3.6 Dry steam

3.6.1 Outline

In this unit we will continue to investigate the phenomena of phase change, returning again to the process of vaporisation. We will see how we might describe the quantity of vapour formed during the vaporisation process and how we might use this in calculations.

We will review the definitions of a saturated liquid, a saturated vapour and a superheated vapour.

We will introduce the term "saturated mixture" and explore the concept of "quality". Finally we will introduce a method to determine mixture properties knowing pure liquid and pure vapour state conditions.

3.6.2 Steam boiler animation

IBB Boiler Animation: http://vimeo.com/50557100

3.6.3 Steam boiler

The animation introduced a typical steam boiler for power generation and this is summarised in this figure.

Here you can see how the hot combustion products from the fuel burner pass over the steam tubes before leaving in the exhaust. You can see where liquid water under pressure enters the feedwater drum and flows through the steam tubes changing state to become vapour. The saturated vapour collects in the steam drum before passing through the superheater tubes to finally leave as superheated steam.

3.6.4 Temperature volume diagram

You learnt about the phase change process from liquid to vapour in an earlier unit and this is repeated here as a reminder.

We can identify the three regions of compressed liquid, a saturated liquid vapour mixture and superheated vapour, exactly those we have just seen in the practical application of a steam boiler. In the figure the pressure is shown to be at 1 atm, but the process is the same for any pressure below the critical pressure.

Remember that the phase change process begins with 100% liquid, only when the liquid has reached the saturation temperature, referred to as saturated liquid. As vapour is formed a mixture of liquid and vapour exists, until eventually only 100% vapour remains. This is referred to as saturated vapour. Throughout the phase change process both liquid and vapour remain at the saturation temperature. However, further addition of heat now increases the temperature of the vapour and this is referred to as superheated vapour. If the vapour is allowed to expand then the pressure remains at the saturation pressure.

3.6.5 Saturated liquid vapour mixture quality

It is going to be useful to state some definitions. Let's start by identifying the specific volume of the saturated liquid. Let's also identify the specific volume of the saturated vapour. We will use the subscripts "f" and "g" to represent liquid and gas respectively. The use of “f” and “g” as subscripts is historical since the terms were originally derived from the German words for liquid, flüssig (for liquid) and gas.

Remember, by convention, the lower case letter “v” is employed to represent specific volume.

3.6.6 Saturated liquid vapour mixture quality

Along the saturated line the mixture changes from 100% pure liquid to become 100% pure vapour. The fraction of the mixture converted to vapour at any intermediate time is represented by the term "vapour quality".

The vapour quality, by convention given the symbol "x", is defined as the ratio of the mass of vapour to the total mass of the mixture. Therefore the quality parameter is a non-dimensional number, which varies between zero, representing saturated liquid, and one, representing saturated vapour.

Remember, at all times, temperature and pressure are dependent properties for a saturated liquid vapour mixture since the phase change process occurs at the constant saturation temperature and pressure.

However the properties of fully saturated liquid and fully saturated vapour are the same whether they exist alone or in a mixture. We can take advantage of this since the properties of a mixture of liquid and vapour may be considered to be a weighted combination of the properties of saturated liquid and saturated vapour. We will see how the vapour quality, “x”, can be used as the weighting factor.

The definition of vapour quality is an important term, which you should remember.

The term "quality" is historical, when in the early days of steam power, it was seen as desirable to have the minimum amount of liquid water remaining when raising steam. Hence a high-quality refers to a high proportion of water vapour or steam.

Note that whilst this unit largely refers to liquid water and vapour, the concepts of saturation temperature, pressure and vapour quality are equally applicable to any pure substance.

3.6.7 Mass of a saturated liquid vapour mixture

If we know the total mass of a mixture and we know the vapour quality at any point along the saturation line, then we can determine the mass of both the vapour and the liquid in the mixture.

Let’s slowly work through some definitions.

Firstly, from the definition of quality, the mass of saturated vapour is equal to the quality multiplied by the total mass.

Then, by definition, the opposite is true and the mass of saturated fluid is equal to (1-x), multiplied by the total mass.

Mass is always conserved in a phase change process, so by definition, the total mass of the mixture is equal to the sum of the mass of the liquid and the mass of the vapour.

3.6.8 Volume of the saturated liquid vapour mixture

We can also determine volumes of vapour and liquid phases in a similar manner.

Let’s start by reminding ourselves of the definition for specific volume, which is defined to be equal to the volume of a substance divided by the mass of the substance.

Now for a mixture with a given total mass and total volume, we should now be able to determine the volume of vapour and the volume of liquid present in the mixture.

Let’s again slowly work through some definitions.

Firstly, from the definition of specific volume, you can see that the volume of vapour, is equal to the specific volume of the saturated vapour multiplied by the mass of vapour present.

In a similar manner, the volume of liquid is equal to the specific volume of the saturated liquid multiplied by the mass of liquid present.

Of course, by definition, the total volume of the mixture is equal to the sum of the volume of the liquid and the volume of the vapour within the mixture.

Note for the moment that the specific volume of the saturated liquid, v_f , and the saturated vapour, v_g , depend upon saturation temperature and pressure. These remain to be determined.

3.6.9 Saturated liquid vapour mixtures

We would like to be able to obtain the properties for arbitrary mixtures of liquid and vapour, that is for any degree of vapour quality. Fortunately a two phase system of a pure substance, of arbitrary quality, can for convenience be treated as a homogenous mixture with so-called *wet* or *average* properties.

The term "wet" indicates that when the quality is less than 100% liquid will be present.

Let’s again slowly work through the definitions.

Firstly, the specific volume of the wet mixture can be simply defined as the total volume of the mixture divided by the total mass of the mixture.

By expanding the definition of volume and substituting the terms for vapour and liquid fractions we can define the specific volume for the “wet” mixture in terms of the saturated specific volume of the liquid and vapour and the mass of the respective liquid and vapour proportions.

So, substituting for the definitions of the mass of liquid and vapour and eliminating the term for total mass, allows us to derive a simple expression for the wet specific volume.

If you examine this expression carefully you can see that the wet properties are determined from straightforward linear interpolation between the saturated liquid state and the saturated vapour state, where the interpolating factor is the quality, x. This is perhaps more clearly illustrated in the figure to the right.

Note again that the specific volume of the saturated liquid and saturated vapour depend upon the saturation temperature and pressure. So before we can do any calculations we must be able to calculate or look up these values.

3.6.10 Properties of steam

The properties of steam have been traditionally been determined by looking up in a book of so-called steam tables. Over the last three centuries the data has been refined by repeated experiment and analytical models and is now defined according to international agreement. Unfortunately the use of tabulated data is time-consuming and prone to error, today it is more convenient to use a computational implementation.

3.6.11 Properties of steam freely available methods.

A wide range of freely available methods now exist, according to the computer package that you prefer to use. Some of these are presented here, why not spend some time and investigate yourself.

Links are provided to macros for Excel, Matlab, Mathcad and a standalone web based service from the National Institute of Standards, NIST, in the USA.

Excel - http://www.me.ua.edu/ExcelinME/thermo.htm

Matlab - http://www.mathworks.co.uk/matlabcentral/fileexchange/9817-x-steam-thermodynamic-properties-of-water-and-steam

Mathcad - http://cdejonge.com

NIST Database - http://webbook.nist.gov/chemistry/fluid/

3.6.12 Properties of steam an example – Isobaric properties

In this example the NIST online database has been used to determine the properties of water when the pressure is kept constant, so-called isobaric properties.

A word of caution, when you use any of these computer-based packages you should always check the units. Do not use any values until you are quite sure about their units ! For example, you will often find that pressure is expressed in units of bar, that is multiples of 100 kPa, and temperature is expressed in units of Celsius. The NIST site allows you to choose from a selection of units.

In this example the pressure was required to be the fixed property, or input, and so the option to determine isobaric properties was selected.

Here the pressure was chosen to be equal to 1 bar, that is approximately 1 atm, to ensure that we should be familiar with the results. A range of properties are output from the database, an extract of some of these are shown in the table.

For the defined saturation pressure, of 1 bar, we can see that the saturation temperature for water is shown to be equal to 99.61°C. Remember that the saturation temperature is defined to occur when both vapour and liquid exist together.

The result agrees with our expectations and corresponds to the boiling point of water at just below atmospheric pressure (101325 Pa).

3.6.13 Properties of steam an example – Isobaric properties

From the table we can extract individual data for both properties of the saturated liquid and properties of the saturated vapour and these are summarised here.

For the moment notice that specific volume, in units of m3/kg, is one of the output parameters. We can see that the specific volume for saturated liquid at a pressure of one bar is equal to 0.001043 m3/kg and the specific volume of the saturated vapour is equal to 1.694 m3/kg. That is, the liquid has a very low volume and vapour a much greater volume, per unit mass. This too is not an unsurprising result if you consider the quantity of steam that would result from vapourising 1 litre of liquid water (equivalent to 1kg).

3.6.14 Properties of Steam – Example – Isothermal properties

Alternatively the saturation temperature may be defined, in which case the saturation pressure will be output along with the other parameters, as summarised in this table.

Why not visit the NIST web site and investigate the properties of steam. Can you follow the results from the earlier virtual experiment ? Can you find the critical pressure ?

NIST Database - http://webbook.nist.gov/chemistry/fluid/