3.4 A cup of tea on Everest

3.4.1 Outline

In this unit we will continue to investigate the phenomena of liquid to vapour phase change. The term “boiling point” is very common and we will explore further what this implies.

We will review the concept of saturation temperature, commonly referred to as the boiling point and then explore how saturation temperature varies with pressure.

We will also revisit the issue of independent thermodynamic properties and introduce the concept of critical temperature and pressure. Finally we will use of phase diagram to estimate the changing boiling point with pressure for some practical applications.

3.4.2 Effect of pressure

Let's revisit our virtual experiment. This time we will carry out the experiment over a range of increasing operating pressures, starting at atmospheric pressure, 0.1 MPa and then increasing the pressure to over 20 MPa.

Let's start by again running the experiment at atmospheric pressure.

Now let's run the experiment that 2.25 MPa. That is almost 22.5 atm. Notice how the graph shows the same trends as at atmospheric pressure. Initially the liquid water heats up, then there is a region of constant temperature as vapour is formed and finally a superheated vapour region. Notice that in the constant temperature region, the so-called saturation temperature is this time equal to 218.45°C.

Repeating the experiment at the increased pressure of 20MPa, that is almost 200 atm, demonstrates a similar trend. Note again that the saturation temperature has further increased to 365.81°C.

You should also have noticed that as the pressure increased, the liquid expanded more before vapour formed and similarly the volume of the final pure vapour decreased with increasing pressure. That is the saturated region containing a mixture of liquid and vapour is decreasing. This is perhaps not unsurprising, given the increasing pressure.

This trend of a saturated region continues until we reach a pressure of 22.09 MPa, at which pressure we can no longer distinguish between the liquid and vapour regions. The condition of 22.09 MPa and temperature of 374.14°C is referred to as the critical pressure and critical temperature for water.

3.4.3 Temperature volume phase diagram

The trends that we have seen in our virtual experiment are summarised here, showing temperature as a function of specific volume.

Each pink line represents an experiment carried out at constant pressure ranging in this case from 0.01 MPa until 25 MPa. We can clearly see how the region of constant temperature is decreasing with increasing pressure up to the critical point. Beyond the critical point. There are no saturated regions and we can no longer distinguish between liquid and gas.

Remember that the temperature corresponding to the horizontal line is referred to as the saturation temperature and the pressure at which this occurs is referred to as the saturation pressure. We can see that at one atmosphere pressure the saturation temperature is approximately 100°C, we would normally referred to this as the boiling point.

Something else you should notice, as the pressure increases so does the saturation temperature or the boiling point. We will come back to this later.

3.4.4 Pressure volume phase diagram

The same trends can be seen when we plot pressure as a function of specific volume.

Here you can see what might be referred to as the saturated liquid vapour dome, to the left of which is the liquid region and to the right of which is the super-heated vapour region. Above the critical point, we can no longer distinguish between liquid and vapour.

3.4.5 Boiling point

We have already mentioned that the common expression, boiling point, refers to the saturation temperature. The common use of the term, boiling point, is implied to refer to the saturation temperature of a pure substance under a pressure of exactly one atmosphere.

3.4.6 Of course there are other ways to reach boiling point !

3.4.7 Independent properties

Do you remember the phase diagram for water, shown on the left ? This was introduced in an earlier unit and shows pressure as a function of temperature for water, illustrating the different phases that water may take.

We referred to this as a phase diagram for water and used it to introduce the concept of thermodynamic properties. We stated that pressure and temperature could only be used in isolation as thermodynamic properties for single phase system. That is, pressure and temperature are only independent of each other in a single phase system.

Do you remember the definition ?

"Two properties are defined to be independent if one property can be varied while the other is held constant"

Now, have a look at the illustration on the right, which shows how pressure varies as a function of volume at different temperatures. You can see now that in a single phase system pressure and temperature uniquely define the state of a substance. However, during phase change this is not the case. As a consequence of the horizontal saturated liquid vapour region, it is not possible to fix the pressure and vary temperature, similarly, it is not possible to fix temperature and vary the pressure during phase change.

However, note that the volume can be varied independently of either pressure or temperature. Therefore, during phase change, the more appropriate pair of thermodynamic properties might be either pressure and volume, or temperature and volume.

3.4.8 Pressure dependence

Referring again to the phase diagram for water, note that the axis for pressure is on a logarithmic scale, whilst that for temperature is on a linear scale.

The solid black line separating the liquid and vapour region is commonly referred to as the saturation line. Remember that pressure and temperature are not independent of each other during phase change. The saturation line represents the phase change process where pure liquid changes phase to become pure vapour.

We would commonly refer to the saturation temperature and the saturation pressure as being the boiling point of the liquid. You can clearly see now, how, as we follow the saturation line, the boiling point will increase with pressure.

3.4.9 Pressure dependence linear scale

Over a small temperature or pressure range it is more convenient to use a linear scale for pressure as shown in this illustration.

The boiling point of water at a pressure of 100kPa, that is 1 atm, is highlighted in light blue. We can see now that if the pressure is increased by a factor of 3 to 300 kPa, as illustrated by the purple line, then the saturation temperature, that is the boiling point, increases to about 406K.

This phenomena is extremely important in a wide range of both domestic and engineering applications.

3.4.10 Boiling water

We are not the first to notice the pressure dependence of boiling, Jules Verne commented on this in his novel "Off on a comet", in 1911.

Servadac reflected. It cannot be that the fire is hotter, he said, the peculiarity must be in the water. And taking down centigrade thermometer which hung upon the wall, he plunged it into the skillet. Instead of 100°C, the instrument registered only 66°C.

Why not explore more and read the novel by Jules Verne. It is freely available at Guttenberg.org.

http://www.gutenberg.org/files/1353/1353-h/1353-h.htm

3.4.11 A cup of tea on Everest

We can now answer the serious question about the feasibility of boiling water on the summit of Everest to make a cup of tea!

The summit of Mount Everest is at an altitude of 8850m. We need to know what the corresponding atmospheric pressure is at this altitude, this can be found by referring to the International Standard Atmosphere shown in the bottom left. Referring to this chart you can see that on the summit of Mount Everest, at an altitude of 8850 m, the atmospheric pressure will be 31.5 kPa.

Now referring to the phase diagram for water, shown in the upper right, you can see that at this pressure the intersection with the saturation line is at a temperature of just over 70°C. So on the summit of Mount Everest, water will boil at a temperature of 71°C.

The question is, will this make a good cup of tea, or are you better advised to take a thermos flask ?

3.4.12 The Tea stylist

Well, according to the Tea Stylist, it is possible to make an acceptable cup of green tea when water boils at 80°C. That would correspond to the summit of Mount Logan in Canada. However, they don't recommend any variety of tea when water only boils at a temperature of 70°C !

This is an important issue for many people, for example you can see that the city of Denver in Colorado is at an altitude of 1600m, where the boiling point of water is only 94°C. In such locations, special care must be taken when cooking and recipes adjusted or cooking times extended.

In general, you can expect there to be a 3° C drop in boiling point, per thousand metres increase in altitude.

http://theteastylist.com/2012/01/03/the-boiling-point/

3.4.13 Boiling an egg on Everest

Boiling an egg is a serious culinary art and obtaining exactly the right boiled egg, either soft or hard as desired, depends upon cooking at a precise temperature for a precise period of time. This means that as altitude increases and the boiling point of water decreases the time required to boil an egg will increase. In principle, you could use the time required to boil an egg is an indication of altitude - an egg boiling altimeter!

Why not explore more and find out about the science boiling an egg?

Towards the perfect soft boiled egg, by Martin Lersch

See more at: http://blog.khymos.org/2009/04/09/towards-the-perfect-soft-boiled-egg

The Science of Boiling an Egg, by Charles D. H. Williams

http://newton.ex.ac.uk/teaching/CDHW/egg/

3.4.14 Why do we use pressure cookers?

We have seen that as altitude increases and atmospheric pressure decreases so the boiling point of water decreases and cooking times will be correspondingly longer. Conversely, if we increase pressure, then the saturation temperature, that is the boiling point, will increase. This is a technique that can be used to decrease cooking times.

They are not so common now, but have you seen a pressure cooker, once very popular before the advent of the microwave.

The invention of the pressure cooker is attributed to Denis Papin, a French physicist in the late 17th century, two later examples are illustrated here.

The modern saucepan style pressure cooker was first introduced the 1939 New York world's fair.

3.4.15 The answer

Of course, we already know the answer!

You understand now that the saturation temperature, that is the boiling point, increases with pressure. You know that at 1 atm, that is 100 kPa, water boils at a temperature of 373K, that is 100°C. Referring to the pressure-temperature phase diagram for water and following the saturation line, we reach a pressure of, for example 3 atm, and see that the corresponding saturation temperature is 407K, that is water boils at a temperature of 407 Kelvin, or 134°C, an increase of 34°C. Although only a relatively small increase in temperature, the corresponding cooking times are dramatically decreased.

3.4.16 The benefits of cooking using a pressure cooker

Why not explore and find out more about cooking with a pressure cooker. This late 1940's film shows one of the earliest TV celebrity chefs, Marguerite Patten, explaining how a pressure cooker works.

http://www.youtube.com/watch?v=T4Hxr6KAbVM