

Steam and Steam Engines

Fundamentals

Before going further into how steam, and steam engines work, let's take a few moments to establish the accepted definitions of some of the key elements: - my apologies to those who already know these by heart.

The states of matter: -

1. A solid has fixed shape and volume.
2. A liquid has fixed volume but no fixed shape.
3. A gas has neither fixed volume or shape.

This is naturally a simplification....Then I am a simple person!

Sitting between the liquid and gas states is the vapour, or fluid, state, of which 'STEAM' is a very common example.

HANDS UP ALL THOSE WHO THOUGHT IT WAS GAS?

Temperature

During the 19th century and earlier part of the 20th century, many engineering problems were explained by the pre-nuclear concept of the atom: being an ultimate and indivisible particle. We now know this to be untrue, however, it is of little consequence, since it changes nothing of any significance for the purpose of this basic document.

These so called particles could collect together, united by elastic bonds, to form molecules. (Now known as co-valent bonding) and it is the motion of these molecules, which has led to the CONCEPT of temperature.

As the motion increases (vibratory in a solid, mostly free-flight motion in a gas) then what we know as 'HOTNESS' increases.

As the motion slows down, then 'HOTNESS' decreases.

There is of course a limit to slowing down, (ie STOPPED...there is no going in reverse in physics...he he) therefore there is also a limit to 'COLDNESS'.

This is known as the absolute zero of temperature. Nothing colder can exist, and it is the point at which all molecular motion ceases, regardless of the material/element.

On the Centigrade scale (Celsius), Absolute Zero (unattainable by man) is at 273 degrees below the freezing point of water (-273 deg C) ...459.4 degrees below zero on the Fahrenheit scale. (-459.4 deg F).

Temperature measured from Absolute Zero (using Centigrade deg. intervals) are called degrees K (KELVIN) thus 20 deg C can also be written as 293 deg K.

That's BI***y cold.

For mortals such as us who, for the most part, live in the real world (not one of high level physics) then the choice of the freezing point of water (0 deg C or 32 deg F) is the normal reference used. Cold enough for most of us.

Pressure

Pressure, as well as Temperature, in a gas or vapour may also be explained using the simple molecule model.

As molecules in random free flight collide with, and bounce off the walls of any vessel containing them, then they exert a force on it. The number of collisions, and therefore force, on a given area of the container surface (square metre or sq in) is the pressure.

In a vapour, such as steam, groups of molecules are bunched together, not having acquired sufficient energy to tear themselves completely apart.

In a gas the molecules are in free and independent flight.

In a solid they are in a state of vibration, which is not violent enough to separate them.

Specification of pressure

As with Temperature, in the real life world, Pressure is also measured from an arbitrary datum – this being the pressure of the atmosphere. This being 14.7 lb sq in at mean sea level. The main reason for this choice of datum is that it is easier to make a gauge, which reads upwards from the atmosphere's pressure than to make one which reads from an absolute zero of pressure. (0 lbs sq in).

For the purpose of the remainder of this, and any subsequent document, I will use Pounds per square inch (psi) when referring to pressure and, unless otherwise stated, this shall mean the gauge pressure above atmospheric. (should really be (psig), but I'm lazy).

For those of you who prefer to use Bar pressure then, whilst not strictly accurate, but close enough, 1 atmosphere pressure (14.7psi) is equivalent to 1Bar

Take a look at fig.1

The pressure at point X can be specified as either: -

1. Gauge pressure above atmosphere, or
2. Absolute pressure above zero.

At point Y the pressure is below that of the atmosphere and is usually referred to as the vacuum at Y. This is somewhat loose terminology, but is widely used.

A true vacuum only exists below the zero point.

Ok, we have now got two properties introduced: Temperature and Pressure.
We need two more to complete the required set.

Mass

The specification of the mass being considered is required, and is generally taken as unity e.g. lb or kg.

And the specific volume of a substance may be written as m^3/kg or ft^3/lb .

The fourth, and final property is a tough one....and is known as Entropy.

This has no physical existence and it has an arbitrary datum, however its changes can be precisely calculated (by mortals of much higher mathematical capability than I). Such changes are listed in steam tables and plotted on charts. It is of no value to try to find an analogy for entropy. There is none. It must be accepted and used. (If necessary)

For water steam, entropy is given the arbitrary value of zero at 0°C (32°F) and increases as a factor of heat input, pressure and temperature.

Entropy is given the designation letter S and is/may be expressed in Btu/lb $^{\circ}\text{F}$ or for the metric guys kJ/kg K.

Energy, work and heat.

Energy is a fundamental of the universe, which can appear in many forms. Heat and work are transient forms of energy, which often appear when it is changing from one form to another.

E.G. Energy from the sun arrives in the form of radiation (radiant heat) and we can sense its presence when it adopts the transient form of heat.

Energy can be stored in a chemical form by organic nature.

E.G. We cannot sense the energy in a lump of coal until it begins to burn, when again we sense the transient presence of heat.

The energy contained in a high mountain lake is in a potential form.

If, under controlled conditions, this water is fed down a suitable pipe it can be made to form a jet. The transient form of work can then be exhibited on a turbine wheel.

Energy cannot be destroyed: it may only undergo change.

A form of energy, which can produce the transient of work, is a high-grade energy and one that cannot is a low-grade form.

Energy always tends to go spontaneously to a lower grade.

The reverse process, the spontaneous upgrading of energy, does not take place.

Working Substance

Energy requires a physical medium if mechanical work is to be produced.

Combustible gasses (such as Propane gas) and water steam are well known examples, there are many others.

Work can only be obtained if there is an orderly change of state.

The energy of a steam boiler is made up of the random motion of large numbers of molecules.

If the pressure is reduced in an orderly way, such as, behind a retreating piston in a steam engine, the transient of work can appear on the piston, and hence this may be transferred to the rotating shaft.

As some of the molecules collide with, and bounce off the piston, then they leave some of their energy with the piston and retreat more slowly.

It should be mentioned again here, that to extract all of the energy of the molecules, they would have to be expanded until they were brought to rest, or until they had cooled down to a temperature of Absolute Zero. This is impossible in any engine system having a net delivery of work. They can only be cooled to the lowest surrounding temperature, i.e. that of the surrounding medium, such as the atmosphere or the sea.

Reversibility of energy

A fundamental idea is that of reversibility.

If a process in which energy forms are changed can be reversed, then both forms of energy are of the same grade. This, by implication, means there has been no degradation, or the process was a perfect one. (Never yet achieved by man)

The degree of reversibility is then the criteria of perfection.

Rapid compression of a gas by a piston can often be followed by rapid expansion, as the piston returns, thus restoring some of the compression work, however, there are always losses.

This process is nearly reversible, however, not quite and it remains a discontinuous process. Perpetual motion is impossible.

Cyclic process

Power production always involves a discontinuous process, even though it may appear, superficially, to be continuous.

In a steam engine the energy put into the generation of the steam will always be more than that which can be extracted in the form of mechanical work, the process is again almost reversible, in that water is turned to steam by the application of heat, which in turn is passed to the piston during the expansion stage and the remainder is lost in the condensation phase, usually outside the engine, and in overcoming the inevitable frictional and other losses involved in the mechanics and in the ever present leakage of steam.

What 'input' energy remains in the recovered steam, eventually is given up as it returns to water, ready for the next cycle.

Eventually, of course, the fuel supply runs out, or the lost water depletes the boiler and so the process is discontinuous.

Negative work

In accepting the cyclic process above it is implied that the working substance must get back to its original state so as to be in a position to start again. This means that both positive and negative work must occur in any heat engine system.

Positive work is associated with the giving (input) of heat and an increase in volume;

Negative work is associated with the rejection (loss of or removal) of heat and a diminishing in volume.

In a steam plant, the majority of negative work is associated with the energy absorbed by frictional losses and by any the energy absorbed by the water feed pump (if fitted) or the energy required to drive the vacuum pump in a multiple expansion engine.

Ok, enough of the definitions, lets look at how they apply to steam generation.

Water Steam

As a substance, water steam is ideally suitable as a working substance for earth bound heat engine power plants.

Its properties are such that they may be adapted to small engines with relatively simple engineering or to the largest power plant that we, as mortal men, are able to contemplate.

Some of its most endearing properties are:

Non-poisonous;

A pressure-volume relationship, which is convenient relative to normal atmospheric temperature;

It exhibits a large change in volume between steam and water making the design of an engine having a small negative work a practical possibility.

Dry and Saturated steam

So, 'finally', here we are at one of the unexplained Facts, left over from part 1.

I know the words '*dry*' and '*saturated*' appear to be contradictory but this is largely due to the everyday association of '*saturated*' with wetness, so read on....

If we take a strong metal container, say a small boiler, fitted with a pressure gauge, a safety valve and, by some means a thermometer, and half fill it with water but leave the filler cap off (the thermometer could possibly be mounted through this using a suitable gland).

If we now apply heat until the water boils, then the forming steam will quite quickly expel the air contained in the space above the water.

Now fit the filler plug (and thermometer) and turn off the heat, and allow the thing to settle down to a 'steady state' (a minute or two should be quite sufficient).

A certain pressure and temperature can be now observed.

The pressure is said to be that corresponding to the temperature, and the steam in the space above the water is said to be both *dry* and *saturated*.

Dry because our postulated steady state means that any particles projecting out of the water into the space above are balanced by steam particles diving back into the water.

Saturated because the space when in contact with the water can only contain a fixed amount of vapour.

The introduction of more vapour would be excess being condensed back into water.

The removal of vapour would lead to more evaporation until equilibrium was restored.

If we now re-apply the heat, then another set of corresponding pressure and temperature may be observed.

With sufficient readings a unique curve (Fig 2) of corresponding pressure and temperature can be plotted.

Saturated steam in contact with water cannot be made hotter without also increasing its pressure.

From this we can see that Temperature and pressure are inextricably linked, which for most steam purposes means we may exchange the terms.

In everyday practice, *dry* and *saturated* steam is rare. The formation of steam bubbles within in the water and their, inevitable, projection in to the space above, places particles of water into suspension in the steam. These are entrained and carried away with the steam supply. To some extent water can be removed from steam by mechanical means, however, complete removal generally requires the application of heat, after the steam has left the boiler. (Steam dryer or superheater).

The above description of steam formation represents a 'constant volume' process, and serves well as a demonstration in technical teaching. It is, however, approximated to in a domestic pressure cooker.

For power generation, steam must be raised at constant pressure during what is described as a flow process (i.e. water and energy flow into the boiler and steam flows out).

Steam Tables

In earlier times these impressive documents referred to '*heat of formation*', which consisted of '*sensible heat*', '*latent heat*' and '*total heat*' for the successive change from water to '*dry saturated steam*'. More recently, for philosophical reasons, this terminology is considered as unsatisfactory and an alternative term '*enthalpy*' has been invented. This is now used in most steam tables.

It is generally denoted by the letter h, with a suffix indicating the state being referred to.

I will use both terminologies in the following, since the former is probably more understandable by people with non-engineering backgrounds. I still think in terms of the original terminology, but then I'm a simple person...Ha Ha.

Steam Formation

Two stages are envisaged in the formation of a unit mass (kg or lb) of steam:

- (1) *Sensible heat* or h_f

The first stage is to raise the temperature of the water from that of the supply to that corresponding to the evaporation pressure. If this were carried out in a separate feed water heater, then a temperature difference between inlet and outlet could be observed by means of thermometers. For this reason older engineers (like what I are) referred to this as sensible heat, meaning the heat obviously going into the raising of the water temperature.

- (2) *Latent heat* or h_{fg}

Heat supplied for evaporation, makes no difference to the temperature.

The temperature of the steam leaving the boiler is the same as that of the water from which it was formed.

Thus, heat manifestly entering, but giving no indication on a thermometer, is said to be '*Latent*'.

Alternatively, the '*Latent*' heat of steam is that required to change the state of a unit mass of water to '*dry*' and '*saturated*' steam at the same temperature.

The '*latent*' heat of steam is not a CONSTANT, but falls as the temperature rises, becoming zero at the critical point*. (see later)

3. *Total heat* or h_g .

This is the sum of the above two properties and is thus the '*Total heat of formation*'.

These properties are shown graphically in fig 2.

It can be seen from this that, within range plotted,

- (a) That the sensible heat h_f rises steadily,
- (b) That the latent heat h_{fg} falls and would become zero at the critical point.

The sum of these '*total heat of formation h_g* ' rises quite slowly; in fact it only rises about 4% between atmospheric pressure and 210 psi.

I have indicated '*Enthalpy*' in (kj/kg) and the alternative figures, enclosed in square brackets, are the approx equivalents expressed in Btu/lb at various pressures as are typically used for model steam boilers.

Wet steam- dryness fraction.

Ok, take a look at fig 3.

This is a typical graphical representation of temperature (T) vs entropy (S).

3 distinct states are expressed: Liquid (water), Wet steam (mixture) and Vapour.(saturated)
These are separated by the liquid line/curve, on the left, and the Saturated vapour line/curve, on the right.

These two lines/curves meet at the '*critical point*', where the distinction between liquid and vapour disappears.

Critical point (also critical pressure, temperature)

A point on the pressure-volume representation (graphical diagrams) of fluid properties.
Above this critical temperature, no amount of pressure can liquify the fluid.

Also shown, in as dotted curves, are lines representing the dryness fraction.

In the lower parts of the liquid region, lines of constant pressure crowd so closely together near the liquid line as to appear to coincide with it.

With this proviso let's look at a typical cycle of raising steam, using this chart, and then hopefully, all will become clearer...(He says, tongue in cheek)...

A unit mass of feed water at temperature T_1 is raised to a pressure corresponding to the desired evaporation temperature T_2 along a constant pressure line (close to the liquid line) between points A and B. (*Sensible heat* or h_f)

At point B the temperature corresponds to the desired pressure.

The next stage is the reception of '*Latent heat* or h_{fg} , between points B and C at a constant temperature, as the water evaporates.

Once it has completely evaporated, further heating would move the state point up the inclined, constant pressure, superheat slope (P2).

Note: this would not happen in a normal boiler, unless it boiled dry, in which case you've got big problems!!...

This function would normally take place outside the boiler, remember, steam which remains in contact with the water from which it was formed, cannot have its temperature raised, since this would also mean a rise in pressure.

If the steam is removed from contact with the water from which it was formed, its temperature can then be increased as far as practical circumstances permit.

Any such water vapour, which is at a higher temperature than that corresponding to its pressure is called, superheated steam.

The sum of the heat between A and C is the *Total heat of evaporation* or h_g .

If the supply of latent heat were cut off during the evaporation phase, at point X, the result would be wet steam of dryness fraction BX/BC. (In this case approx 0.68 or 68%). However, its temperature remains the same.

So...Fact...Wetter steam can be at the same temperature.

Ok, clear as a wet kippers armpit?

Expansion

So now we arrive at the best bits (at least as far as steam engines are concerned)

There are two extremes of expansion, which must be recognised.

First we have 'Resisted expansion' this is the extreme, which is aimed for behind a piston on which work is being done.

This type of expansion is meant to be orderly, not creating eddies or turbulence in the steam (rarely achieved).

As each molecule of steam bounces off the retreating piston it gives up some of its energy and thus comes away with a lower velocity.

In this case, if the steam were initially dry, and the process was an efficient one, then the steam must get wetter as the expansion proceeds and the energy passes to the piston.

Line C-D on fig 3

This is what I meant with the **Fact..as soon as you try to perform work with steam, it gets wetter.**

Incidentally: if the steam was initially at a higher pressure/temperature (point C1 on fig 3) then it would actually end up wetter than in the lower pressure condition...I will let you figure that one out

So what about the **Fact...expanding steam can get dryer?**

Ok, the other extreme of expansion is 'un-resisted' expansion, and this is what takes place when steam has its pressure dropped by a throttle valve. Here the object is to increase the disorder of the flow, and the energy, previously manifested by the initial pressure, must appear as disordered velocity of the molecules in the form manifested by temperature. As a result the steam **now gets dryer, or even superheated** in an extreme case, since the temperature may be lower than at the start, but might remain higher than that corresponding to the new pressure.....Spooky!!.

The line C – E1 represents such an expansion

Ok then, I think that is enough for this chapter, as I am sure you have all gone to sleep by now...I know I have.....He Ho.

Part 3 will take a more in-depth look at steam engines proper, and will attempt to explain what actually goes on inside the cylinders, and beyond. I will also look at the requirements for single and multiple expansion engines.

This should put Eddy off triple expansion...Grrr. Ha Ha.