

# THERMODYNAMICS

## TUTORIAL 2 – PROPERTIES OF LIQUIDS AND VAPOURS

This is set at the Level QCF 3.

On completion of this tutorial you should be able to determine the various thermodynamic properties of liquids and vapours and in particular water and steam.

You should be able to:

- Explain the properties of water and steam
- Find the properties from your tables and charts or computer data base.

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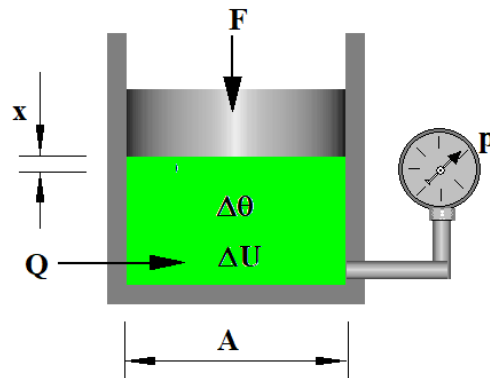
## 1. Introduction

This tutorial is necessary to prepare you for solving problems involving the energy transfer that occurs in steam plant such as boilers. In more advanced studies it will help you prepare you to solve problems involving other vapours and liquids such as in refrigeration.

You should ensure that you have a copy of 'Thermodynamic and Transport Properties of Fluids' by Mayhew and Rogers although these days properties can be found more easily with computer data bases. Remember that computer data bases may not be available to you in an examination so you should learn to use tables as well as the data base.

## 2. Energy in Water

In the earlier tutorials you studied the heat transfer into gas and learned the difference between internal energy and enthalpy. Let's apply the same idea to water.



Suppose a quantity of heat  $Q$  is passed into the water. This will make the temperature rise  $\Delta\theta$  and the water will expand and raise the piston a distance  $x$ .

The pressure of the water is constant and due to the weight of the piston and atmosphere pressing down.

$$p = F/A = \text{constant}$$

The work done raising the piston is  $F x = pAx = p \Delta V$

The energy transfer into the water is then  $Q = \Delta U + pV = \Delta H$

This is the change in enthalpy as before. ( $H = U + pV$ )

We have shown that the increase in the internal energy is  $\Delta U = m c_v \Delta\theta$   
 $c_v$  is the specific heat capacity of the water at constant volume.

We have also shown that  $\Delta H = m c_p \Delta\theta$

$c_p$  is the specific heat capacity of the water at constant pressure.

The important point to be made here is that **water expands very little** compared to gas so  $x$  and  $\Delta V$  are small and it follows that  $Q = \Delta H \approx \Delta U$  and that  $c_p \approx c_v = c$

The specific heat of water  $c$  is normally 4.186 kJ/kg K. If the pressure is high and the temperature change large, then  $\Delta H$  is significantly different from  $\Delta U$  and  $c_p$  is significantly larger than  $c_v$  so the foregoing becomes inaccurate.

The most accurate way to find  $U$  and  $H$  are through published tables. When looking these up in tables you will find the specific values  $h$  and  $u$ .

Remember that:

$$h = u + p v$$

$$H = \text{mass} \times h \text{ and } U = \text{mass} \times u$$

$v$  is the specific volume of water and this is about  $0.001 \text{ m}^3/\text{kg}$  unless it is very hot and/or the pressure  $p$  is very large, the  $p v$  term is small and  $h \approx u$

The internal energy and enthalpy can be calculated by use of the specific heat

$$H \approx U = m c \Delta T$$

In tables it is normal to give values of  $u$  and  $h$  relative to  $0.01^\circ\text{C}$ . This means that  $u$  and  $h$  are both zero at  $0^\circ\text{C}$  and low pressure.

The values at other temperatures and low pressures are hence  $h \approx u \approx c \theta$

It follows that when we heat water (or any other liquid) the temperature rises directly proportional to the heat received.

Note that water that is colder than its boiling point (saturation temperature) is called sub saturated or unsaturated. This will be explained later.

### **WORKED EXAMPLE No. 1**

Calculate the specific internal energy and enthalpy of water at 1 bar and  $60^\circ\text{C}$ .  
Take  $c = 4.186 \text{ kJ/kg } ^\circ\text{C}$  and  $v = 0.001 \text{ m}^3/\text{kg}$

#### **SOLUTION**

$$u = c \theta = 4.186 \times 60 = 251.16 \text{ kJ/kg}$$

$$p v = 1 \times 10^5 \times 0.001 = 100 \text{ J/kg or } 0.1 \text{ kJ/kg}$$

$$h = u + p v = 251.26 \text{ kJ/kg}$$

### **WORKED EXAMPLE No. 2**

Repeat example 1 but this time the pressure is 100 bar. Show that this makes a significant difference between  $u$  and  $h$ .

Assume  $c = 4.186 \text{ kJ/kg } ^\circ\text{C}$  and  $v = 0.001 \text{ m}^3/\text{kg}$  as before.

#### **SOLUTION**

$$u = c \theta = 4.186 \times 60 = 251.16 \text{ kJ/kg}$$

$$p v = 100 \times 10^5 \times 0.001 = 10\,000 \text{ J/kg or } 10 \text{ kJ/kg}$$

$$h = u + p v = 261.16 \text{ kJ/kg}$$

The table below gives the specific enthalpy of water at various temperatures and pressures. You can find these values and others at precise temperatures and pressures on the web site <http://www.spiraxsarco.com/resources/steam-tables.asp>

Note from the tables that at 60°C,  $h = 251 \text{ kJ/kg}$  and this is the figure calculated in example 1 at 1 bar. At 100 bar the tables give 259 kJ/kg which is more accurate than the figure calculated in example 2 because the values of  $c$  and  $v$  were not precise.

**TABLE FOR THE ENTHALPY OF HIGH PRESSURE WATER**

All enthalpy values are given in kJ/kg

Temp °C	Pressure in bar										
	0	25	50	75	100	125	150	175	200	221	250
0	0	2.5	5	7.5	10	12.6	15	17.5	20	22	25
20	84	86	87	91	93	96	98	100	103	105	107
40	168	170	172	174	176	179	181	183	185	187	190
60	251	253	255	257	259	262	264	266	268	270	272
80	335	337	339	341	343	345	347	349	351	352	355
100	419	421	423	425	427	428	430	432	434	436	439
120	504	505	507	509	511	512	514	516	518	519	521
140	589	591	592	594	595	597	599	600	602	603	605
160	675	677	678	680	681	683	684	686	687	688	690
180	763	764	765	767	767	769	790	772	773	774	776
200	852	853	854	855	856	857	858	859	861	862	863

Screen shot below from the Spirax Sarco web site from the section on sub saturated water. Enter the pressure and temperature and all the other properties will be revealed showing  $h = 258 \text{ 125 J/kg}$

Pressure   ▼

Temperature   ▼

Vapour Pressure   ▼

Saturation Temperature   ▼

Specific Enthalpy of Water ( $h_f$ )   ▼

Density of Water   ▼

Specific Volume of Water ( $v$ )   ▼

### 3. Saturated Water

If water is heated, it reaches a temperature where it can absorb no more energy and in this state it is called **Saturated Water**. Further heating will make the water evaporate. The temperature at which this occurs is called the **Saturation Temperature**. (In simple language it reaches the boiling point).



The energy contained in the water at this condition is called the **Sensible Energy** and could be either internal energy or enthalpy. In tables these are denoted  $u_f$  and  $h_f$ . The specific volume is denoted  $v_f$  but will not normally be much different from the volume at colder temperatures. It is of interest to note that there is an enormous change in volume when water changes into steam, and when steam changes back into water, more so than for any other liquid and this is why it is so useful in steam engines and turbines.

The saturation temperature is denoted as  $t_s$  in tables. This will increase with the pressure (see the next diagram). At atmospheric pressure (1.013 bar), water boils at 100°C but in pressurised boilers, the water is hotter. This explains why food cooks much quicker in a pressure cooker. On the top of a high mountain where the pressure is less than 1.013 bar, water boils at a lower temperatures which explains why you can't make a decent cup of tea on top of mount Everest. It should also be noted that if the temperature of a liquid is kept constant, it may be made to boil by changing the pressure.

### 4. Evaporation and Latent Heat

When water is saturated with energy, adding more energy makes it evaporate and change into vapour. This is called a change of state from liquid to gas form. The vapour given off is at the same saturation temperature as the water. The vapour is called **Dry Saturated** and in the case of water it is **Dry Saturated Steam** (d. s.s. for short).



A vapour is defined as a gas near to the temperature at which it will condense and so we would have difficulty using gas laws to calculate the properties of dry saturated steam. This is why we use tables. Once the water is boiling we must go on applying energy to make it evaporate.

The change in the enthalpy and internal energy when 1 kg of saturated water changes into 1 kg of d.s.s. is called the latent energy and this is either enthalpy denoted  $h_{fg}$  or internal energy denoted  $u_{fg}$  in tables. These are the **Latent Enthalpy and Latent Internal Energy** respectively.

### WORKED EXAMPLE No. 3

Go to the web site <http://www.spiraxsarco.com/resources/steam-tables.asp> and find the values of  $h_f$  and  $h_{fg}$  at 1.01325 bar and 100 bar. Also find the saturation temperature. These are absolute pressures.

### SOLUTION

On the web page navigate to steam tables and click on 'dry saturated steam line'.

Enter the absolute pressure and click on calculate. Look up the value of  $h_f$ ,  $h_{fg}$  and  $t_s$ .

The screen shots give the answers:

418.55 kJ/kg, 2256.8 kJ/kg and 99.97°C at 1.01325 bar

1407.5 kJ/kg, 1317.4 kJ/kg and 311 °C at 100 bar.

Pressure	<input type="text" value="1.01325"/>	<input type="text" value="bar absolute"/>	
	<input type="button" value="Calculate"/>	<input type="button" value="Reset"/>	<input type="button" value="Print"/>

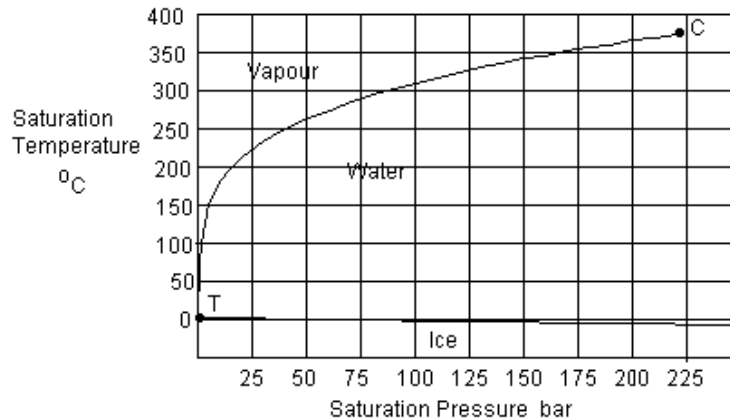
Saturation Temperature	<input type="text" value="99.9743"/>	<input type="text" value="°C"/>
Specific Enthalpy of Water ( $h_f$ )	<input type="text" value="418546"/>	<input type="text" value="J/kg"/>
Specific Enthalpy of Evaporation ( $h_{fg}$ )	<input type="text" value="2.25647E06"/>	<input type="text" value="J/kg"/>

Pressure	<input type="text" value="100"/>	<input type="text" value="bar absolute"/>	
	<input type="button" value="Calculate"/>	<input type="button" value="Reset"/>	<input type="button" value="Print"/>

Saturation Temperature	<input type="text" value="310.997"/>	<input type="text" value="°C"/>
Specific Enthalpy of Water ( $h_f$ )	<input type="text" value="1407.55"/>	<input type="text" value="kJ/kg"/>
Specific Enthalpy of Evaporation ( $h_{fg}$ )	<input type="text" value="1317.43"/>	<input type="text" value="kJ/kg"/>

## 5. More about the Saturation Temperature

If we look up the values of  $t_s$  and  $p$  for water in the tables and plot them we get the graph below. The pressure at which it boils is called the **Saturation Pressure** and is denoted as  $p_s$  in the tables. The graph below also shows the freezing point of water plotted against pressure (pressure has little effect on it).



The two graphs cross at point T where  $t_s = 0.01^\circ\text{C}$  and  $p_s = 0.006112$  bar. This point is called the **Triple Point**. The graph shows the three phases of ice, water and steam. At the triple point, all three can occur together. Below the triple point, ice can change into steam without a liquid stage (and vice versa). All substances have a triple point. To be precise, in tables  $h$  and  $u$  are taken as zero at the triple point and not at  $0^\circ\text{C}$ . The difference is very small.

If you did the exercise of plotting the above graph you would find that you cannot plot anything after the point denoted C where  $p = 221.2$  bar and  $t_s = 374.15^\circ\text{C}$ . Above this pressure and temperature, the phenomenon of evaporation does not occur and no latent energy stage exists. This point is called the **Critical Point** and every substance has one.

## 6. Dry Saturated Steam

The energy contained in 1 kg of dry saturated vapour must be the sum of the sensible and latent energy and this is denoted  $h_g$  and  $u_g$ . It follows that :

$$\begin{aligned} h_g &= h_f + h_{fg} \\ u_g &= u_f + u_{fg} \end{aligned}$$

If dry saturated steam is heated, it becomes hotter than the boiling point and the more it is heated, the more it becomes a gas. This is called **Superheated Steam**. When the pressure and temperature is above the critical point it is called **Supercritical Steam**.

### WORKED EXAMPLE No. 4

0.2 kg of water at  $20^\circ\text{C}$  is put in a kettle and boiled until it has all changed to steam at standard atmospheric pressure (1.01325 bar). Calculate the heat transfer.

#### SOLUTION

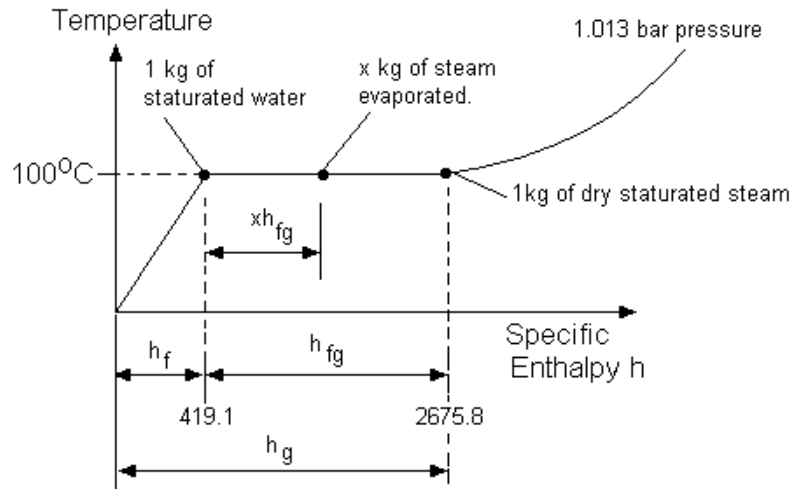
At  $20^\circ\text{C}$  and 1.013 bar,  $h_1 \approx 4.186 \times 20 = 83.72$  kJ/kg. The web site (sub saturated water region) gives 83.96. We will take 84 as the answer.

When it is all steam, the enthalpy is  $h_g$ . On the web site (dry saturated steam line) find  $h_g = 2675.7$  kJ/kg. Round off to  $h_2 = 2676$  kJ/kg

$$Q = \Delta H = m \Delta h = 0.2(h_2 - h_1) = 0.2(2676 - 84) = 518.4 \text{ kJ}$$

## 7. Wet Vapour

Wet vapour is a mixture of dry saturated vapour and liquid droplets. It may also be thought of as a partially evaporated substance. In order to understand its properties, consider the evaporation of 1 kg of water illustrated with a temperature - enthalpy graph.



Starting with water at atmospheric pressure and 0.01°C, the enthalpy is arbitrarily taken as zero. Keeping the pressure constant and raising the temperature, the enthalpy of the water rises to 419.1 kJ/kg at 100°C. At this point it is saturated water and the sensible enthalpy is  $h_f = 419.1$  kJ/kg. The addition of further heat will cause the water to evaporate.

During evaporation, the temperature remains at 100°C. When the latent enthalpy  $h_{fg}$  (2 256.7 kJ/kg) has been added, the substance is dry saturated vapour and its specific enthalpy  $h_g$  is 2 675.8 kJ/kg.

This graph may be drawn for any pressure and the same basic shape will be obtained but of course with different values. At the critical pressure it will be found that  $h_{fg}$  is zero.

The point of interest is the enthalpy value at some point along the evaporation line. Any point on this line represents wet steam. Suppose only fraction  $x$  kg has been evaporated. The latent enthalpy added will only be  $x h_{fg}$  and not  $h_{fg}$ . The enthalpy of the water/steam mixture is then

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

The fraction  $x$  is called the **Dryness Fraction** but it is rarely given as a fraction but rather as a decimal. If no evaporation has started, then  $x = 0$ . If all the liquid is evaporated then  $x = 1$ .

The same logic applies to internal energy and it follows that  $u = u_f + x u_{fg}$   
 $x$  cannot be larger than 1 as this would mean the vapour is superheated.

## 8. Volumes

The specific volume of saturated water is denoted  $v_f$ . The specific volume of dry saturated steam is denoted  $v_g$ . The change in volume from water to steam is  $v_{fg}$ . It follows that the specific volume of wet steam is  $v = v_f + x v_{fg}$

Since the value of  $v_f$  is very small and the specific volume of dry steam is very large (in all but the extreme cases), then  $v_{fg}$  is practically the same as  $v_g$  and  $v_f$  is negligible. The specific volume of steam is then usually calculated from the formula  $v \approx x v_g$

The volume of  $m$  kg of wet steam becomes  $V \approx m x v_g$

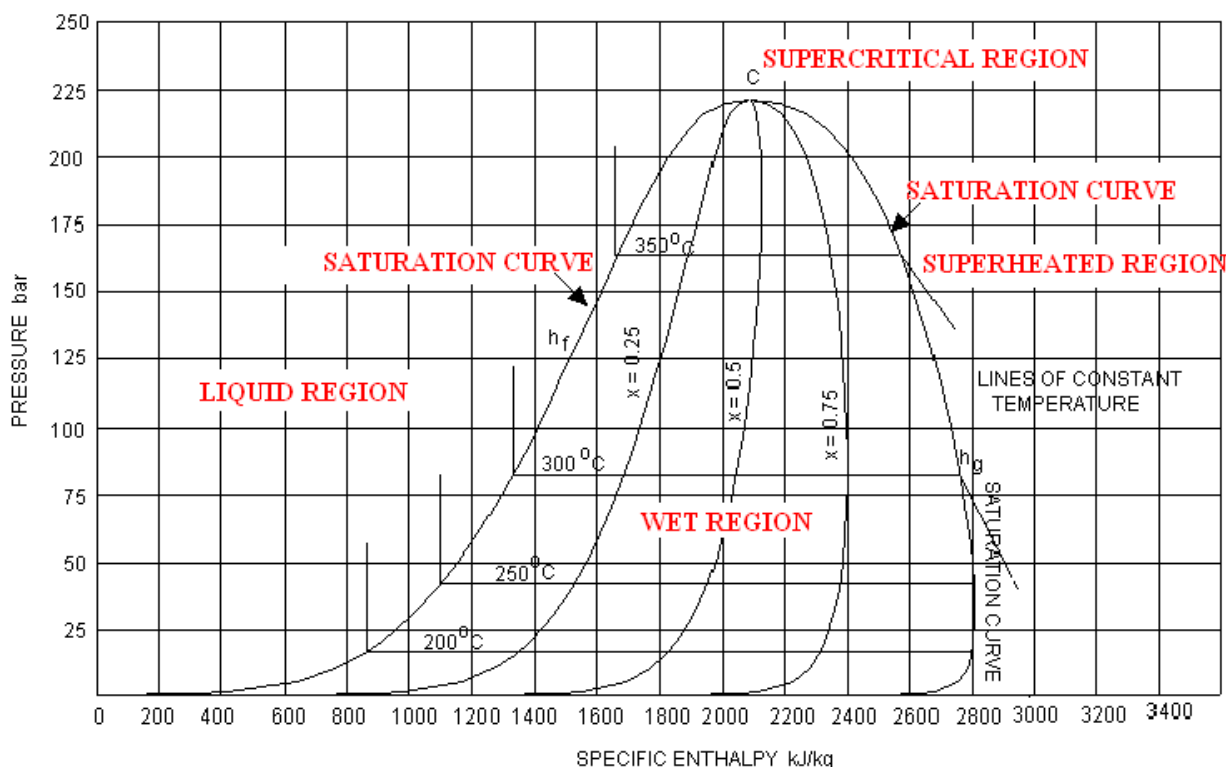


## 9. Superheated Steam

When all the water is evaporated into dry saturated steam, further addition of heat will cause the temperature to rise and the substance becomes superheated vapour. Superheated vapour behaves more like gas. Note that a dryness fraction cannot be greater than 1 as this would indicate the steam is superheated. To find the enthalpy or internal energy, you need both a temperature and pressure.

## 10. Saturation Curve

If we plot a graph of  $h_f$  and  $h_g$  against either temperature or pressure, we get a property chart. The graph itself is the **Saturation Curve**. Taking the p-h graph as an example, temperatures and dryness fractions may be drawn on it and with the resulting graph, the enthalpy of water, wet, dry or superheated steam may be found. The pressure - enthalpy chart is popular for refrigerants but not for steam so you won't come across professional versions of the chart below.



## 11. Use of Tables

It is vitally important for you to be able to use the fluid tables in order to find the properties of steam. Regarding water/steam, the tables contain a section on saturated water/steam and a section on superheated/supercritical steam.

The saturated water/steam tables are laid out as follows with an example of values. Check this out for yourself on page 4.

p	$t_s$	$v_g$	$u_f$	$u_g$	$h_f$	$h_{fg}$	$h_g$	$s_f$	$s_{fg}$	$s_g$
10	179.9	0.1944	762	2 584	763	2 015	2 778			

Don't worry about the columns headed s at this stage. This is the property called entropy which is not covered later.

The latent internal energy  $u_{fg}$  is not listed because of lack of room. However you do need to remember that it is the difference between  $u_f$  and  $u_g$ . Note that in all cases the value of  $h_{fg}$  is the difference between the values on either side of it.

The superheat tables are laid out differently. In this case the property value depends upon the pressure and temperature since the steam can exist at any pressure and temperature above the saturation values. This by necessity makes the tables very concise. More detailed tables are published. Interpolation is required to find values between those tabulated.

In the superheat tables (e.g. page 6), you must locate the temperature along the top and the pressure down the side. This results in a set of values at these co-ordinates giving  $v$ ,  $u$ ,  $h$  and  $s$ .

### WORKED EXAMPLE No. 5

Find the specific enthalpy, internal energy and volume of steam at 3 bar and 200°C .

### SOLUTION

On page 6 of your tables locate the column with 200°C at the top and come down the page to the row with 3 bar at the left side. At this point you have a block of 4 figures. The enthalpy value is the third figure down and is 2866 kJ/kg. The second figure down is the internal energy and is 2651 kJ/kg. The first figure is the volume and is 0.7166 m<sup>3</sup>/kg. You don't need the fourth figure at this stage.

p/bar	t	50	100	150	200	250
3 (133.5)					0.7166.....volume 2651.....int. energy 2866.....enthalpy 7.312.....entropy	

If you use the web site to check you will find a small difference in the values, the reason being that a slightly different arbitrary zero is used. This won't matter in the solution of problems because they involve finding the changes in value which would be the same. Navigate to the superheated steam page and enter the absolute pressure and superheat temperature.

Pressure	<input type="text" value="3"/>	bar absolute
Superheat Temperature	<input type="text" value="200"/>	°C
	<input type="button" value="Calculate"/>	<input type="button" value="Reset"/> <input type="button" value="Print"/>
Saturation Temperature	<input type="text" value="133.522"/>	°C
Degrees Superheat	<input type="text" value="66.4776"/>	°C
Specific Enthalpy of Water ( $h_f$ )	<input type="text" value="560915"/>	J/kg
Specific Enthalpy of Evaporation ( $h_{fg}$ )	<input type="text" value="2.16346E06"/>	J/kg
Specific Enthalpy of Superheated Steam ( $h$ )	<input type="text" value="2.86538E06"/>	J/kg
Density of Steam	<input type="text" value="1.39582"/>	kg/m <sup>3</sup>
Specific Volume of Steam ( $v$ )	<input type="text" value="0.716424"/>	m <sup>3</sup> /kg

### WORKED EXAMPLE No. 6

Find the enthalpy, internal energy and volume of 3 kg of steam at 11 bar and dryness 0.75.

### SOLUTION

From page 4 of the steam tables determine the row corresponding to 11 bar and look up the following values.

$$h_f = 781 \text{ kJ/kg} \quad h_{fg} = 2\,000 \text{ kJ/kg} \quad h_g = 2\,781 \text{ kJ/kg}$$

$$u_f = 780 \text{ kJ/kg} \quad u_g = 2\,586 \text{ kJ/kg}$$

$$v_g = 0.1774 \text{ m}^3/\text{kg}$$

Next deduce  $u_{fg} = 2\,586 - 780 = 1\,806 \text{ kJ/kg}$

Now find the enthalpy.  $H = m(h_f + xh_{fg}) = 3(781 + 0.75 \times 2\,000) = 6\,843 \text{ kJ}$

Next find the internal energy in the same way.

$$U = m(u_f + xu_{fg}) = 3(780 + 0.75 \times 1\,806) = 6\,403.5 \text{ kJ}$$

Finally the volume  $V = m \times v_g = 3 \times 0.75 \times 0.1774 = 0.399 \text{ m}^3$

If you use the web site navigate to the wet steam region and enter the pressure and dryness fraction (as %).

Saturation Pressure	<input type="text" value="11"/>	<input type="text" value="bar absolute"/>
Dryness	<input type="text" value="75"/>	<input type="text" value="%"/>
	<input type="button" value="Calculate"/>	<input type="button" value="Reset"/> <input type="button" value="Print"/>
Saturation Temperature	<input type="text" value="184.062"/>	<input type="text" value="°C"/>
Specific Enthalpy of Water ( $h_f$ )	<input type="text" value="780.516"/>	<input type="text" value="kJ/kg"/>
Specific Enthalpy of Evaporation of Wet Steam	<input type="text" value="1499.72"/>	<input type="text" value="kJ/kg"/>
Specific Enthalpy of Wet Steam ( $h$ )	<input type="text" value="2280.23"/>	<input type="text" value="kJ/kg"/>
Density of Wet Steam	<input type="text" value="7.49797"/>	<input type="text" value="kg/m³"/>
Specific Volume of Wet Steam ( $v$ )	<input type="text" value="0.133369"/>	<input type="text" value="m³/kg"/>

$$H = m(h_f + xh_{fg}) = 3(2\,280) = 6840 \quad 6843 \text{ kJ}$$

$$V = m \times v_g = 3 \times 0.1333 = 0.3999 \text{ m}^3$$

Unfortunately they do not give the internal energy values.

## SELF ASSESSMENT EXERCISE No. 1

1. Using your steam tables, plot a graph of  $h_f$  and  $h_g$  against pressure horizontally and mark on the graph the following:

- i. the superheat region
- ii. the wet steam region.
- iii. the liquid region.
- iv. the critical point.

Also label the saturation curve with dry saturated steam and saturated water.

2. Using your steam tables, plot a graph of  $v_g$  horizontally against pressure vertically. Also plot  $v_f$

Show on the graph:

- i. the superheated steam region.
- ii. the wet vapour region.
- iii. the liquid region.
- iv. the critical point.

Also label the saturation curve with dry saturated steam and saturated water.

3. Use your steam tables to do the following. You may use the web site <http://www.spiraxsarco.com/resources/steam-tables.asp> if tables are not to hand.

- i. What is the saturation temperature at 32 bars ?
- ii. What is the specific enthalpy and internal energy of saturated water at 16 bars?
- iii. What is the specific enthalpy and internal energy of dry saturated steam at 16 bars?
- iv. Subtract the enthalpy in 2 from that in 3 and check that it is the latent enthalpy  $h_{fg}$  at 16 bars in the tables.
- v. What is the specific enthalpy and internal energy of superheated steam at 10 bar and 400°C?
- vi. What is the specific volume of dry saturated steam at 20 bars ?
- vii. What is the volume of 1 kg of wet steam at 20 bars with dryness fraction  $x = 0.7$ ?
- viii. What is the specific enthalpy and internal energy of wet steam at 20 bars with a dryness fraction of 0.7?
- ix. What is the specific volume of superheated steam at 15 bars and 500°C.
- x. What is the volume, enthalpy and internal energy of 3 kg of wet steam at 5 bar with dryness fraction 0.9.
- xi. What is the enthalpy of 1.5 kg of superheated steam at 8 bar and 350°C ?
- xii. What is the internal energy of 2.2 kg of dry saturated steam at 11 bars ?
- xiii. What is the volume of 0.5 kg of superheated steam at 15 bar and 400°C ?

### Answers part 3

Compare your answers with those below. If you find your answers are different, go back and try again referring to the appropriate section of your notes.

- i. 237.4°C.
- ii. 859 and 857 kJ/kg.
- iii. 2794 and 2596 kJ/kg.
- iv. 1935 kJ/kg and 1739 kJ/kg.
- v. 3264 and 2957 kJ/kg.
- vi. 0.09957 m<sup>3</sup>/kg.
- vii. 0.0697 m<sup>3</sup>/kg.
- viii. 2232 and 2092.1 kJ/kg.
- ix. 0.2351 m<sup>3</sup>
- x. 1.012 m<sup>3</sup>, 7.61 MJ, 7.11 MJ.
- xii. 4.74 MJ.
- xiii. 5.69 MJ.
- xiv. 0.101 m<sup>3</sup>.

## 12. Entropy

Entropy is mentioned throughout this book. The meaning of entropy is explained in more detail in a later tutorial. It will be necessary for you to find entropy values of steam so this section is needed for those who are not familiar with it.

The definition of entropy that is most useful to these studies is as follows. If an infinitesimally small heat transfer  $dQ$  occurs at temperature  $T$ , there is an infinitesimally small change in entropy  $dS$ .

$$dQ = T dS$$

Entropy  $S$  has units of J/kg K and specific entropy has units of kJ/ kg K

Heat transfer often takes place by transporting entropy in a fluid so it follows that a fluid may have entropy as a property.

### 7.1 Finding Entropy Values

Entropy values for vapours may be found in your thermodynamic tables or by using the same internet sources as before. You may look up values in the  $s$  columns in exactly the same way as you do for enthalpy and internal energy.

The suffixes have exactly the same meaning as for other properties hence

$s_f$  is the specific entropy for saturated liquid.

$s_g$  is the specific entropy for dry saturated vapour.

$s_{fg}$  is the specific entropy change during evaporation and  $s_{fg} = s_g - s_f$

For superheated and supercritical vapours look up  $s$  values as appropriate.

If the heat transfer  $Q$  is equal to the change in Enthalpy

$$ds = \frac{dQ}{T} = \frac{dH}{T}$$

During evaporation at constant pressure, temperature is also constant (the saturation temperature). The change in specific enthalpy is  $h_{fg}$  and the change in specific entropy is  $s_{fg}$ .

Since  $T = t_s$  (in Kelvin) it follows that  $\Delta s = h_{fg}/T = s_{fg}$

The entropy values in your steam tables are based enthalpy changes.

### WORKED EXAMPLE No. 7

i. Find the specific entropy of superheated steam at 50 bar and 400°C.

From tables  $s = 6.646$  kJ/kg K A screen show of the same from the Spirax Sarco web tool is shown and gives 6.637 kJ/kg K

Inputs  
Output

Pressure and Superheat Temperature

Single Value  Table

Pressure: 50 bar gauge

Superheat Temperature: 400 °C

Calculate Reset Print

Specific Entropy of Superheated Steam (s): 6637.05 J/kg K

ii. Find the specific entropy of dry saturated steam at 20 bar.

From tables  $s_g = 6.340$  kJ/kg K.

iii. Find the specific entropy of saturated water at 20 bar.

From tables  $s_f = 2.447$  kJ/kg K.

iv Find the specific entropy change during evaporation at 20 bar.

$$\Delta s = s_{fg} = s_g - s_f = 6.340 - 2.447 = 3.893 \text{ kJ/kg K}$$

From the tables this could be found direct under the  $s_{fg}$  column.

### WORKED EXAMPLE No. 8

Find the specific entropy of wet steam at 20 bar with dryness fraction 0.82.

### SOLUTION

The same rule applies as for other properties

$$s = s_f + x s_{fg} = 2.447 + (0.82)(3.893) = 5.639 \text{ kJ/kg K.}$$

Inputs	Saturation Pressure and Dryness	
Output	<input checked="" type="radio"/> Single Value <input type="radio"/> Table	
Saturation Pressure	<input type="text" value="20"/>	bar absolute
Dryness	<input type="text" value="82"/>	%
	<input type="button" value="Calculate"/>	<input type="button" value="Reset"/> <input type="button" value="Print"/>
Specific Entropy of Wet Steam (s)	<input type="text" value="5638.53"/>	J/kg K

### SELF ASSESSMENT EXERCISE No. 2

Find the specific entropy for the following using your tables.

1. Superheated steam at 10 bar and 500°C.  
(Answer 7.761 kJ/kg)
2. Ammonia vapour at 3.983 bar and 98°C.  
(Answer 6.116 kJ/kg)
3. Wet steam at 12 bar and 0.9 dry  
(Answer 6.092 kJ/kg)
4. Wet steam at 200 bar and 0.95 dry.  
(Answer 4.882 kJ/kg)
5. Find the change in specific entropy when steam at 200 bar and 0.95 dry changes to 12 bar and 0.9 dry.  
(Answer -1.21 kJ/kg)