COURSE 225

HEAT & THERMODYNAMICS

MODULE 2

STEAM TABLES

Revised	Verified	Verified
A. Wadham J. Jung E. Abdelkerim	Trng Supt ENTC	Trng Supt WNTC
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MODULE 2

STEAM TABLES

Course Objectives

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

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

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

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

Enabling Objectives

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

STEAM TABLES

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

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

TABLE 1 – SATURATION LINE (TEMPERATURE)

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm³/kg			Temp. °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
100.0	1.013	419.1	2256.9	2676.0	1.3069	6.0485	7.3554	1.0437	1672.0	1673.0	100.0
100.5	1.031	421.2	2255.6	2676.8	1.3125	6.0369	7.3494	1.0441	1644.3	1645.3	100.5
101.0	1.050	423.3	2254.3	2677.6	1.3182	6.0252	7.3434	1.0445	1617.2	1618.2	101.0
101.5	1.069	425.4	2252.9	2678.3	1.3238	6.0136	7.3374	1.0449	1590.6	1591.6	101.5
102.0	1.088	427.5	2251.6	2679.1	1.3294	6.0020	7.3315	1.0453	1564.5	1565.5	102.0
102.5	1.107	429.6	2250.3	2679.9	1.3350	5.9905	7.3255	1.0457	1538.9	1540.0	102.5
103.0	1.127	431.7	2248.9	2680.7	1.3406	5.9790	7.3196	1.0461	1513.8	1514.9	103.0
03.5	1.147	433.8	2247.6	2681.4	1.3462	5.9675	7.3137	1.0465	1489.2	1490.3	103.5
104.0	1.167	435.9	2246.3	2682.2	1.3518	5.9560	7.3078	1.0469	1465.1	1466.2	104.0
104.5	1.187	438.1	2244.9	2683.0	1.3574	5.9446	7.3020	1.0473	1441.4	1442.5	104.5

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

Temperature

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

TABLE 1 – SATURATION LINE (TEMPERATURE)

[redacted]	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm³/kg			Temp. °C
[redacted]	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
[redacted]	1.013	419.4	2256.9	2676.0	1.3069	6.0485	7.3554	1.0437	1672.0	1673.0	100.0
	1.031	421.2	2255.6	2676.8	1.3126	6.0369	7.3494	1.0441	1644.3	1645.3	100.5
	1.050	423.3	2254.3	2677.6	1.3182	6.0252	7.3434	1.0445	1617.2	1618.2	101.0
	1.069	425.4	2252.9	2678.3	1.3238	6.0136	7.3374	1.0449	1590.6	1591.6	101.5
	1.088	427.5	2251.6	2679.1	1.3294	6.0020	7.3315	1.0453	1564.5	1565.5	102.0
	1.107	429.6	2250.3	2679.9	1.3350	5.9905	7.3255	1.0457	1538.9	1540.0	102.5
	1.127	431.7	2248.9	2680.7	1.3406	5.9790	7.3196	1.0461	1513.8	1514.9	103.0
	1.147	433.8	2247.6	2681.4	1.3462	5.9675	7.3137	1.0465	1489.2	1490.3	103.5
	1.167	435.9	2246.3	2682.2	1.3518	5.9560	7.3078	1.0469	1465.1	1466.2	104.0
	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	[redacted]	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm³/kg			Temp. °C
t_s	[redacted]	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
100.0	[redacted]	419.1	2256.9	2676.0	1.3069	6.0485	7.3554	1.0437	1672.0	1673.0	100.0
100.5		421.2	2255.6	2676.8	1.3125	6.0369	7.3494	1.0441	1644.3	1645.3	100.5
101.0		423.3	2254.3	2677.6	1.3182	6.0252	7.3434	1.0445	1617.2	1618.2	101.0
101.5		425.4	2252.9	2678.3	1.3238	6.0136	7.3374	1.0449	1590.6	1591.6	101.5
102.0		427.5	2251.6	2679.1	1.3294	6.0020	7.3315	1.0453	1564.5	1565.5	102.0
102.5		429.6	2250.3	2679.9	1.3350	5.9905	7.3255	1.0457	1538.9	1540.0	102.5
103.0		431.7	2248.9	2680.7	1.3406	5.9790	7.3196	1.0461	1513.8	1514.9	103.0
103.5		433.8	2247.6	2681.4	1.3462	5.9675	7.3137	1.0465	1489.2	1490.3	103.5
104.0		435.9	2246.3	2682.2	1.3518	5.9560	7.3078	1.0469	1465.1	1466.2	104.0
104.5		438.1	2244.9	2683.0	1.3574	5.9446	7.3020	1.0473	1441.4	1442.5	104.5

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

is 4 MPa then the pressure in bar = 4×10^3 kPa = $\frac{4 \times 1000}{100}$ bar = 40 bar.

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

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm^3/kg			Temp °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
200.0	15.549	852.4	1938.6	2790.9	2.3307	4.0971	6.4278	1.1565	126.00	127.16	200.0
201.0	15.877	856.9	1934.6	2791.5	2.3401	4.0802	6.4203	1.1580	123.46	124.62	201.0
202.0	16.210	861.4	1930.7	2792.1	2.3495	4.0633	6.4128	1.1596	120.97	122.13	202.0
203.0	16.548	865.9	1926.7	2792.7	2.3590	4.0464	6.4054	1.1612	118.55	119.71	203.0
204.0	16.893	870.5	1922.8	2793.2	2.3684	4.0296	6.3980	1.1628	116.18	117.34	204.0

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

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

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

<u>Q2.2</u> Saturated steam at 1.985 bar has heat removed until it becomes wet steam at 1.985 bar. Determine the temperature of the steam at the new condition.

<u>Q2.3</u> The temperature in a steam generator has to be raised to 140.0°C. What is the pressure in the steam generator at this temperature?

* * * * *

Sensible Heat

You will recall from module 1 that when sensible heat is applied to the liquid state it causes a change of temperature. The enthalpy of the liquid state is determined by its temperature primarily, ie, for the majority of needs the enthalpy of subcooled water at 140°C and 50 bar is the same as the enthalpy of saturated liquid at 140°C.

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

Examples

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

Temp. °C	Abs.Press. bar	Specific Enthalpy kJ/kg			Specific Entropy kJ/kg °C			Specific Volume dm³/kg			Temp. °C
t_s	p_s	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g	v_f	v_{fg}	v_g	t_s
175.0	8.924	741.1	2030.7	2771.8	2.0906	4.5314	6.6221	1.1209	215.42	216.54	175.0
176.0	9.137	745.5	2027.3	2772.7	2.1004	4.5136	6.6140	1.1222	210.63	211.75	176.0
177.0	9.353	749.9	2023.7	2773.6	2.1101	4.4958	6.6059	1.1235	205.96	207.08	177.0
178.0	9.574	754.3	2020.2	2774.5	2.1199	4.4780	6.5979	1.1248	201.41	202.54	178.0
179.0	9.798	758.7	2016.7	2775.4	2.1296	4.4603	6.5899	1.1262	196.98	198.11	179.0

Try these examples:

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

Q2.5 Feedwater is brought up to the saturation temperature in the preheater. The steam pressure is 4 MPa(a). Determine the enthalpy and temperature of the saturated liquid.

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

Q2.7 Heat is added to the feedwater in the feedheaters and deaerator. If the initial temperature of the feedwater was 35°C and the suction to the boiler feedpump was at 126°C, determine the amount of heat added when the feedwater has reached the boiler feedpump suction.

Check your answers at the back of the module.

* * * * *

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; that happens to be the way the symbol is written.

Example

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

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

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

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

Q2.8 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. (Remember that 5 MPa(a) is equal to 50 bars.)

Q2.9 A condenser produces condensate at 32°C from saturated steam. There is no subcooling of the condensate. Determine the amount of heat which must be removed from the steam in the condenser and the condenser pressure.

* * * * *

Enthalpy of Saturated Steam

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

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

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

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

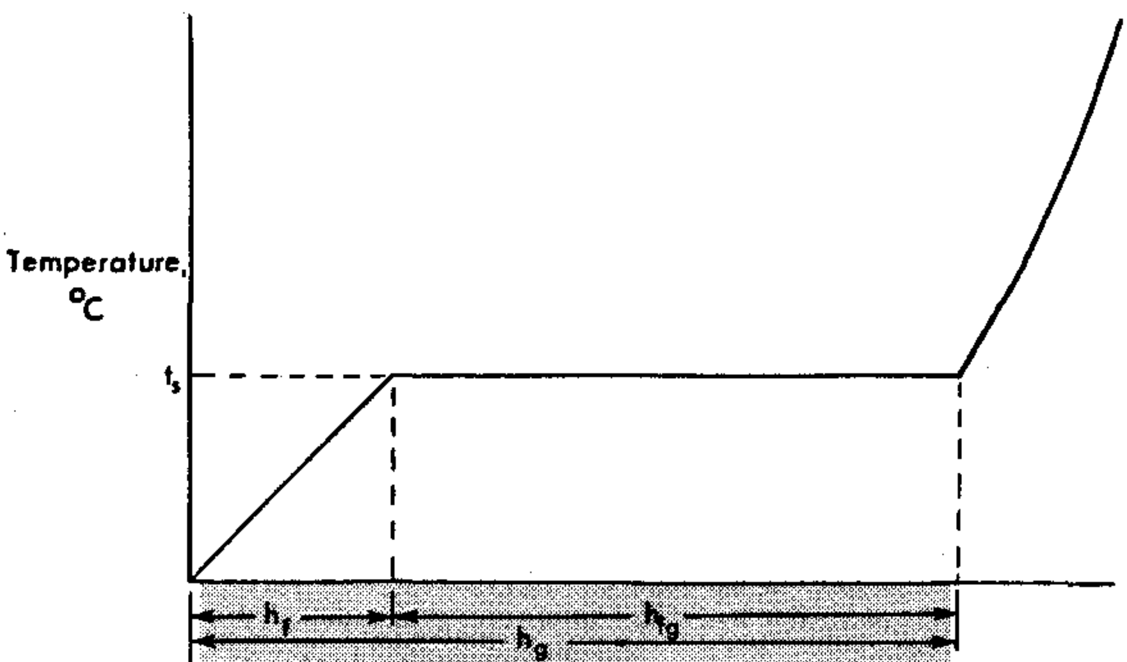

Fig. 2.1

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

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

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

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

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

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

<u>Temperature</u>

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.

<u>Saturated Liquid</u>

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

<u>Latent Heat</u>

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

Enthalpy of Saturated Steam

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

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

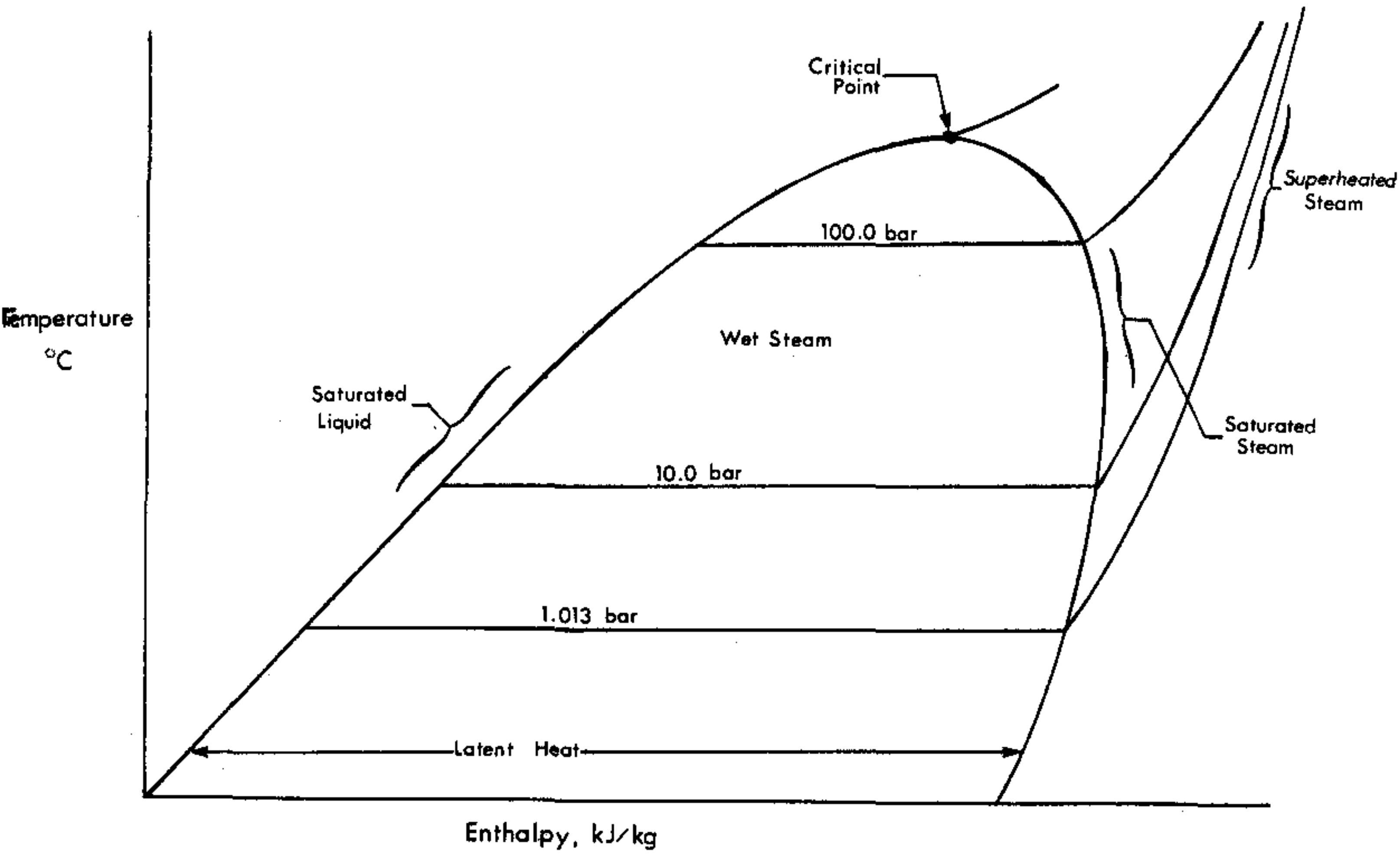

Fig. 2.2

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

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

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

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

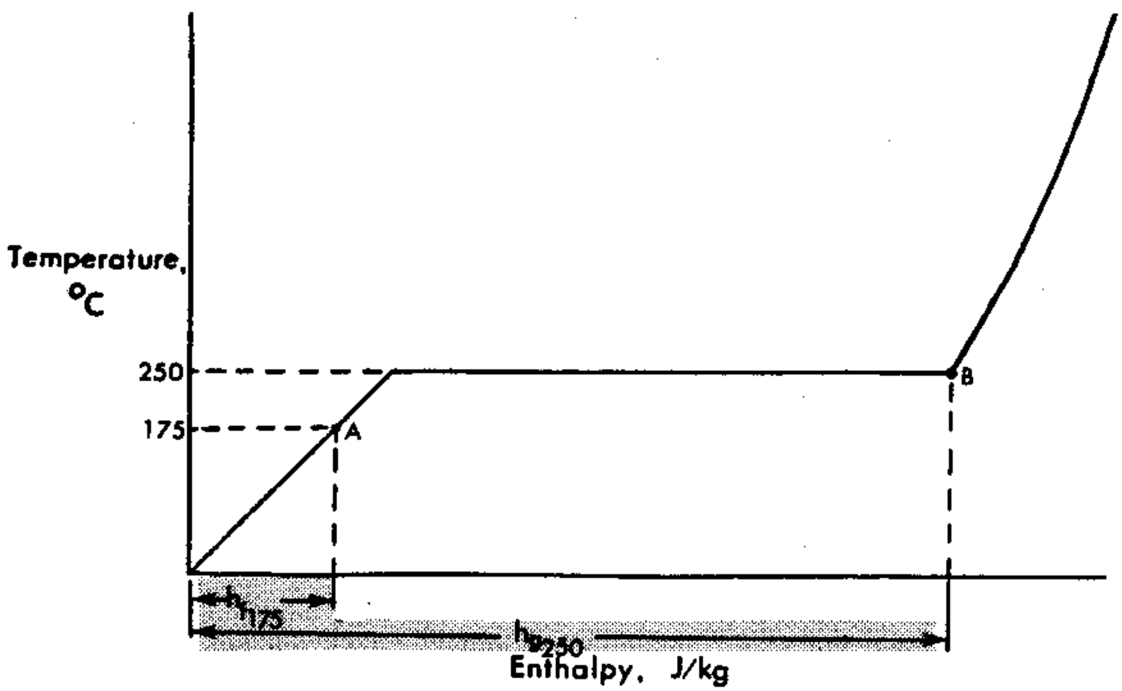

Fig. 2.3

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

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

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

Using steam tables,

h_{g250} = 2800.4 kJ/kg

h_{f175} = 741.1 kJ/kg

Thus Q = 2840.4 - 741.1

= 2059.3 kJ/kg

Before you try some examples, just examine Table 2 of the steam tables. They are based on exactly the same layout at Table 1, except that they use even steps of pressure as the base instead of temperature. Which one do you choose? The answer is simple. Whichever one suits you√ <u>If the temperature is quoted in whole degrees - use Table 1</u>, <u>if the pressure is quoted in whole numbers use Table 2</u>.

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.

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

<u>Q2.11</u> A steam generator produces saturated steam at 186°C. The feedwater, at the suction to the boiler feedpump, which pumps the feedwater <u>directly</u> 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?

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

<u>Q2.13</u> 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 1 that we could describe 'wet steam' as steam which had not received all its latent heat of vapourization. This is a little contradictory and it would be more accurate to describe wet steam as a mixture of water droplets and vapour, both at the saturation temperature.

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

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

Dryness Fraction

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

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

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

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

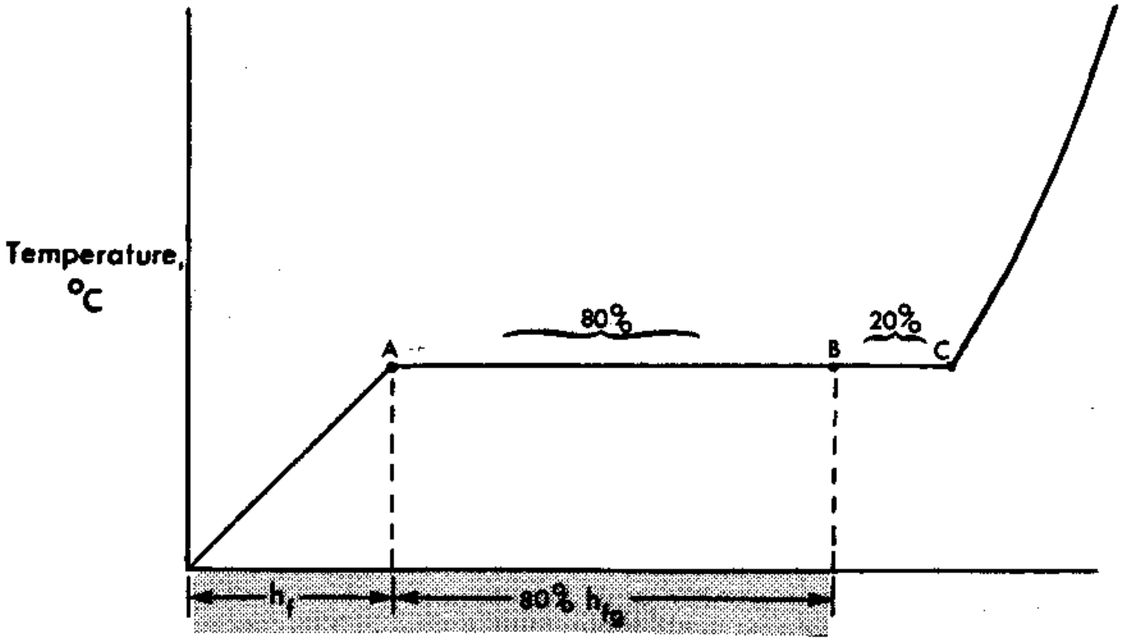

Fig. 2.4

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

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

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

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

Thus enthalpy of steam = 1087.4 + 0.85 x 1712.9 kJ/kg
= 1087.4 + 1456 kJ/kg
= 2543.4 kJ/kg

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

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

Q2.15 4 kg of liquid are removed from a moisture separator. If the steam was 88% dry, what was the mass of wet steam entering the moisture separator? Assume that the steam leaving the moisture separator is saturated.

Q2.16 A steam generator produces wet steam of 92% dryness at 196°C. The feedwater enters the steam generator at 134°C. Determine how much energy is added to the feedwater in the steam generator.

Q2.17 A process heater produces saturated steam at 300°C from 18% wet steam at 18 bar. Determine how much heat has been added to the steam.

Q2.18 A condenser receives 12% wet steam at 35°C. The condensate is subcooled by 5°C. Determine how much heat has been removed in the condenser.

Q2.19 Feedwater enters a steam generator at 160°C and is converted into steam having a saturation temperature of 220°C. The heat supplied by the steam generator is 1900 kJ per kilogram of steam. Determine the dryness fraction of the steam.

* * * * *

Superheated Steam

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

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

TABLE 3 - PROPERTIES OF WATER AND STEAM

p(abs)bar	2.0			3.0			4.0		
t_s °C	120.2			133.5			143.6		
	h	s	v	h	s	v	h	s	v
Sat. Liquid	504.7	1.530	1.061	561.4	1.672	1.074	604.7	1.776	1.084
Sat. Vapour	2706	7.127	885.4	2725	6.991	605.6	2738	6.894	462.2
t °C									
50	209.4	0.703	1.012	209.5	0.703	1.012	[illegible]	0.703	1.012
100	419.1	1.307	1.044	419.2	1.307	1.044	419.3	1.307	1.044
150	2769	7.279	959.5	2760	7.077	633.7	2752	6.929	470.7
200	2871	7.507	1080	2866	7.312	716.4	[illegible]	7.171	534.3
250	2971	7.710	1200	2968	7.518	796.4	[illegible]	7.380	595.2
300	3072	7.894	1316	3070	7.703	875.3	3067	7.568	654.9
350	3174	8.064	1433	3172	7.874	953.5	3170	7.640	713.9
400	3277	8.223	1549	3275	8.034	1031	3274	7.899	772.5
450	3381	8.372	1665	3380	8.184	1109	[illegible]	8.050	830.9
500	3487	8.514	1781	3486	8.326	1187	[illegible]	8.192	889.2
550	3595	8.649	1897	3594	8.461	1264	[illegible]	8.327	947.4
600	3704	8.778	2013	3703	8.590	1341	3702	8.456	1005
650	3815	8.901	2129	3814	8.714	1419	3814	8.580	1063

p(abs)bar	5.0			6.0			7.0		
t_s °C	151.8			158.8			165.0		
	h	s	v	h	s	v	h	s	v
Sat. Liquid	640.1	1.860	1.093	670.4	1.931	1.101	697.1	1.992	1.10
Sat. Vapour	2748	6.819	374.7	2756	6.758	315.5	2762	6.705	272
t °C									
50	209.7	0.703	1.012	209.8	0.703	1.012	209.9	0.703	1.01
100	419.4	1.307	1.044	419.4	1.307	1.043	419.5	1.306	1.04
150	632.2	1.842	1.091	632.2	1.842	1.091	632.3	1.841	1.09
200	2855	7.059	425.0	2850	6.968	352.0	2844	6.886	299.
250	2961	7.272	474.4	2958	7.183	393.9	2954	7.107	336
300	3065	7.461	522.6	3062	7.374	434.4	3060	7.300	371.
350	3168	7.634	570.1	3166	7.548	474.2	3164	7.475	405
400	3272	7.796	617.2	3271	7.709	513.6	3269	7.636	439.
450	3377	7.945	664.1	3376	7.860	552.8	3375	7.738	473.
500	3484	8.088	710.8	3483	8.003	591.8	3482	7.931	506
550	3592	8.223	757.4	3591	8.138	630.8	3590	[illegible]	540.
600	3702	8.353	804.0	3701	8.268	669.6	3700	[illegible]	57..
650	3813	8.477	850.4	3812	8.392	708.4	3811	8.320	607.

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

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

Example

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

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

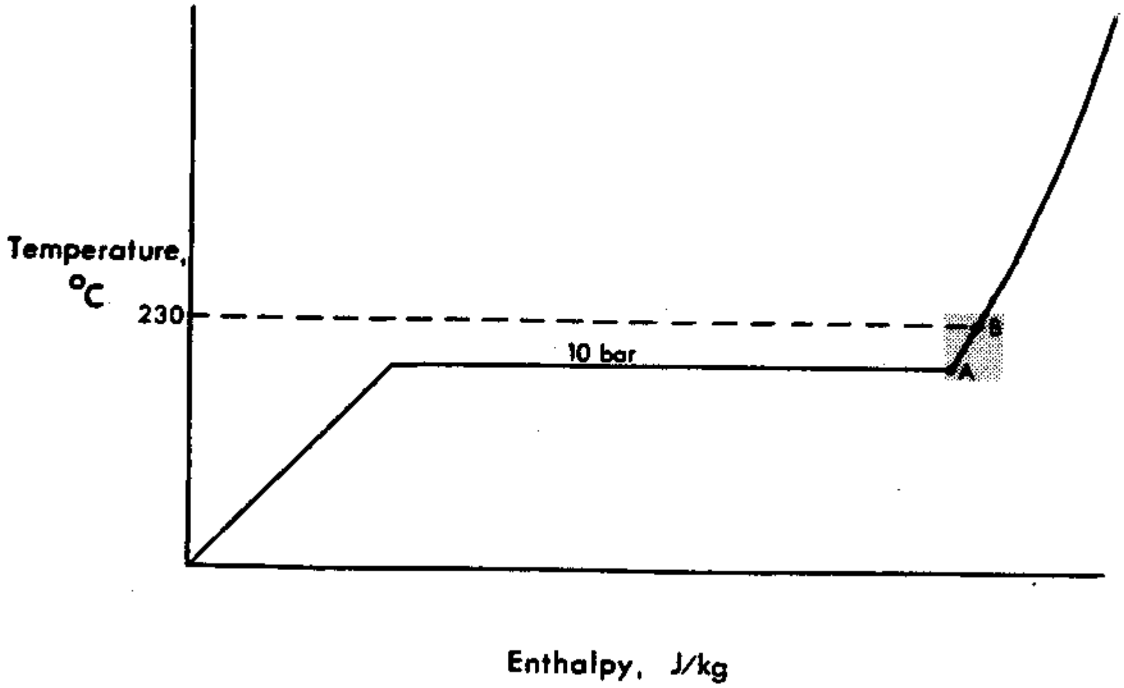

Fig. 2.5

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

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

At 10 bar and 200°C h = 2827 kJ/kg.
and at 10 bar and 250°C h = 2943 kJ/kg.
The difference for 50°C is 2943 - 2827 = 116 kJ/kg.

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

Thus h = 2827 + 3/5 x 116

(a) = 2896.6 kJ/kg

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

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

(b) 2896.6 - 2776 = 120.6 kJ/kg

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

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

Q2.21 380 kJ of heat are added to 1 kg of 15% wet steam at 8 bar. Determine the temperature of the final steam.

* * * * *

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

Q2.22 Given the following information, identify the states of water as:

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

	Enthalpy	Temperature	Pressure
(a)	561.4 kJ/kg	133.5°C	3.0 bar
(b)	2323 kJ/kg	32.9°C	0.05 bar
(c)	2855 kJ/kg	200°C	5.0 bar
(d)	2538.2 kJ/kg	20°C	0.02337 bar
(e)	12.7 kJ/kg	30°C	0.07375 bar

Q2.23 Feedwater enters a steam generator at 180°C and is converted into steam with 4% moisture at 260°C. How much heat is added in the steam generator per kg of steam?

Q2.24 Steam which is 12% wet enters a condenser at 36°C. The condensate is subcooled by 3°C. Determine how much heat is rejected to the condenser per kg of steam.

* * * * *

Volume of Liquid and Vapour

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

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

(a) the cubic meter - 'm^3'

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

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

Volume of Liquid

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

Example

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

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

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

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

Q2.26 Condensate at 36°C is heated to 175°C in the feedheating system. Determine the percentage increase in volume of the feedwater.

* * * * *

Volume of Saturated Steam

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

Example

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

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

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

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

Q2.27 Feedwater enters the steam generator at 175°C. The steam leaving the steam generator is saturated steam at 250°C. Determine the volume increase that occurs within the steam generator.

Q2.28 Saturated steam at 40°C is condensed to subcooled liquid at 35°C. Determine the volume reduction.

* * * * *

Volume of Wet Steam

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

Example

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

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

$v = v_f + qv_{fg}$

$= 1.1082 + 0.88 \times 271.29$

$= \underline{239.8}$ ℓ/kg

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

Q2.29 Saturated steam at 250°C enters the hp turbine and steam with 12% moisture leaves the low pressure turbine at a pressure of 5 kPa(a). Compare the initial steam volume per kg with the final volume.

Q2.30 The low pressure steam in question Q2.29 is condensed to condensate which is subcooled by 3°C. Determine the volume reduction which occurs in the condenser.

* * * * *

Steam Hammer

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

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

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

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

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

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

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

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

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

* * * * *

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

MODULE 2 - ANSWERS

Q2.1

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

Q2.2

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

Q2.3

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

Q2.4

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

Q2.5

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

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

Q2.6

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

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

Q2.7

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

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

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

Q2.8

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

Q2.9

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

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

Q2.10

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

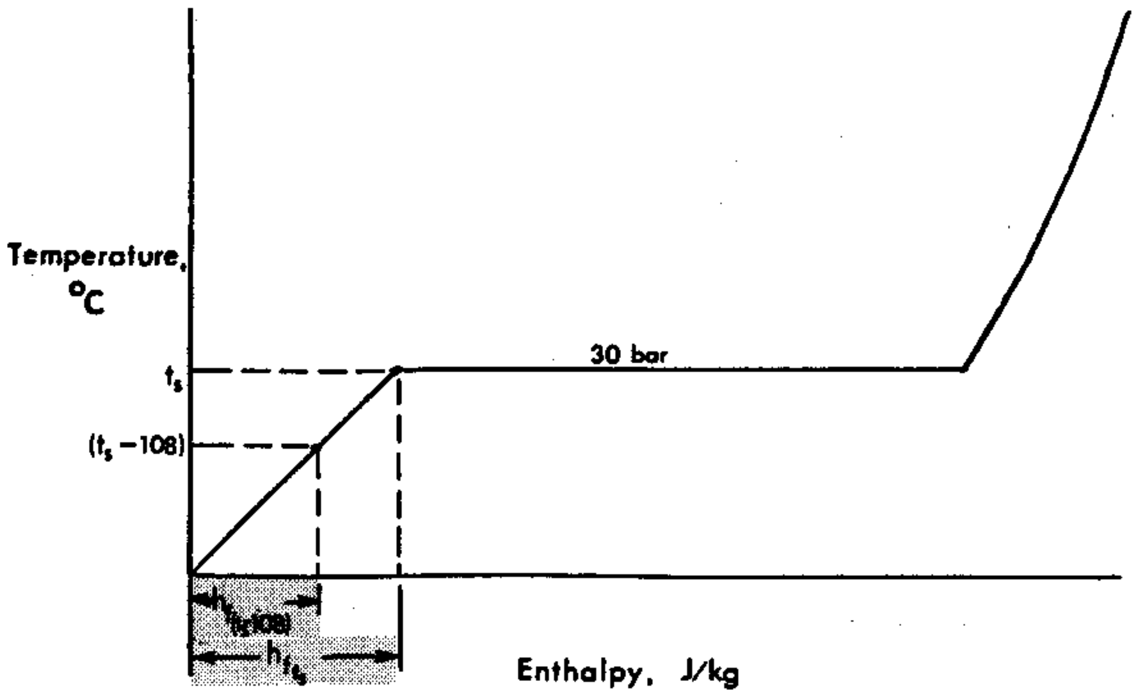

Fig. 2.6

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

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

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

So the heat removed = 1008.4 - 592.2

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

<u>Q2.11</u>

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

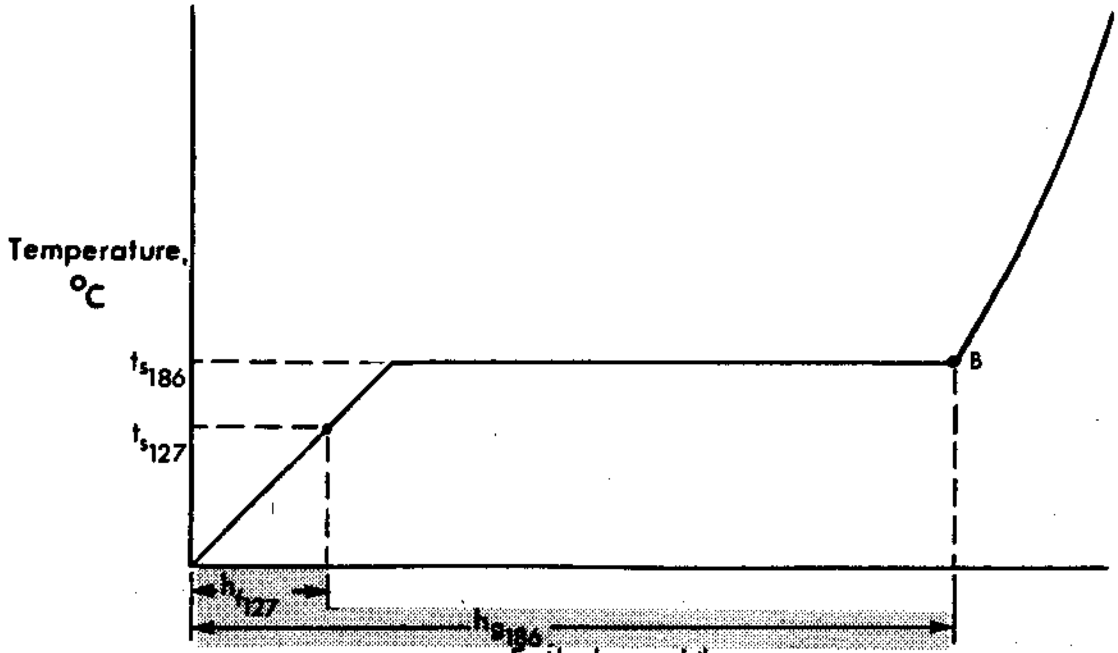

Fig. 2.7

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

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

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

2781.2 - 533.5 = <u>2247.7</u> kJ/kg.

Q2.12

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

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

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

(Both values from Table 1)

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

Q2.13

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

Again a sketch on the temperature enthalpy diagram is worthwhile.

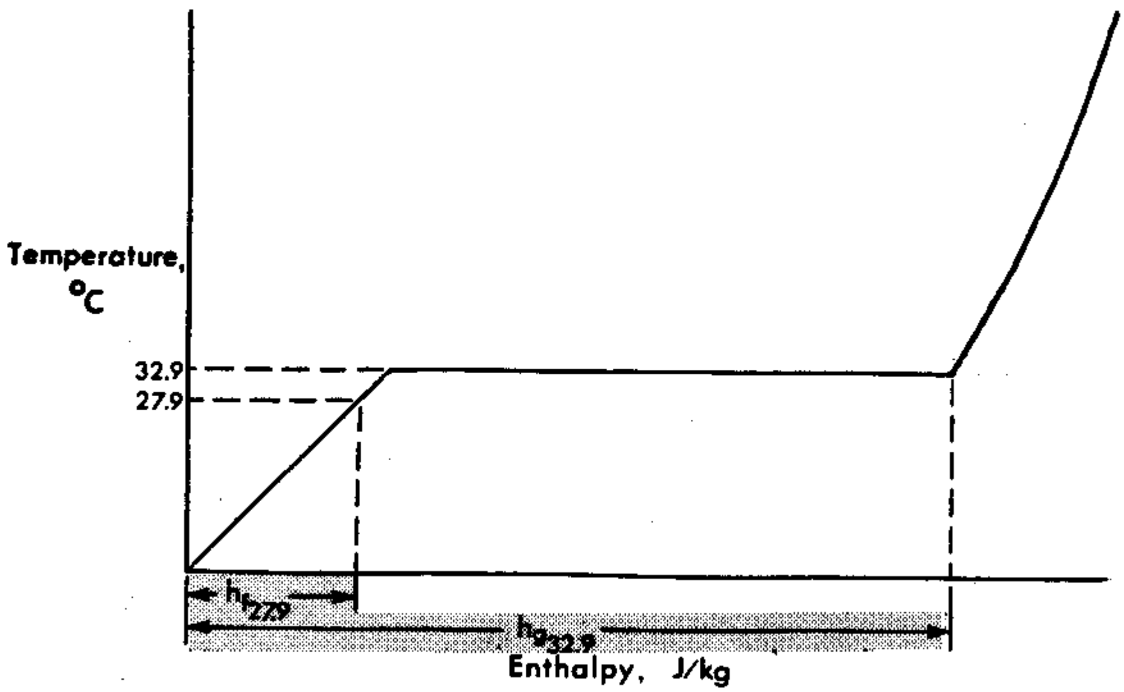

Fig. 2.8

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

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

The enthalpy of the final condition is h_f at 27.9°C, which from Table 1 is 116.9 kJ/kg (obtained by interpolation).

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

Q2.14

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

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

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

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

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

= 151.5 + 2126.1 kJ/kg

= 2277.6 kJ/kg

Q2.15

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

Q2.16

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

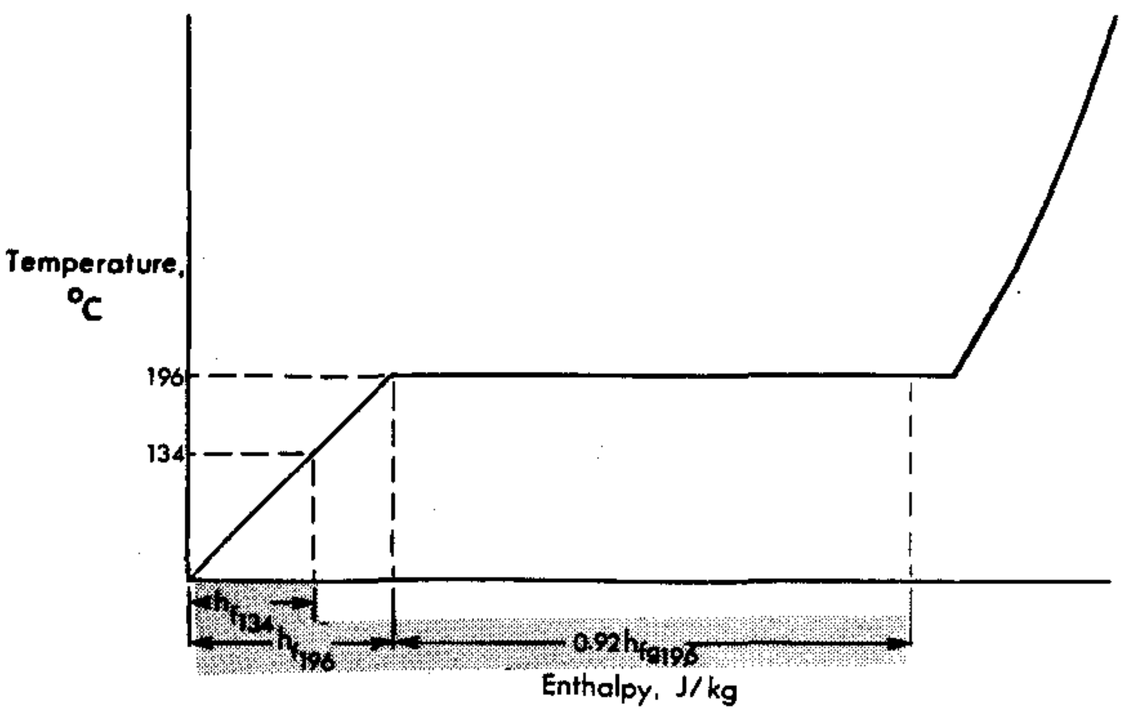

Fig. 2.9

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

The enthalpy of the wet steam is

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

= 834.4 + 1797.8 kJ/kg

= <u>2632.2</u> kJ/kg

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

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

<u>02.17</u>

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 = <u>2751</u> kJ/kg.

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

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

= 884.6 + 0.82 x 1910.3 kJ/kg

= 884.6 + 1566.4 kJ/kg

= 2451.0 kJ/kg

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

2751 - 2451 kJ/kg

= <u>300</u> kJ/kg

Q2.18

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

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

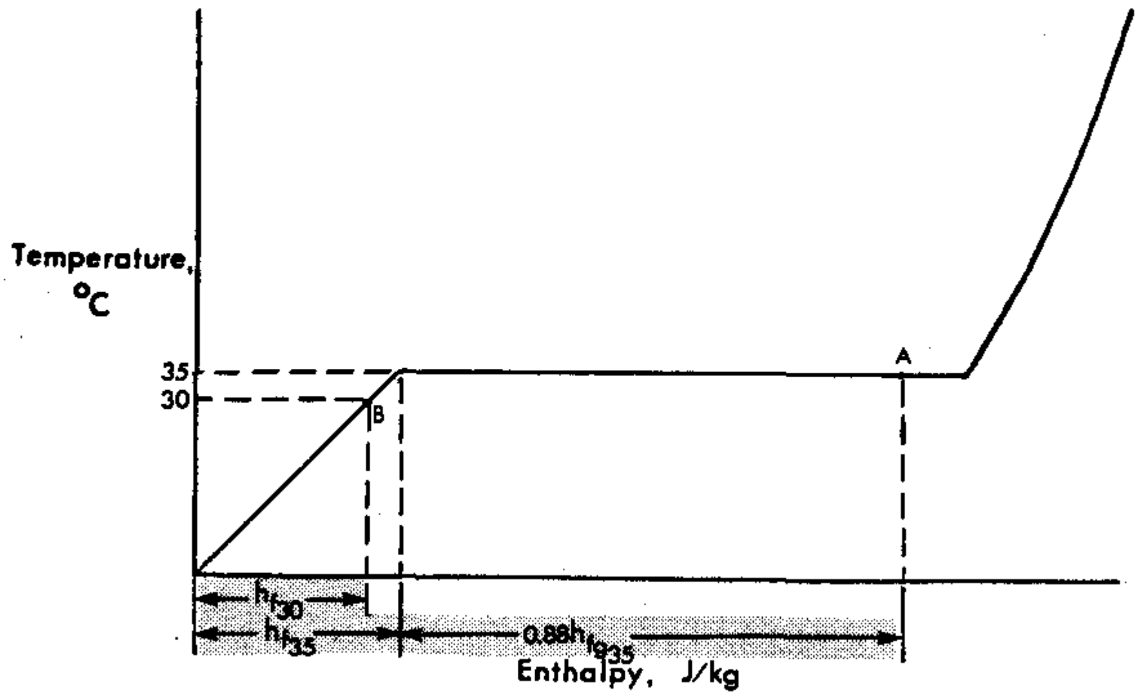

Fig. 2.10

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

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

= 146.6 + 0.88 x 2418.8 kJ/kg

= 146.6 + 2128.5 kJ/kg

= 2275.1 kJ/kg

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

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

2275.1 - 125.7 kJ/kg

= 2149.4 kJ/kg

Q2.19

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

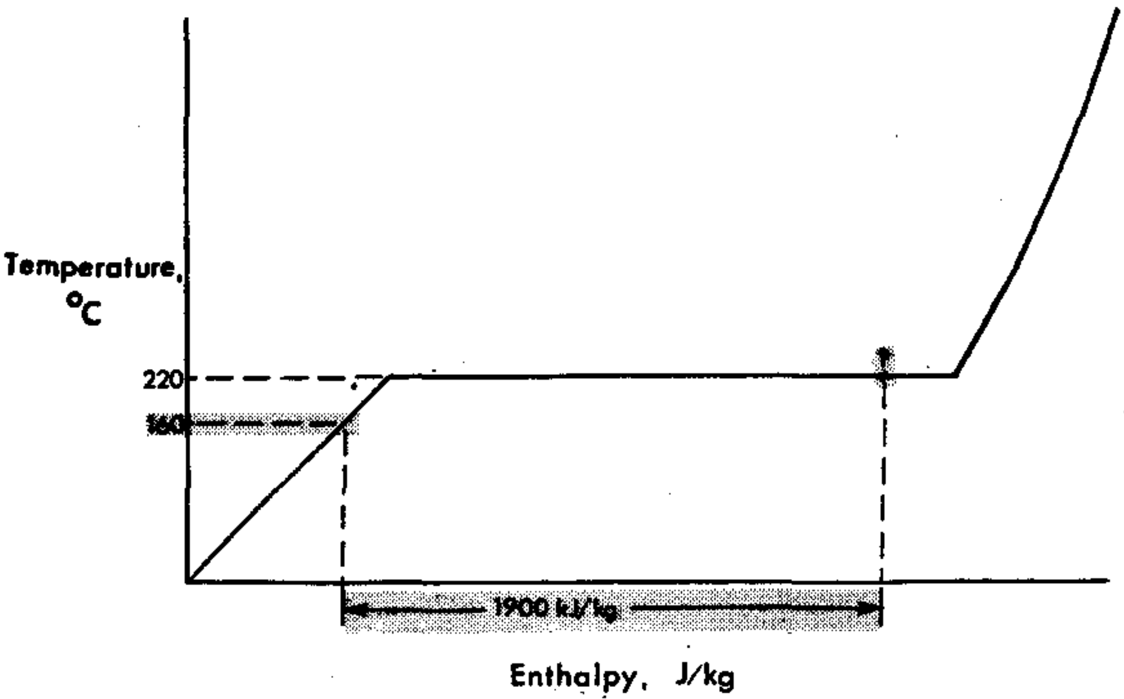

Fig. 2.11

h_{f160} = 675.5 kJ/kg

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

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

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

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

Using $h = h_f + qh_{fg}$

Substituting

2575.5 = 943.7 + q x 1856.2
1631.8 = q x 1856.2
q = (1631.8/1856.2) x 100
= 87.9%

Q2.20

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

= (3139 + 3249) 0.5

= 3194 kJ/kg

Q2.21

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

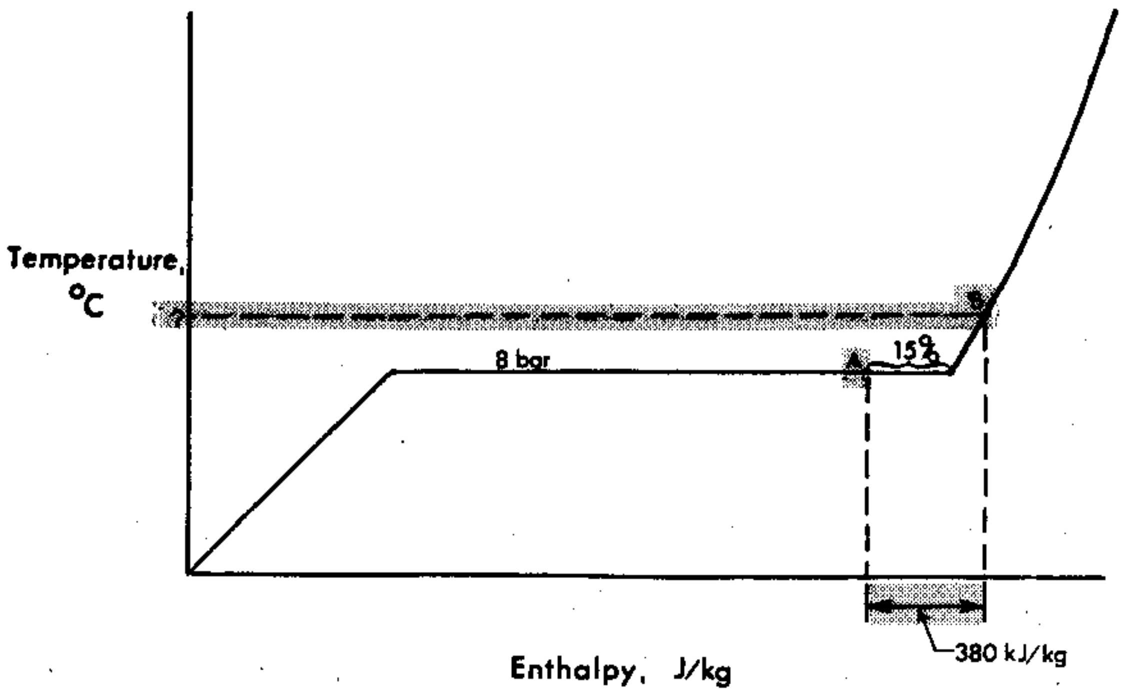

Fig. 2.12

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

h = 720.9 + 0.85 x 2046.5

= 720.9 + 1739.5 kJ/kg

= 2460.4 kJ/kg

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

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

Q2.22

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

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

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

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

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

02.23

Using the temperature enthalpy diagram,

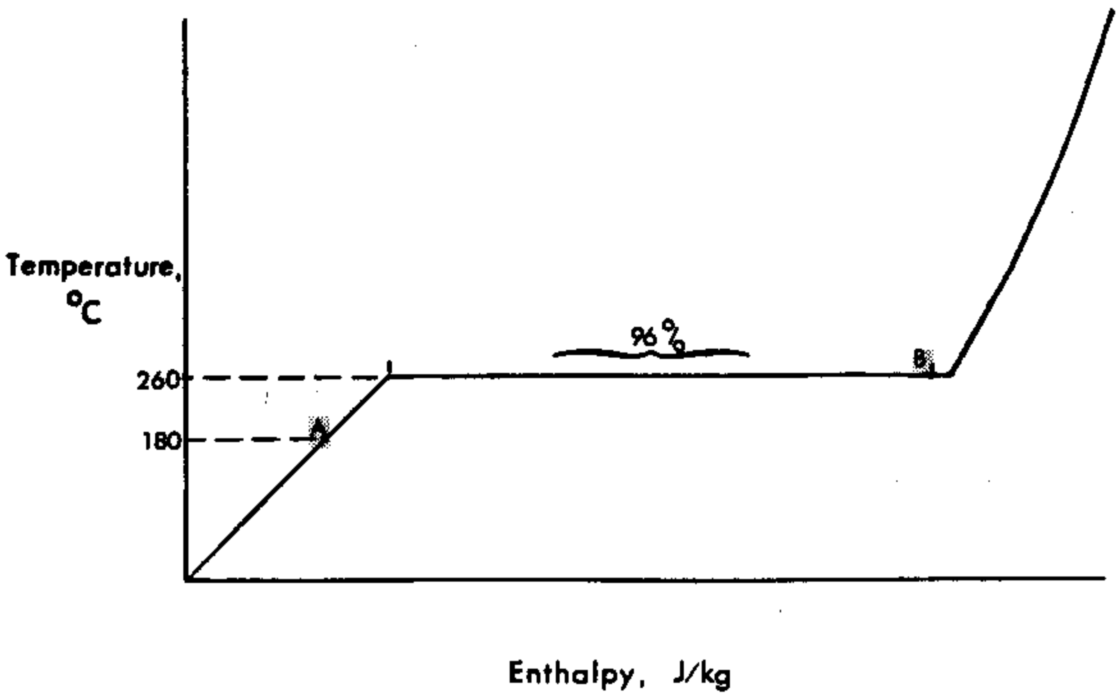

Fig. 2.13

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

h_f at 260°C = 1134.9 kJ/kg

h_{fg} at 260°C = 1661.5 kJ/kg

thus h = 1134.9 + 0.96 x 1661.5 kJ/kg

= 1134.9 + 1595.04 kJ/kg

= 2729.9 kJ/kg

The amount of heat added in the steam generator is the difference between the two enthalpies, ie, 2729.9 - 763.1 = 1966.8 kJ/kg

Q2.24

Again use the temperature/enthalpy diagram.

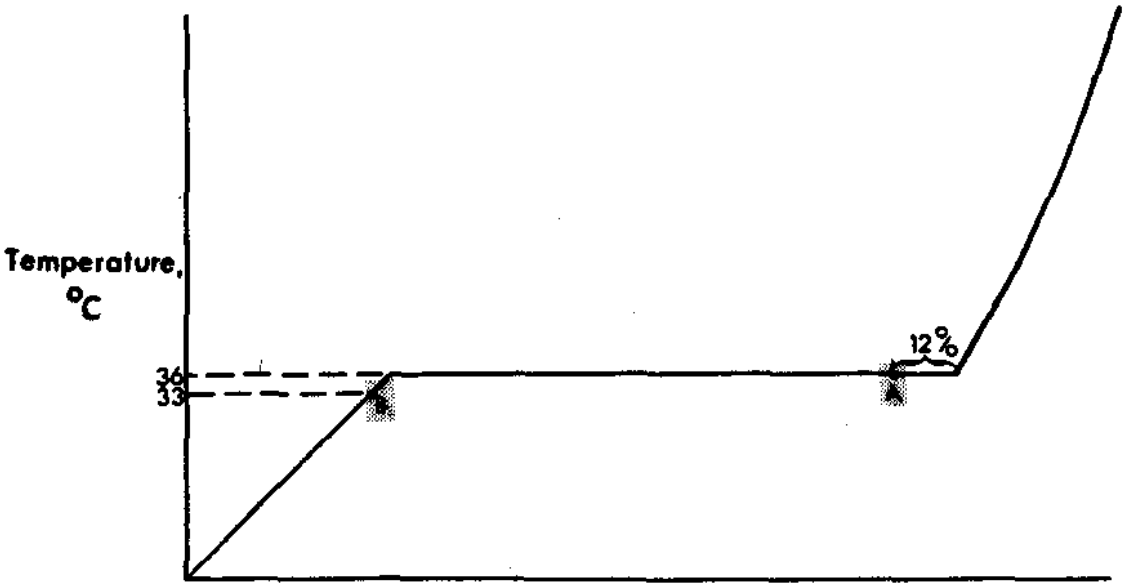

Fig. 2.14

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

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

$= 150.7 + 0.88 \times 2416.4$

$= 150.7 + 2126.4$ kJ/kg

$= \underline{2277.1}$ kJ/kg

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

Thus the heat rejected in the condenser is the difference, ie, 2277 - 138.2 = $\underline{3218.9}$ kJ/kg.

Q2.25

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

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

We can rearrange this equation for mass thus,

mass = volume/specific volume

= 3000/1.0361/kg

= 2895.47 kg

Q2.26

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

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

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

Q2.27

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

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

Q2.28

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

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

Q2.29

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

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

and, v_{fg} at 0.05 bar = 2819.3 ℓ/kg.

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

Thus $v = v_f + qv_{fg}$

$= 1.0052 + 0.88 \times 28193.3$

$= 1 + 24810$

$= 24811$ ℓ/kg

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

Q2.30

The volume of the low pressure steam is, as we already calculated in question Q2.29, 24811 ℓ/kg.

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

Q2.31

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

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