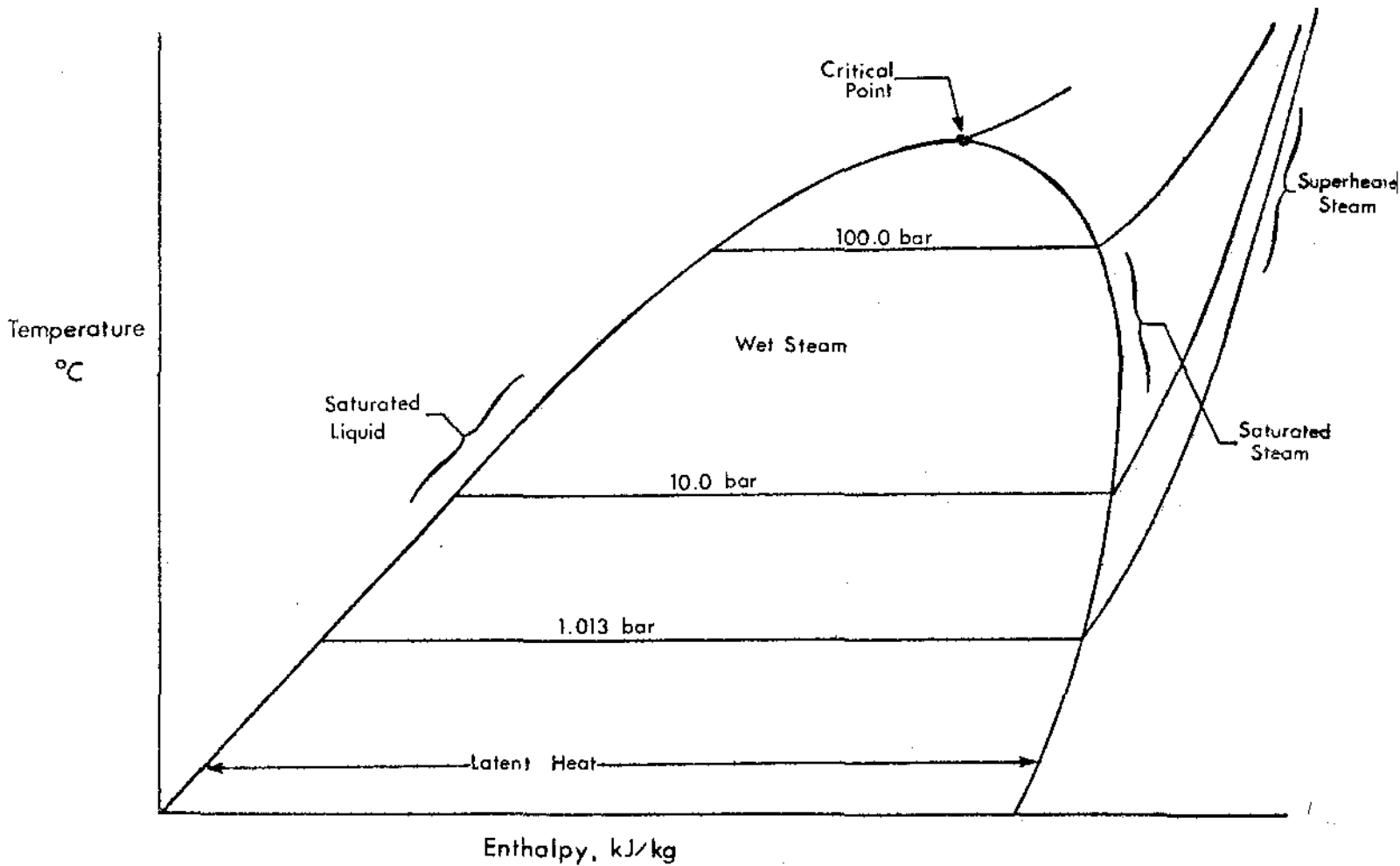


Fig. 5.2

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

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

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

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

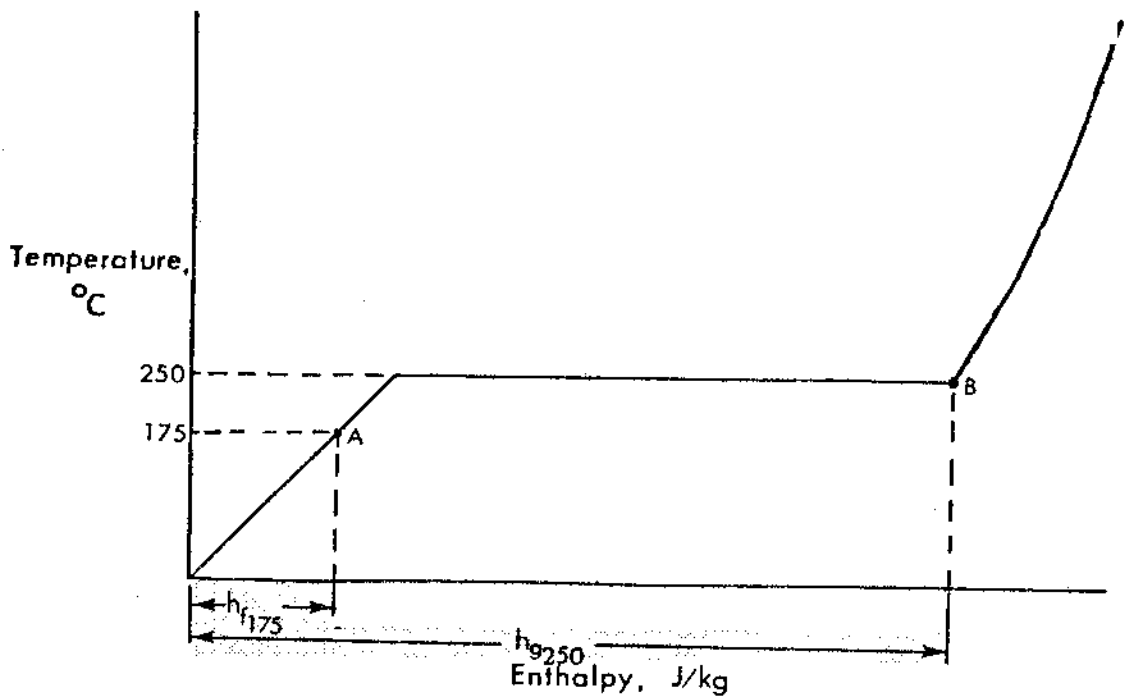


Fig. 5.3

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

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

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

Using steam tables,

$$h_{g250} = 2800.4 \text{ kJ/kg}$$

$$h_{f175} = 741.1 \text{ kJ/kg.}$$

$$\text{Thus } Q = 2800.4 - 741.1$$

$$= 2059.3 \text{ kJ/kg.}$$

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

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

#### B.5.10

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

#### B.5.11

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

#### B.5.12

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

B.5.13

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

Enthalpy of Wet Steam

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

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

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

Dryness Fraction

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

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

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

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

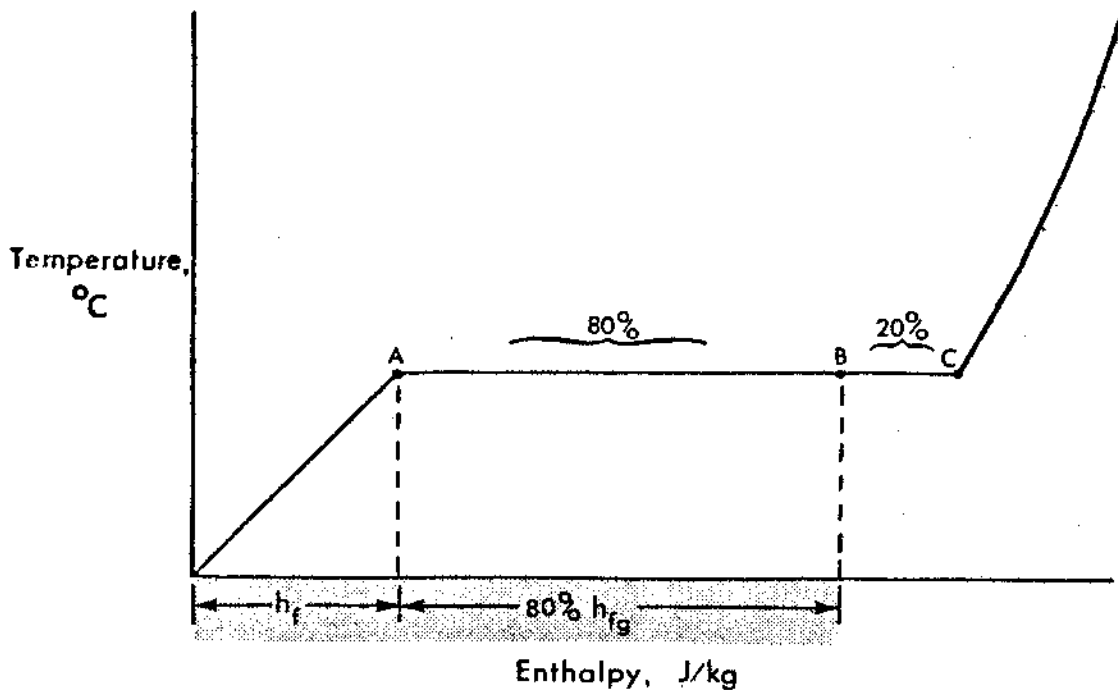


Fig. 5.4

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

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

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

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

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

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

B.5.14

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

B.5.15

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

B.5.16

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

B.5.17

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

B.5.18

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

B.5.19

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

Superheated Steam

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

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

TABLE 3 - PROPERTIES OF WATER AND STEAM

pieib/bar	2.0			3.0			4.0			5.0			6.0			7.0		
$t_s$ °C	120.2			133.5			143.6			151.8			158.8			165.0		
	<i>h</i>	<i>x</i>	<i>v</i>	<i>h</i>	<i>x</i>	<i>v</i>	<i>h</i>	<i>x</i>	<i>v</i>	<i>h</i>	<i>x</i>	<i>v</i>	<i>h</i>	<i>x</i>	<i>v</i>	<i>h</i>	<i>x</i>	<i>v</i>
Sat. Liquid	504.7	1.530	1.061	561.4	1.672	1.074	604.7	1.778	1.084	640.1	1.360	1.092	670.4	1.921	1.101	697.1	1.992	1.10
Sat. Vapour	2706	7.127	885.4	2725	6.991	609.8	2738	6.894	462.2	2748	6.819	371.7	2756	6.738	315.5	2762	6.709	272.
$t$ °C																		
50	203.4	0.703	1.012	203.5	0.703	1.012	205.6	0.703	1.012	209.7	0.703	1.012	209.8	0.703	1.012	209.9	0.703	1.01
100	419.1	1.307	1.044	419.2	1.307	1.044	419.3	1.307	1.044	419.4	1.307	1.044	419.4	1.307	1.043	419.5	1.306	1.04
150	2769	7.279	950.5	2790	7.077	633.7	2752	6.929	470.7	632.2	1.842	1.091	632.2	1.842	1.091	632.3	1.841	1.00
200	2871	7.507	1080	2865	7.312	716.4	2860	7.171	534.3	2855	7.059	423.0	2850	6.963	382.0	2844	6.888	299
250	2971	7.710	1200	2968	7.518	798.4	2965	7.380	595.2	2961	7.272	474.4	2958	7.183	393.9	2954	7.107	338.
300	3072	7.834	1316	3070	7.703	875.3	3067	7.568	654.0	3065	7.461	522.5	3062	7.374	434.4	3060	7.300	371.
350	3174	8.064	1433	3172	7.874	953.5	3170	7.640	713.9	3168	7.634	570.1	3166	7.548	474.2	3164	7.475	405.
400	3277	8.223	1549	3275	8.034	1031	3274	7.859	772.5	3272	7.795	617.2	3271	7.709	513.6	3269	7.636	439.
450	3381	8.372	1665	3380	8.184	1109	3379	8.050	830.9	3377	7.945	664.1	3376	7.860	552.8	3375	7.788	473.
500	3487	8.514	1781	3486	8.326	1187	3485	8.192	889.2	3484	8.098	710.3	3483	8.003	591.9	3482	7.931	506.
550	3595	8.649	1897	3594	8.461	1264	3593	8.327	947.4	3592	8.222	757.4	3591	8.138	620.8	3590	8.063	540.
600	3704	8.778	2013	3703	8.590	1341	3702	8.456	1005	3702	8.353	804.0	3701	8.268	669.6	3700	8.196	572.
650	3815	8.901	2129	3814	8.714	1419	3814	8.580	1063	3813	8.477	850.4	3812	8.392	708.4	3811	8.320	607.

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

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

Example

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



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

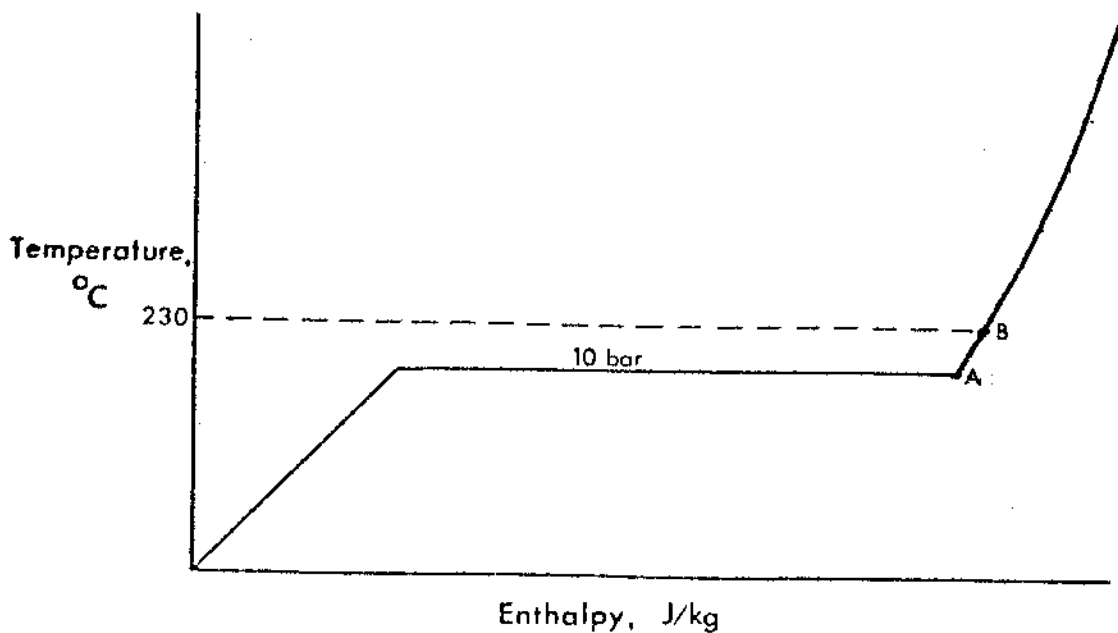


Fig. 5.5

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

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

At 10 bar and  $200^\circ\text{C}$   $h = 2827$  kJ/kg, and

at 10 bar and  $250^\circ\text{C}$   $h = 2943$  kJ/kg.

The difference for  $50^\circ\text{C}$  is  $2943 - 2827 = 116$  kJ/kg.

At  $230^\circ\text{C}$  the enthalpy will be enthalpy at  $200^\circ\text{C}$  +  $30/50$  of the difference 116.

Thus  $h = 2827 + 3/5 \times 116$

a)  $= 2896.6$  kJ/kg.

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

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

b)  $2896.6 - 2776 = 120.6$  kJ/kg.

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

B.5.20

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

B.5.21

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

\* \* \* \* \*

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

B.5.22

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

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

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

B.5.23

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

B.5.24

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

Volume of Liquid and Vapour

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

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

- a) the cubic meter - 'm<sup>3</sup>'
- b) the liter, which is one thousandth of a cubic meter - 'l'.

The steam tables use the liter which they call the cubic decimeter - dm<sup>3</sup>.

Volume of Liquid

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

Example

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

Looking at Table 1, at temperature  $t_g = 55^\circ\text{C}$ , select the value of  $v_f = 1.0145 \text{ l/kg}$ . Thus 30 kg will occupy  $30 \times 1.0145 \text{ l} = 30.435 \text{ l}$ .

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

B.5.25

A tank holds 3 m<sup>3</sup> of water at 90°C. How many kg of water are in the tank?

B.5.26

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

Volume of Saturated Steam

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

Example

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

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

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

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

B.5.27

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

B.5.28

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

Volume of Wet Steam

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

Example

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

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

$$\begin{aligned} v &= v_f + qv_{fg} \\ &= 1.1082 + 0.88 \times 271.29 \\ &= \underline{239.8 \text{ l/kg}}. \end{aligned}$$

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

B.5.29

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

B.5.30

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

Steam Hammer

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

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

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

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

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

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

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

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

\* \* \* \* \*

### B.5.31

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

### Pressure, Volume, Temperature, Mass Relationships

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

#### Example

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

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

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

\* \* \* \* \*

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

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

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

4m<sup>3</sup> of liquid water at 100°C and 4.76 bar represents:

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

Therefore the mass of water will increase  $3831 - 3210 = 621 \text{ kg}$ .

\* \* \* \* \*

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

B.5.32

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

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

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

B.5.33

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

B.5.34

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

\* \* \* \* \*

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

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

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



125 - B.5

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

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

125 - B.5

Answers

MODULE B.5

STEAM TABLES

B.5.1

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

B.5.2

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

B.5.3

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

B.5.4

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

B.5.5

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

B.5.6

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

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

B.5.7

The initial enthalpy at 35°C is  $h_f$  when  $t_s = 35^\circ\text{C}$   
 $h_f = 146.6$  kJ/kg.

The final enthalpy at 126°C is  $h_f$  when  $t_s = 126^\circ\text{C}$   
 $h_f = 529.2$  kJ/kg.

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

B.5.8

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

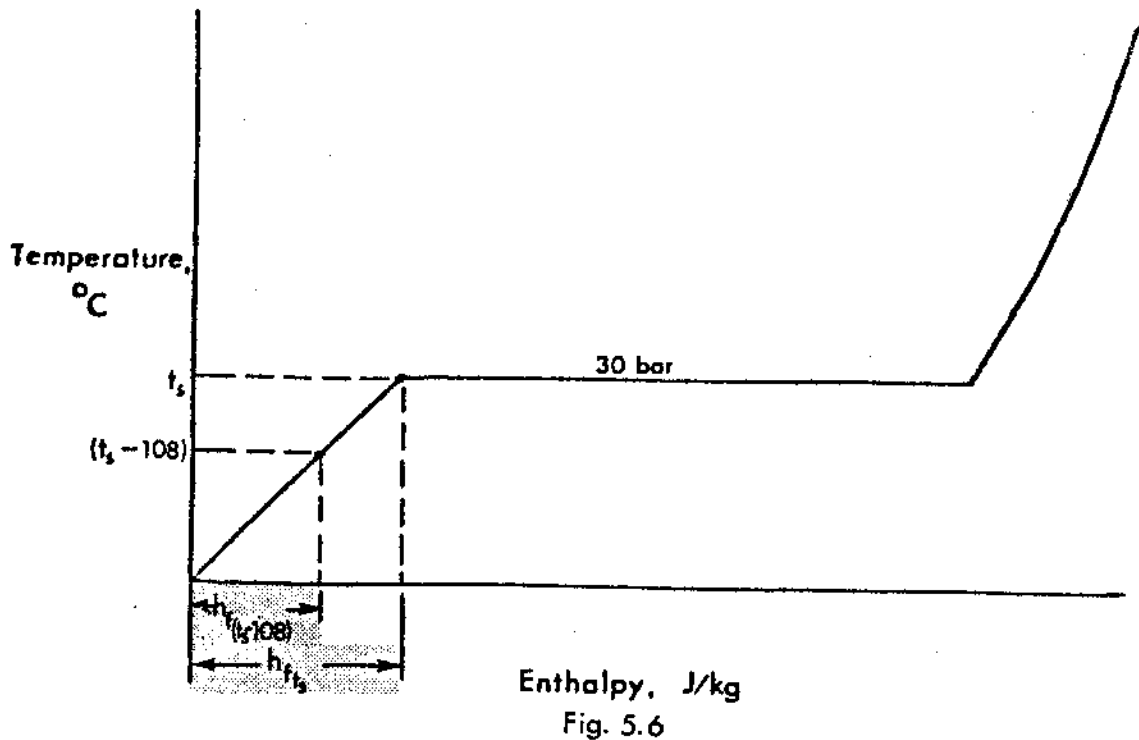
B.5.9

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

The saturation temperature determines the pressure and  $P_s$  at  $t_s = 32^\circ\text{C}$  is 0.04753 bar which is 4.753 kPa(a).

B.5.10

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



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

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

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

$$\begin{aligned} \text{So the heat removed} &= 1008.4 - 529.2 \\ &= \underline{479.2 \text{ kJ/kg.}} \end{aligned}$$

#### B.5.11

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

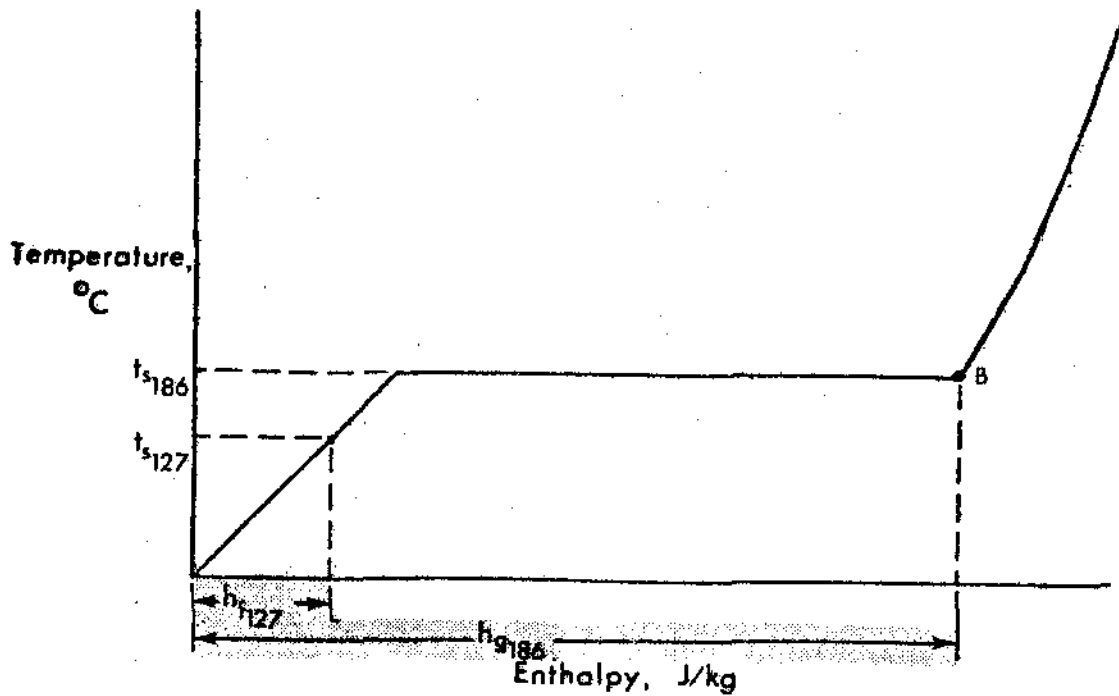


Fig. 5.7

The enthalpy of the saturated steam is  $h_g$  at  $186^\circ\text{C}$ . Using Table 1,  $h_{g186} = 2781.2 \text{ kJ/kg}$ .

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

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

$$2781.2 - 533.5 = \underline{2247.7} \text{ kJ/kg.}$$

### B.5.12

The increase in enthalpy of the cooling water is the difference between the enthalpy of the water at  $41^\circ\text{C}$  and the initial condition of  $17^\circ\text{C}$ .

$$\text{Enthalpy at } 41^\circ\text{C} = h_{f41} = 171.6 \text{ kJ/kg.}$$

$$\text{Enthalpy at } 17^\circ\text{C} = h_{f17} = 71.3 \text{ kJ/kg.}$$

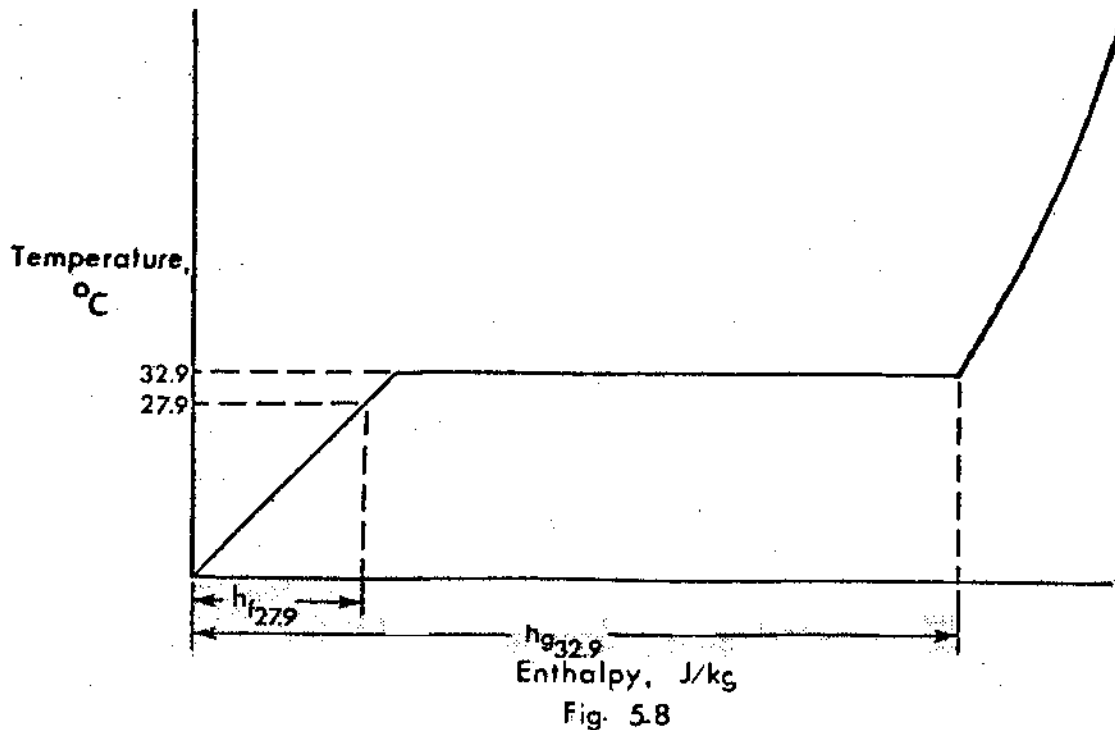
(Both values from Table 1)

$$\text{Thus the increase} = 171.6 - 71.3 = \underline{100.3} \text{ kJ/kg.}$$

B.5.13

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

Again a sketch on the temperature enthalpy diagram is worthwhile.



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

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

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

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

B.5.14

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

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

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

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

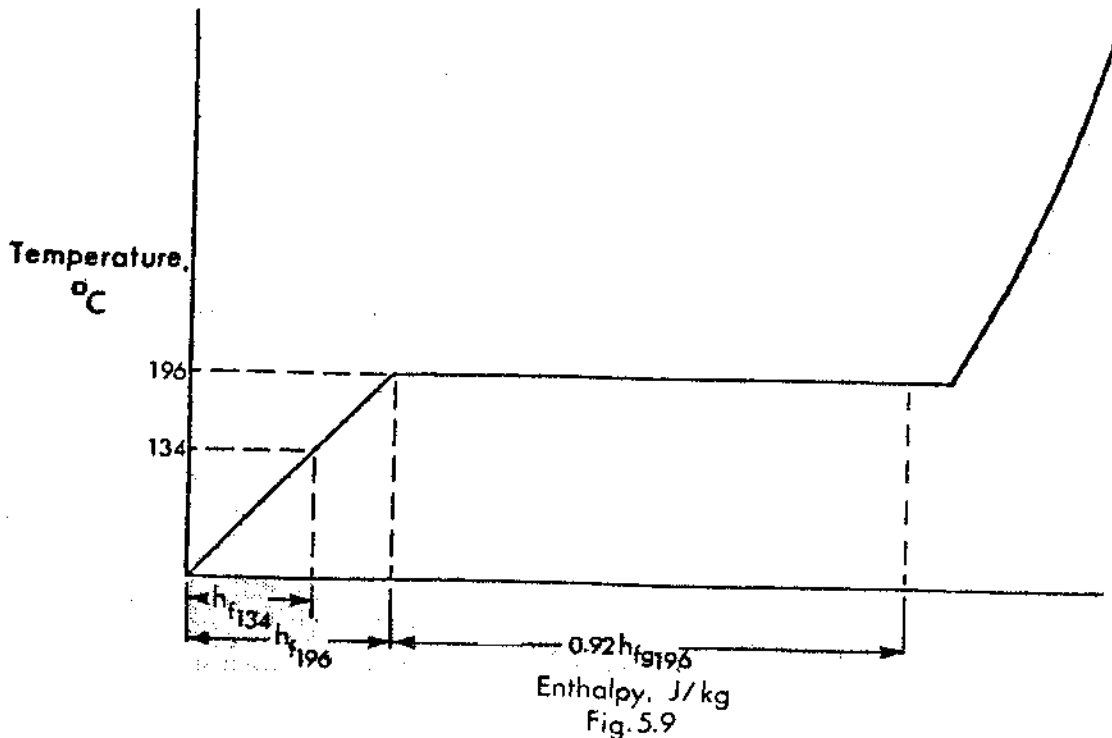
The enthalpy of the wet steam =  $151.5 + 0.88 \times 2416.0$  kJ/kg  
 =  $151.5 + 2126.1$  kJ/kg  
 = 2277.6 kJ/kg.

B.5.15

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

B.5.16

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



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

The enthalpy of the wet steam is

$$\begin{aligned} h_f + qh_{fg} &= 834.4 + 0.92 \times 1954.1 \text{ kJ/kg} \\ &= 834.4 + 1797.8 \text{ kJ/kg} \\ &= \underline{2632.2} \text{ kJ/kg.} \end{aligned}$$

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

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

#### B.5.17

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

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

$$\begin{aligned} \text{Enthalpy of wet steam is } h_f + qh_{fg} \\ &= 884.6 + 0.82 \times 1910.3 \text{ kJ/kg} \\ &= 884.6 + 1566.4 \text{ kJ/kg} \\ &= 2451.0 \text{ kJ/kg.} \end{aligned}$$

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

$$\begin{aligned} &2751 - 2451 \text{ kJ/kg} \\ &= \underline{300} \text{ kJ/kg.} \end{aligned}$$

#### B.5.18

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

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



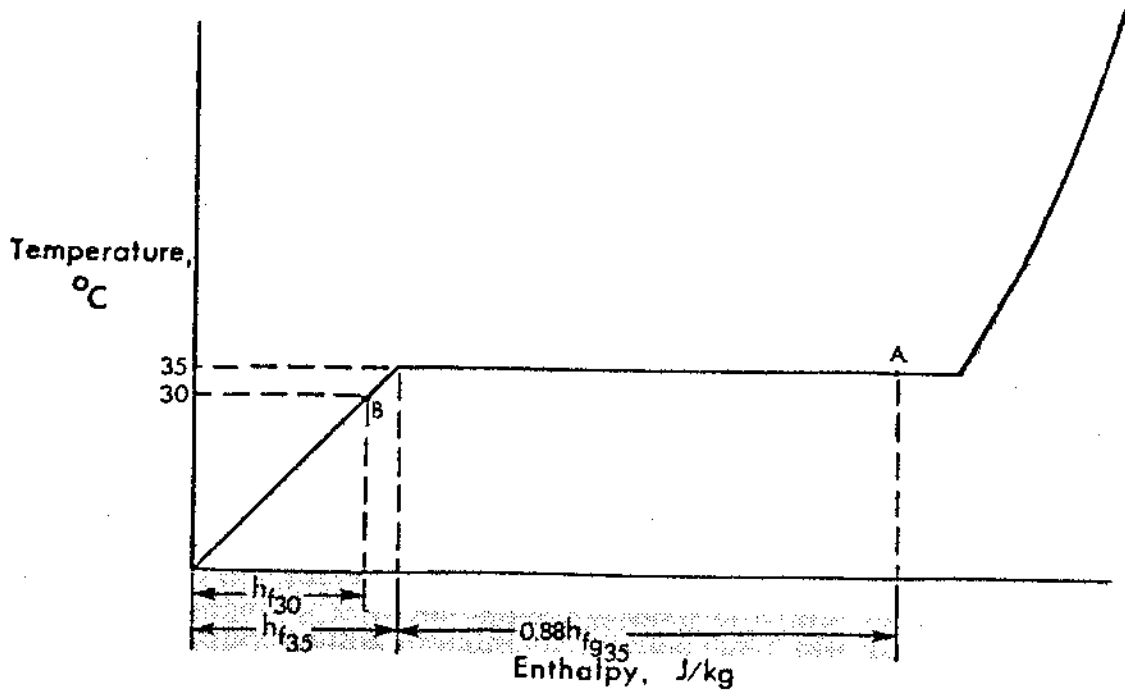


Fig. 5.10

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

$$\begin{aligned}
 \text{Enthalpy of wet steam} &= h_f + qh_{fg} \\
 &= 146.6 + 0.88 \times 2418.8 \text{ kJ/kg} \\
 &= 146.6 + 2128.5 \text{ kJ/kg} \\
 &= \underline{2275.1 \text{ kJ/kg}}.
 \end{aligned}$$

The final condition is of condensate at  $30^\circ\text{C}$ .

$$h_{f30} = \underline{125.7 \text{ kJ/kg}}.$$

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

$$\begin{aligned}
 &2275.1 - 125.7 \text{ kJ/kg} \\
 &= \underline{2149.4 \text{ kJ/kg}}.
 \end{aligned}$$

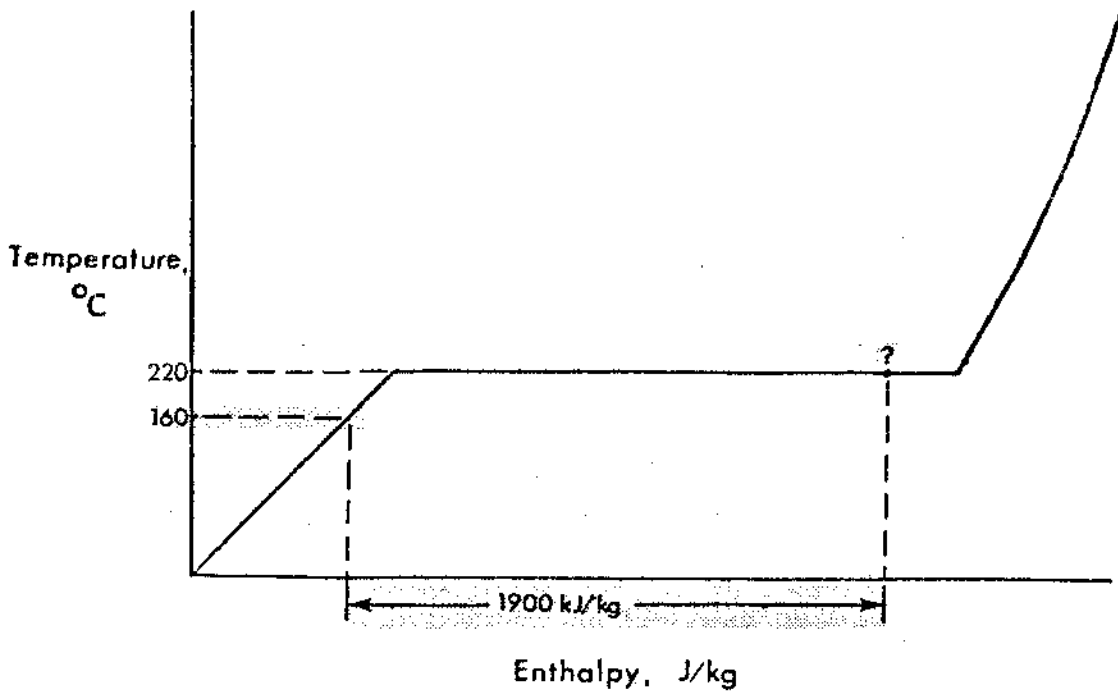


Fig. 5.11

## B.5.19

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

$$h_{f160} = 675.5 \text{ kJ/kg.}$$

$$\text{Final enthalpy is } 675.5 + 1900 = \underline{2575.5} \text{ kJ/kg.}$$

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

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

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

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

Substituting:

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

$$1631.8 = q \times 1856.2$$

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

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

B.5.20

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

= 3194 kJ/kg.

B.5.21

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

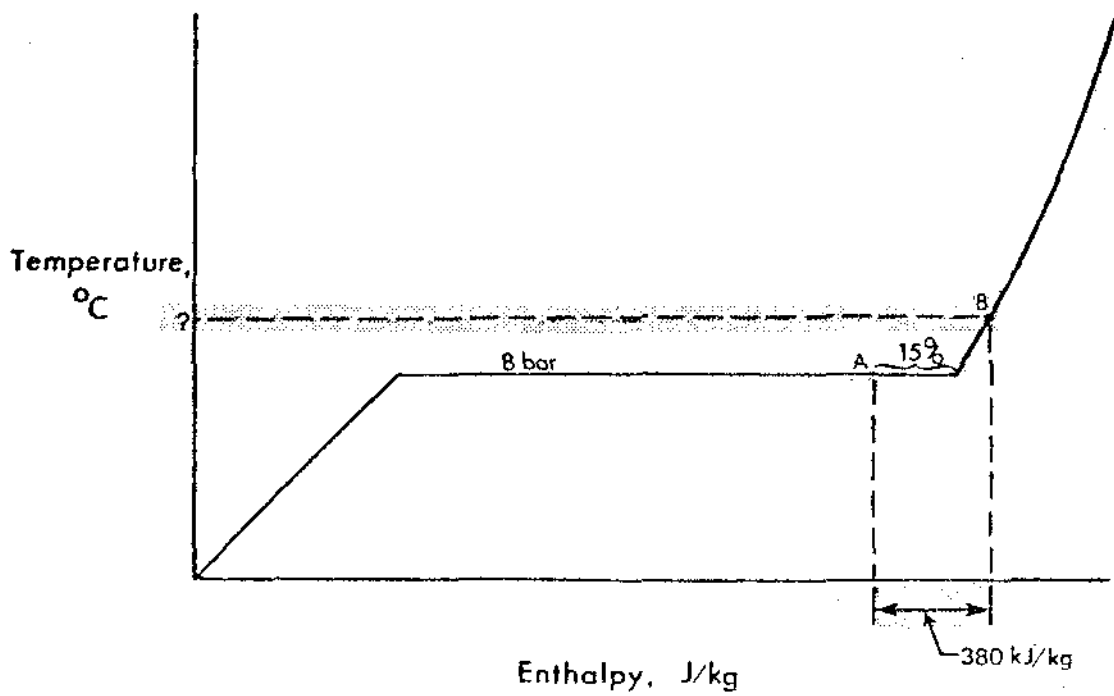


Fig. 5.12

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

$$\begin{aligned} h &= 720.9 + 0.85 \times 2046.5 \\ &= 720.9 + 1739.5 \text{ kJ/kg} \\ &= \underline{2460.4} \text{ kJ/kg.} \end{aligned}$$

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

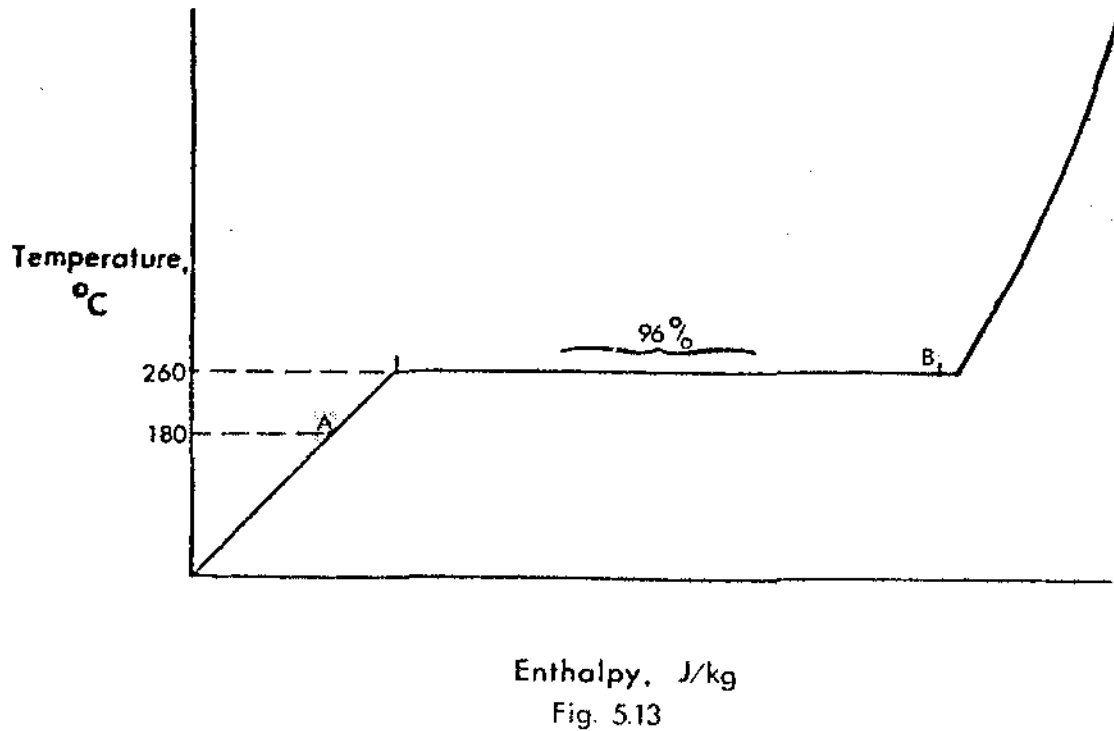
Using Table 3, under pressure column 8 bar, we see that the new enthalpy is for steam just fractionally hotter than  $200^\circ\text{C}$ , near enough for convenience.

#### B.5.22

- a) Using Table 2, at 3.0 bar the  $t_s$  is  $133.5^\circ\text{C}$  so the condition is at  $t_s$ .  $h_f$  at  $t_s = 561.4 \text{ kJ/kg}$  so the condition is saturated liquid.
- b) Using Table 2, at 0.05 bar,  $t_s$  is  $32.9^\circ\text{C}$  so again the condition is at  $t_s$ .  $h_f$ , at  $t_s$ , =  $137.8 \text{ kJ/kg}$  so the condition is greater than that of saturated liquid.  $h_g$ , at  $t_s = 2561.6 \text{ kJ/kg}$ . Now this is more enthalpy than the stated  $2323 \text{ kJ/kg}$  so the fluid is not saturated steam. It is somewhere between saturated liquid and saturated vapour, ie, wet steam.
- c) Using Table 2, at 5.0 bar  $t_s = 151.8^\circ\text{C}$  and we are told the steam is at  $200^\circ\text{C}$ , so obviously the steam is superheated.
- d) Using Table 1, at  $20^\circ\text{C}$  the  $p_s$  is 0.02337 bar, so the condition of the fluid is at the saturation temperature.  $h_f$  at  $20^\circ\text{C}$  is  $83.86 \text{ kJ/kg}$  and the quoted enthalpy was  $2538.2 \text{ kJ/kg}$  so the condition is well above the saturated liquid condition. In fact as may be seen from the tables, the value of  $h_g$  at  $20^\circ\text{C}$  is  $2538.2 \text{ kJ/kg}$  so the condition is saturated steam.
- e) Using Table 1, at  $30^\circ\text{C}$  the  $p_s$  is 0.04241 bar which is less than the quoted pressure. The saturation temperature for the quoted pressure is  $40^\circ\text{C}$  so the condition is subcooled liquid.

B.5.23

Using the temperature enthalpy diagram,



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

$$h_f \text{ at } 260^\circ\text{C} = 1134.9 \text{ kJ/kg.}$$

$$h_{fg} \text{ at } 260^\circ\text{C} = 1661.5 \text{ kJ/kg.}$$

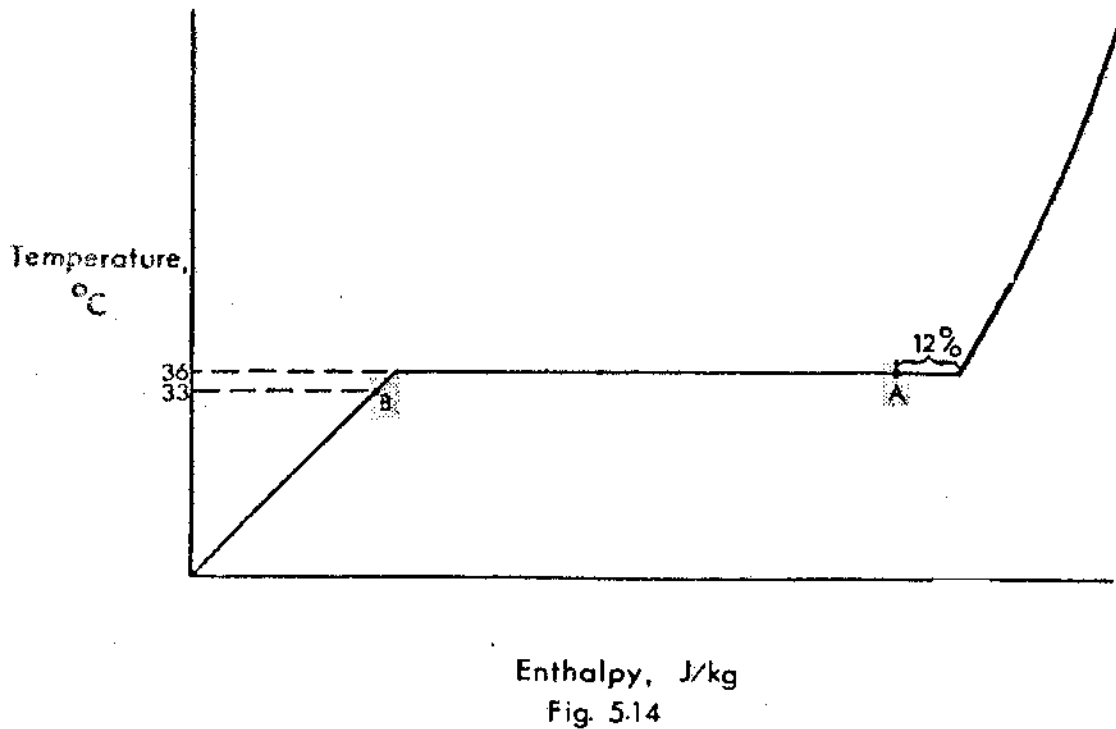
$$\begin{aligned} \text{Thus } h &= 1134.9 + 0.96 \times 1661.5 \text{ kJ/kg} \\ &= 1134.9 + 1595.04 \text{ kJ/kg} \\ &= \underline{2729.9} \text{ kJ/kg.} \end{aligned}$$

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

$$= \underline{1966.8} \text{ kJ/kg.}$$

## B.5.24

Again use the temperature/enthalpy diagram.



The initial condition is 12% wet steam at 36°C. The final condition is condensate at  $36 - 3 = 33^\circ\text{C}$ .

$$\begin{aligned} h_A &= h_{f36} + 0.88 \times h_{fg36} \quad (12\% \text{ wet} = 88\% \text{ dry}) \\ &= 150.7 + 0.88 \times 2416.4 \\ &= 150.7 + 2126.4 \text{ kJ/kg} \\ &= \underline{2277.1} \text{ kJ/kg.} \end{aligned}$$

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

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

## B.5.25

The tank of water has a volume of  $3 \text{ m}^3 = 3000 \text{ l}$ . Looking at Table 1,  $v_f$  at  $90^\circ\text{C} = 1.0361 \text{ l/kg}$ .

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

We can rearrange this equation for mass thus,

$$\begin{aligned} \text{mass} &= \text{volume}/\text{specific volume} \\ &= 3000/1.0361 \text{ kg} \\ &= \underline{2895.47 \text{ kg}}. \end{aligned}$$

#### B.5.26

Using Table 1,  $v_f$  at  $36^\circ\text{C} = 1.0063 \text{ l/kg}$  and  $v_f$  at  $175^\circ\text{C} = 1.1209 \text{ l/kg}$ .

The increase in  $v_f$  is  $1.1209 - 1.0063 = 0.1146 \text{ l/kg}$ .

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

#### B.5.27

Using Table 1,  $v_f$  at  $175^\circ\text{C} = 1.1209 \text{ l/kg}$  and  $v_g$  at  $250^\circ\text{C} = 50.037 \text{ l/kg}$ .

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

#### B.5.28

From Table 1,  $V_g$  at  $40^\circ\text{C}$  is  $19546.1 \text{ l/kg}$  and  $v_f$  at  $35^\circ\text{C} = 1.0059 \text{ l/kg}$ .

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

#### B.5.29

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

Using Table 2,  $v_f$  at 0.05 bar =  $1.0052 \text{ l/kg}$

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

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

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

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

### B.5.30

The volume of the low pressure steam is, as we already calculated in question B.5.29, 24811  $\ell/\text{kg}$ .

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

### B.5.31

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

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

### B.5.32

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



Since the liquid volume remains at  $5 \text{ m}^3$ , the vapour volume is  $0 \text{ m}^3$  and this volume also remains constant.

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

### B.5.33

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

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

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

### B.5.34

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

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

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