3.3 Ice water steam

3.3.1 Outline

In this unit we will again look at the transition from one phase to another, paying particular attention to the amount of energy required to change from a solid to a liquid and finally to a gas. We will review the concept of phase change and explore the energy required for phase change to occur. We will conclude by investigating a practical, real-world consequence.

3.3.2 Phase

You will remember from the previous unit that a phase is identified as having a distinct molecular arrangement, one that is homogenous throughout and separated from the other phases by easily identifiable boundary surfaces.

In this unit we are not concerned with phases, thermodynamic properties and state diagrams, but rather the transition from one phase to another.

You will be familiar with the concept that energy is typically required or indeed released when a change of phase occurs, for example, we know that ice and snow melt when the weather warms up and that water vapour condenses on a cold window.

Let's explore this a little more.

3.3.3 Boiling an egg

Consider boiling an egg in a pan of water. Once the water has been brought to the boil, does it matter how high we turn up the heat ? Can we heat up the water more and boil the water quicker so the egg cooks quicker ? Certainly at first sight that would be our natural thought.

Let's investigate this a little more by considering a simpler example. Let’s take the egg out and also let’s remove the water air interface.

3.3.4 Constant pressure phase change

Imagine that we have a piston cylinder arrangement, containing some liquid water, with the piston resting on the water and no air present. The piston is free to move and the pressure exerted on the water is equal to the weight of the piston and the external ambient pressure. So therefore any changes that occur to the water will occur at constant pressure because the external forces are constant and we may assume that equilibrium is maintained.

Now let's heat the water, assuming that we can do so uniformly throughout. Initially the water begins to warm up and slowly expands. After a while the water reaches its boiling point and then vapour begins to form. Vapour is less dense than the water and begins to collect above the liquid water below the piston. As the vapour forms the volume of the liquid of vapour mixture increases so the piston slowly moves upwards. At all times, the process occurs under a constant pressure equal to the weight of the piston and the external ambient pressure.

Eventually all of the liquid water is vaporised and the cylinder contains only water vapour.

Now let's consider a virtual experiment and measure the change in temperature as a function of change in volume of the liquid vapour mixture.

3.3.5 Virtual experiment

This experiment is similar to that previously described. You can see a cylinder containing water with a piston resting on the surface of the water. The piston is free to move as the liquid expands. We have temperature measurement gauges recording the temperature, just below the piston and the temperature at the bottom of the cylinder. We also have a pressure gauge.

In this experiment. We will set the pressure to be equal to 1 bar or 0.1 MPa, approximately atmospheric pressure.

Now let's start heating the water. As we heat the water it slowly expands and the temperature rises, in this case to 99.63°C.

Now let's add some more heat. We see that vapour begins to form and as the volume of the liquid-vapour mixture increases the piston moves slowly upwards. Interestingly the temperature does not change. The temperature of both liquid and vapour, as indicated by the two temperature gauges, remains at 99.63°C.

Now let's add some more heat. More vapour continues to be formed and the piston continues to move upwards until all of the liquid is converted into vapour. Throughout this process, the temperature has remained at 99.63°C.

Now let's add yet more heat. Finally, now that no more liquid remains, we see that the temperature of the vapour begins to increase, up 120°C, when the experiment finishes.

Throughout this experiment the pressure has remained constant at 0.1 MPa as the internal pressure within the cylinder remains in equilibrium with the external ambient pressure and the weight of the piston.

3.3.6 Temperature volume diagram

The result of the virtual experiment is summarised here, showing the variation of temperature against volume, or rather specific volume. Remember, for a fixed mass, specific volume is linearly proportional to volume.

We can see the region where the water is initially heated and increases in temperature; the second region where the liquid slowly changes phase to vapour at constant temperature and the third region where the temperature of the vapour increases. We note that with each region there is a corresponding increase in volume of the liquid vapour mixture.

We can now introduce some new terms that are commonly employed when discussing the phase change from liquid to vapour.

Sometimes you will hear the pure liquid region referred to as a compressed liquid, the constant temperature region referred to as a saturated mixture of liquid and vapour and the final region of pure vapour referred to as superheated vapour. These terms are largely historic but remain in common use.

Location number two, where we have pure liquid about to vaporise, is sometimes referred to as saturated liquid and location number four, where we have pure vapour, about to condense, is sometimes referred to as saturated vapour.

The constant temperature region is frequently referred to as the saturation temperature and the pressure at which this occurs is referred to as the saturation pressure. In everyday terms, we refer to the saturation temperature as the boiling point.

Next time you say to your friends that you are going to boil a kettle of water, why not instead say that you're going to raise the temperature of the water to its saturation temperature, at a saturation pressure equal to atmospheric pressure!

3.3.7 Heating curve

The virtual experiment has demonstrated that energy is required to change phase and that the change of phase occurs at constant temperature. We see this illustrated very nicely here, which shows temperature as a function of heat added. You can see regions where the temperature linearly increases as heat is added and regions where the temperature remains constant when phase change occurs.

As suggested, we can imagine that energy is required to break the intermolecular forces that bind the atoms and molecules. Initially in a tight regular manner that represent a solid, melting to form the more mobile form that represent a liquid, and finally evaporating to becoming very mobile, as represented by a gas.

3.3.8 Latent heat

The amount of energy required to change phase is referred to as latent heat. The energy is absorbed or released, according to the direction of the phase change process.

The latent heat of fusion is defined as the amount of energy absorbed what a solid melts, which is equivalent to the amount of energy released when a liquid freezes.

The latent heat of vaporisation is defined as the amount of energy absorbed during vaporisation, which is equivalent to the energy released when a vapour condenses.

In both cases energy is conserved and the same amount of energy that is required to change phase, from for example solid to liquid, is released when the phase changes from liquid to solid.

3.3.9 Latent heat of phase change

The concept is concisely summarised here for the different latent heats of phase change.

We can see the common phase changes between liquid and solid, either melting or freezing, and between gas and liquid, either vaporising or condensing.

We can also see a phase change directly from solid to gas, referred to as sublimation and the reverse phase change from gas to solid, referred to as deposition. We will investigate these two phase changes in a later unit.

In each case there is a corresponding latent heat of phase change. In standard SI units we will refer to the latent heat in units of joules, or kilojoules, per kilogram.

3.3.10 Condensing gas boiler

Let's look at a practical consequence. Do you remember in the news a few years ago, during a particularly cold winter. There were lots of problems when domestic gas boilers were failing. If you read a little more carefully you will see that in particular condensing gas boilers were having problems.

3.3.11 Why do we see steam from a condensing gas boiler flue ?

What is a condensing gas boiler, why do we have condensing gas boilers and why were they suffering problems?

Next time you are at home. If you have a gas boiler, have a look at the external flue. In cold weather, do you see water vapour?

In the combustion of all hydrocarbons, including natural gas, water vapour is formed. In a traditional gas boiler the exhaust flue gases are relatively hot, often over 100°C and rise rapidly in the outside air. They cool quickly and the water vapour condenses, but the resulting liquid water droplets are so dispersed that they are not visible.

However, in a condensing gas boiler the flue gases are already cool and condensing, perhaps around 50°C, any remaining water vapour immediately cools and is visible before being dispersed.

Just pause for thought and think why might we prefer to condense the water vapour inside the boiler, rather than letting it escape outside.

3.3.12 Traditional gas boiler

On the right we can see a typical installation of a traditional gas boiler for central heating. You can see the gas burner and the heat exchanger. Cold water returning from the radiators enters the heat exchanger and hot water leaves that heat exchanger going to the radiators. The combustion products from the burner pass through the heat exchanger heating the water and the cooler flue gases are exhausted through the flue vent, expelled by an electric fan.

Carbon dioxide and water are the major combustion products from any hydrocarbon, including natural gas. In a traditional gas boiler the combustion products, including carbon dioxide, water vapour and inert nitrogen pass through the heat exchanger and are exhausted into the flue. The water vapour that is formed during the combustion process leaves the exhaust as a vapour. Therefore, some energy, represented by the latent heat of vaporisation is lost.

3.3.13 Condensing gas boiler

On the right you can now see a typical installation of a condensing gas boiler. The configuration is very similar, but an additional heat exchanger has been added to pre-heat the incoming cold return from the radiators and further cool the combustion products. You can also see the indication of a condensation drain, which suggests that any water vapour is being cooled by the additional heat exchanger to form liquid water. Therefore the latent heat of vaporisation is recovered and not wasted in the form of water vapour in the flue gases.

In principle, therefore, a condensing gas boiler should be more efficient than a traditional gas boiler. As a minimum, this should be of order 10%, and allowing for other design improvements potentially up to 30% more efficient than an old traditional gas boiler.

3.3.14 Condensing boiler efficiency

Here is a boiler efficiency curve for a typical condensing commercial boiler from the American company Lochinvar. The Lochinvar Crest condensing commercial boiler.

The data shows how overall efficiency varies as a function of return water temperature, expressed in degrees Fahrenheit, for a 20°F rise. There are different curves according to different demand, 100% demand represent the design point and 5% demand represent a grossly oversized heat exchanger.

As you would expect we can see that the larger the heat exchanger, the more efficient it is. What we can also see, is that at lower return water temperatures we can achieve higher efficiencies, around 98%.

At typical ambient pressures water vapour from the combustion of natural gas will begin to condense at its dew point temperature, which is about 56°C or 130°F. That is why we can see that at temperatures above about 130°F the overall efficiency rapidly decreases to about 86%. That is a loss in efficiency of about 12%. This can be attributed to the loss of energy associated with the latent heat of vaporisation escaping with the water vapour in the flue gases.

3.3.15 UK Boiler efficiency database

Building regulations in the UK require that all domestic central heating boilers are condensing boilers.

Why not explore more and find out about the efficiency of the boiler installed in your home.

http://www.boilers.org.uk/

3.3.16 Ideal heating.

Why not explore and find out more about domestic central heating boilers. Ideal heating are leading manufacturer based in the city of Hull.

Ideal Heating - http://idealheating.com/videos/logicplus-video.php

3.3.17 Does dry wood contain 50% more energy than wet wood ?

Now remember that original question posed in the video, does dry wood contain 50% more energy than wet wood ?

In reality, the question is slightly misleading because it doesn't quite define on what basis we should compare dry wood to wet wood.

Let's put in some numbers and see if we can work it out.

3.3.18 Answer – Mass basis

A little bit of research will show that 1 kg of kiln dried wood will release about 20 MJ of energy when burnt in air.

We already know that the latent heat of vaporisation of water is 2.25 MJ/kg.

Let's compare 1 kg of kiln dried wood to 1 kg of wet wood and let's assume that the wet wood is 50% dry wood and 50% water, so half a kilogram of dry wood and half a kilogram of water.

A quick calculation will show that half a kilogram of dry wood will release 10 MJ of energy and that we will require just over 1 MJ of energy to vaporise half a kilogram of water.

So the net energy released on burning 1 kg of wet wood will be approximately 9 MJ. So indeed this is equivalent to about 45% of the energy released by burning 1 kg of dry wood, as claimed in the video.

3.3.19 Answer – Volume basis

Note how however, that this conclusion is slightly misleading and it would perhaps be better to make a comparison on a volume basis.

Since wood does not shrink by much on drying and certainly does not gain any extra mass, then on a volume basis, a 1kg wet log releases about 9MJ of energy compared to a dry log, only losing 1MJ as latent heat to vaporise the moisture.

This is equivalent to 90% of the energy released by burning the same log after being kiln dried.

We should note that this conclusion assumes that the water produced during the actual combustion process remains as vapour and the latent heat is not recovered – that is the log stove behaves like a traditional gas boiler, not a condensing boiler !

3.3.20 Energy content of wood as function of water content

Why not explore more to find out about the energy content of wood and the use of biomass in general

http://www.seai.ie/Renewables/Renewable_Energy_Library/Biomass/