MM2TF2 THERMOFLUIDS

Thermodynamics section

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Structure of this part of the module

The overall aim is driven by the learning objectives:

LO1-Comprehend the concepts of practical thermofluid systems (knowledge and comprehension)

LO2-Represent applications of thermofluids in conceptual form by appropriate formulae (comprehension)

LO3-Quantify the scale of thermofluid situations by appropriate use of thermofluid data tables (application of knowledge)

LO4-Apply the conceptual principles of fluid mechanics and thermodynamics to practical situations (application of knowledge)

LO5-Analyse complex thermodynamic and fluid systems from real applications (analysis)

The following topics will be covered:

1. **Properties of steam, gases and liquids** – 2 lecture hours, 1 seminar hour

2. **Vapour power cycles** – 3 lecture hours, 2 seminar hours

3. **Refrigeration and air conditioning** – 4 lecture hours, 2 seminar hours

4. **Reciprocating compressors** – 3 lecture hours, 1 seminar hour

5. **Combustion chemistry** – 4 lecture hours, 2 seminar hours

6. **Convective heat transfer correlations** – 2 lecture hours, 1 seminar hour

7. **Heat exchangers** – 3 lecture hours, 2 seminar hours

Topic 1. Thermodynamic properties and transport properties of steam and other fluids

Aim of this section

Several aspects of state have been studied in the first year of the course, but the properties upon which state is so dependent, and the variation of property with temperature, have not hitherto been looked at in depth. This section of the module seeks to expand on understanding the significance of fluid properties, and on dealing with fluids which change phase.

Aim: learn how to find properties of fluids for thermodynamic analysis

Objectives: understand the concept of state, property, and phase; understand the difference between thermodynamic and transport properties of fluids; extract and use data from saturated water and steam tables sorted in order of temperature and pressure; extract data from superheated steam tables; use linear interpolation to extract data from the tables which is between the tabulated data points.
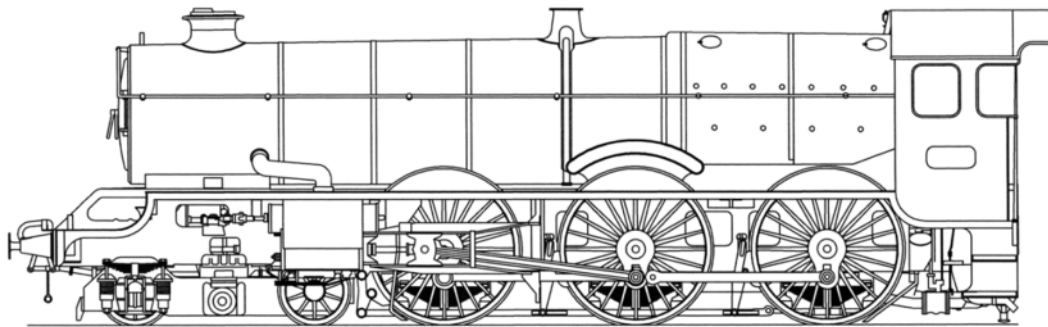

Fig.1. a convenient steam locomotive, from:
http://en.wikipedia.org/wiki/Steam_locomotive#mediaviewer/File:AutoCAD_drawing_of_a_Great_Western_King.png

An enjoyable glass reciprocating steam engine is at:

http://www.youtube.com/watch?v=73txXT21aZU&list=PLUXfvjXFn-cwgW73q93398k8l2ZLP4mh5


Fig 2. A typical low pressure steam turbine from Alstom as used in a power generation station.

1. A thermodynamic property describes the thermal condition, or 'state', of a fluid.

A fluid, whether gas or liquid, has molecular characteristics which give it a unique response to a thermal stimulus, such as adding energy. These responses are described well by thermodynamic *properties*, which usually vary with *state*.

From a thermodynamic point of view, where we want to use heat transfer (thermo-) to drive a machine to produce work (-dynamics), it is important to understand the working fluid, which is what receives the heat transfer, moves in a fluid way to a working surface, and then drives the external surfaces of the machine to produce work in the outside world. Two common examples are the steam engine and the steam turbine.

State.
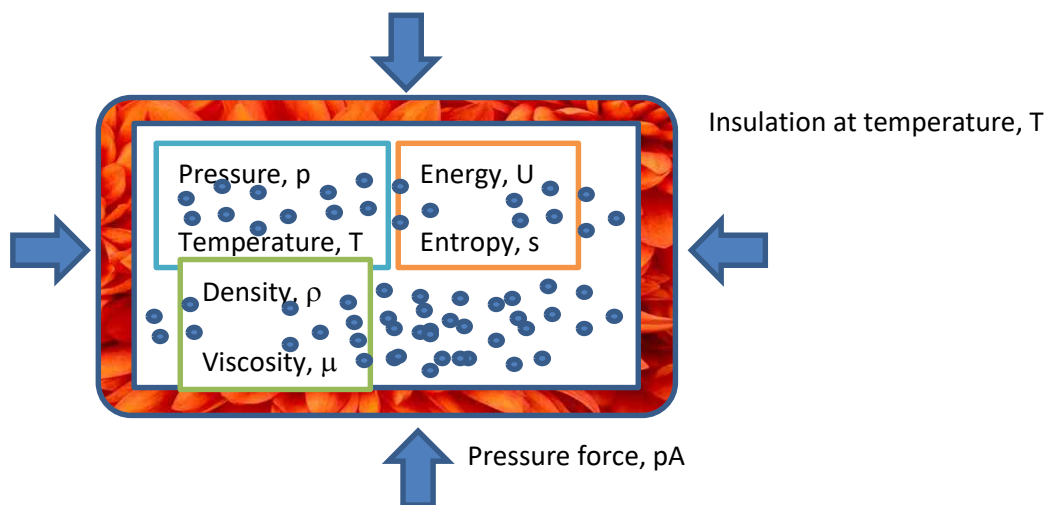
Figure 1 thermodynamic state properties

It is important to remember what *thermodynamic* state means, and firstly it is not to be confused with 'solid, liquid, gas state' as used in texts on physics or heat transfer. It is the condition that a fluid finds itself subjected to at a particular place and time. State is defined by the values of a fluid's thermodynamic *properties*. Likewise, the properties reflect the state that the fluid is in, and have been measured by experiment and are collected in tables of data. State is completely described by any two of the condition:

intensive properties: i.e. a thermodynamic property that <u>doesn't change with amount of substance</u> - p,T, and all the specific quantities, h [J/kg], s [J/kgK], v [m³/kg], u [J/kg], c_p [J/kgK], c_v [J/kgK], R [J/kgK] and importantly, density [kg/m³], (which are determined by the conditions at the boundary of the fluid, and are independent of how much mass of it there is (because if mass dependent then we consider only 1kg).

and/or

extensive properties: i.e. any thermodynamic property that needs the amount to be stated, i.e how many kg, so total quantities for a mass of substance, H [J], S [J/K], V [m³], and U [J/K] (which vary with quantity of the fluid).

The figure shows that the properties are affected by the conditions maintained on the fluid. The boundary of the fluid that we are looking at forms a thermodynamic **system** for analysis. In the case in the figure it is controlled for heat by the perfect insulation layer (not achievable in practice) which is maintaining a constant temperature of the fluid by allowing no heat transfer, and controlled for work by the pressure maintained on the vessel walls, either by external fluid pressure or by mechanical stresses. The properties of the fluid are dependent on the condition caused by these boundaries, but also upon the molecular nature of the fluid, which has to do with molecule size and structure, which is as much varied as there are number of different fluids in the world.

Thermodynamic property

As state is determined by the boundary conditions as well as the properties of the particular fluid, exact values of the properties usually vary with the state that the fluid is held in. Changing temperature in particular has a significant effect on all thermodynamic fluids. Pressure change often has a lesser effect than temperature on the properties, although it affects state significantly.

Therefore, conditions of heat flux and physical work on the boundaries of a fluid affect the state that the fluid is in, as reflected in the properties, which are mainly described by temperature and pressure, but can also be described by the other, material, properties at that state. And the extensive properties are dependent on the material.

Phase

Phase of a fluid, meaning liquid, solid or gas, is affected by state, and there can be a change of phase during a thermodynamic process (i.e. adding heat or work to the system). In particular for this module it is important to understand the most important fluid on our planet - water. Changes between liquid and gas state of water due to thermodynamic processes cause changes in the properties of the fluid.

The following sections demonstrate how the available data can be used from the tables of data:

G.R.C. Rogers and Y.R. Mayhew, Thermodynamic and Transport Properties of Fluids, Fifth Edition.

Thermodynamic system

A system simply describes a region containing a fluid, which is separated from its surroundings by boundaries. The boundary may be solid, in which case it is a closed system, or it may have some open boundaries which permit flow of the fluid; e.g. a section of tube with a fluid flow through it may have boundaries which are solid at the walls, and open which are virtual boundaries where entering and leaving properties may be measured. Open systems are considered in this course, and the changes in the properties that occur in systems within multicomponent overall systems (such as engine systems). The changes of properties represent the work or heat transfer to the system.

2. Availability of property information

Fluid material properties have been thoroughly analysed by prior research and data is available in several forms. The significance of this is that you don't have to measure the property when you need to know it for all common materials - if you know the state of the fluid, e.g. T and p, then you can find properties for the fluid. This data can be found in tabulated written data, and on-line resources, which, although not so accurate, are useful for preliminary calculation.

Tabulated data for water and steam

For the following, you will need the Thermodynamic and Transport Properties of Fluids booklet by Rogers and Mayhew, which is available in limited supply in the library, but is also available from the book shop.

For water and steam the data have been meticulously investigated in the past because of the significance of steam power processes, such as steam turbines which power most large electricity generation installations globally. The International Association for the Properties of Water and Steam (IAPWS for short, which can be found at http://iapws.org/ and the really keen might find interesting the formulae that have been put together on http://iapws.org/relguide/IF97-Rev.html) have done very detailed interpolation with increasing accuracy on the available steam experimental data.

3. Inspecting the saturated water and steam tables on p.2 and p.3 and on p.4 and p.5

Immediately, we need to inspect the data available, and this is the point of this part of the module – for a particular condition of a working fluid, we need to be able to get its properties. We start with saturated water and steam, i.e. water which is at boiling point and either in liquid or vapour phase.

On p.2, the temperature is varied on the left hand column and several properties of water and steam are stated.

Saturated means either a state where vapour is just at the point of starting to condense to the liquid phase, or liquid is just at the point of starting to boil and produce vapour.

Variation of saturation pressure with temperature

Look at the variation of pressure with temperature: for example when the temperature is 100°C, what is the pressure in the pressure column?

Alternatively, what is the pressure when temperature is 30°C?

Given that this is so much less than at 100°C, what do you think it means?

This pressure is the saturation pressure, which is the pressure at which the water will boil. That is, if the pressure is saturation pressure for 100°C, then water will boil at that temperature. Likewise, the lower temperature water will boil at its saturation pressure.

Subscripts are really important in representing data quantities

The subscript 'sat' or simply 's' indicates saturation condition on these tables. Similarly, subscript 'g' *generally* means a gas or vapour state is being referred to. And subscript 'f' means liquid state.

Variation of specific volume with temperature

Look at the column for specific volume, v_g, and inspect the table on p.10 for further properties of water and steam, for v_f.

Thinking about the units, what does specific volume mean? Considering the units, what is the property represented by the inverse of the specific volume? And what do the subscripts 'g' and 'f' indicate? Why is it that v_g is so large when the temperatures get lower?

Vapour and liquid have different response to pressure

Saturated liquid and saturated vapour both have a specific volume dependent on temperature. Liquid volume is not much affected by pressure applied to it - liquids are incompressible. But the vapour pressure produces a volume of vapour if the pressure is reduced to the saturation condition.

Consider what happens if the pressure is reduced below the saturation pressure for water at a particular temperature?

https://youtu.be/glLPMXq6yc0

> *It is possible to use a vacuum pump on water in a rigid vessel. So if water at 40 ℃ is subjected to a vacuum pressure of 5 kPa by a vacuum pump which sucks vapour from above the liquid in a rigid vessel, what will the response of the liquid be?*
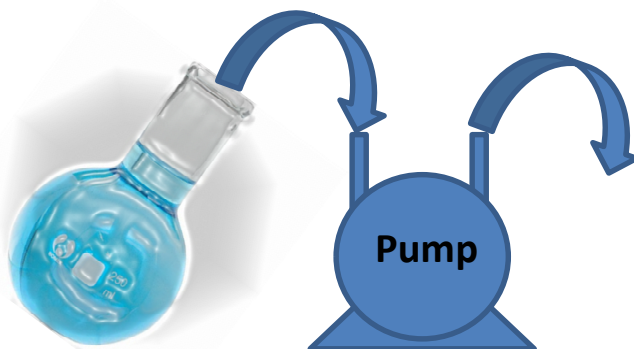
The liquid will in fact boil as soon as it is exposed to the lower pressure, because the saturation pressure is maintained by the vacuum pump. The liquid must exist in equilibrium with the new pressure, and there is no alternative but to drop to the temperature at which the saturation pressure is 5 kPa, i.e. 32.9C.

Thermo topic 1, Thermodynamic and transport properties of fluids
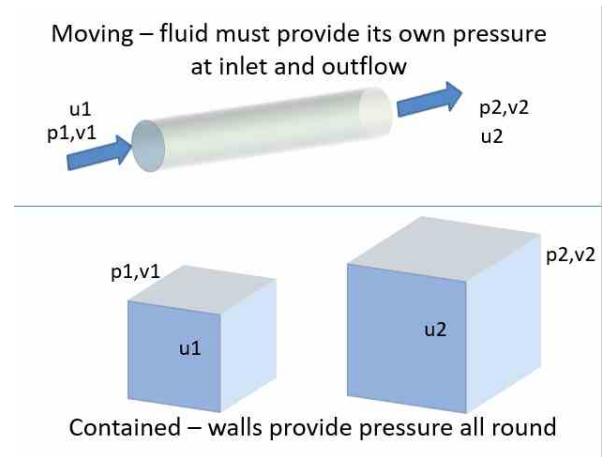
Energy content of steam and water

Look at the columns h_f and h_g on p.2 of the booklet. These represent the enthalpy, which is thermal energy stored by the fluid at a particular temperature, with subscripts f and g having their meanings as above.

At 100C, work out the difference between h_f and h_g.

This is the energy required to boil 1kg of water from liquid at 100C to vapour at 100C. Note that your difference is the same as the value in the column h_{fg}; the subscript 'fg' here refers to the difference between the enthalpy of saturated liquid, h_f, and that of saturated steam, h_g.

What is enthalpy?

When fluids flow in thermodynamic machines, they do work. Whenever they flow into a system they do work on the system. Whenever they leave the system, the system does work on them. Work is pV. So enthalpy is the energy of the fluid due to temperature, u, and the work it does in getting into a system, pv.

Moving – fluid must provide its own pressure at inlet and outflow

Contained – walls provide pressure all round

Sorting data by pressure instead of temperature

p.3 of the tables shows the same data for water and steam sorted by pressure. It is interesting to see how things look when it is turned around like this. Instead of having 100°C, our expected boiling point, it is now not there, and we see that at 1bar, water boils at only 99.62°C. All the other columns of data are in the same order as the table by temperature. The pressure data also extends over the page on to p.4 and p.5 for higher pressure steam all the way up to the supercritical point, 221.2 bar and 374.15°C.

Calculations with saturated water and steam

How much energy is required to boil 200g of water for a cup of tea from tap water at 10C?

Given that this is done by a 3kW kettle, how long does it take to boil, assuming that the kettle does not take any energy to heat?

It is important to realise that in raising water to boiling point, we do not boil it to vapour, so making a cup of tea does not consume so much energy really. It is also important to realise that we have assumed that the kettle has zero thermal mass, and that it takes no energy to heat it as it heats the water.

What energy would be required to boil the 200g of water from 10C to vapour at 100C?

And time to do this assuming perfectly efficient 3 kW heating element?

Thermo topic 1, Thermodynamic and transport properties of fluids

When liquid boils, it takes in significant energy. But it stores this energy, ready to give it back when it condenses. This is particularly important for this module since power from steam is a central theme for this year. The large majority of terrestrial power generation by humans uses steam cycles using steam raised by heat sources, which is then used in steam turbines.

Interpolation of data

There is a question of what to do when a data value you want is not stated. In our tables of saturated water and steam, this is not a big problem mostly, since the data is well populated with values, but suppose we only had data tabulated every 10°C. What would be done then? This is a common situation in the data that we will be using this year.

Here is a plot of p_s from 0.01 to 100C.

Water saturation pressure
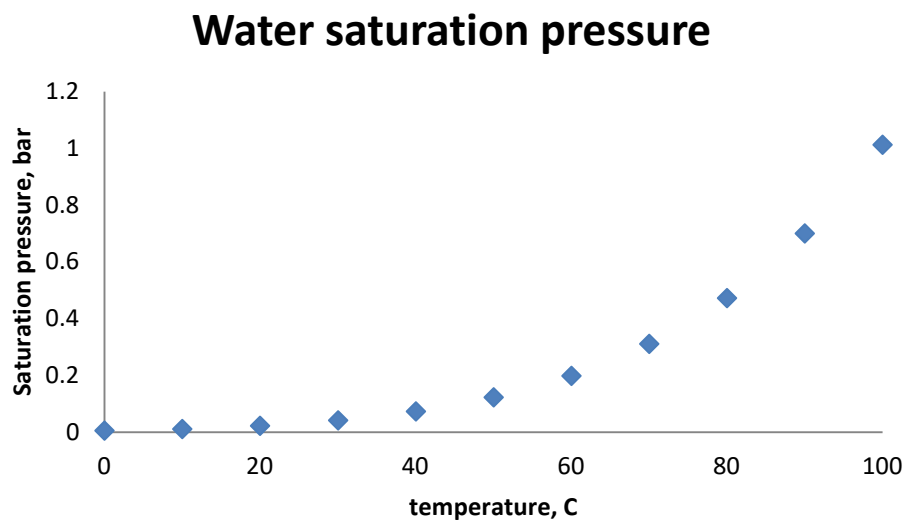
Figure 2 Graph of saturation pressure of pure water with temperature.

From the graph it can be seen that a reasonable way to get data at temperatures in between the given temperature points is by drawing a straight line between the data points and marking on that line the point at which the temperature line crosses it, then read the corresponding saturation pressure for that point.

Rather than drawing a graph to do this, it can be done by straightforward equation of a line in the form $(y-y_1)/(y_2-y_1)=(x-x_1)/(x_2-x_1)$, or in terms of the variables considered, for the particular example of 65°C:

$(p_{s65C}-p_{s60C})/(p_{s70C}-p_{s60C})=(65C-60C)/(70C-60C)$

which becomes:

MMME2047 Thermodynamics, 21-22

Thermo topic 1, Thermodynamic and transport properties of fluids

$p_{s65C} = 1/2.(p_{s70C} - p_{s60C}) + p_{s60C}$

$p_{s65C} = 0.5*(0.3116-0.1992)+0.1992 = 0.2554$ bar

Compare with the value given actually in this case (*yes, it was all for nothing because we already had it, but that wasn't the point – we now have a technique when it does happen that the data is not there*) which is 0.2501 bar – so not a bad representation.

This principle of interpolation can be used on any tabulated data in the Thermodynamics tables. In fact the source of the tables is from much more complex multi-dimensional interpolation based on the experimental data points collected carefully by scientists. See the website for the IAPSW.

4. Superheated steam

Consider trying to boil water in a rigid walled pressure vessel. If the pressure vessel is full of water, then it won't be possible to make the water boil, because the density of the water is $1000kg/m^3$, and if the water were to boil then it would have to become vapour at $1000kg/m^3$ - which would be supercritical, a point above which the fluid has properties of liquid and gas at the same time, and at very high pressure. However, if we consider boiling water from a vessel with an exhaust port with a pressure sensitive valve, what then? We could set that valve to any pressure we like and if the pressure exceeds that pressure, then contents will erupt out of the vessel through the valve.

Throttle to reduce p

Heat, Q
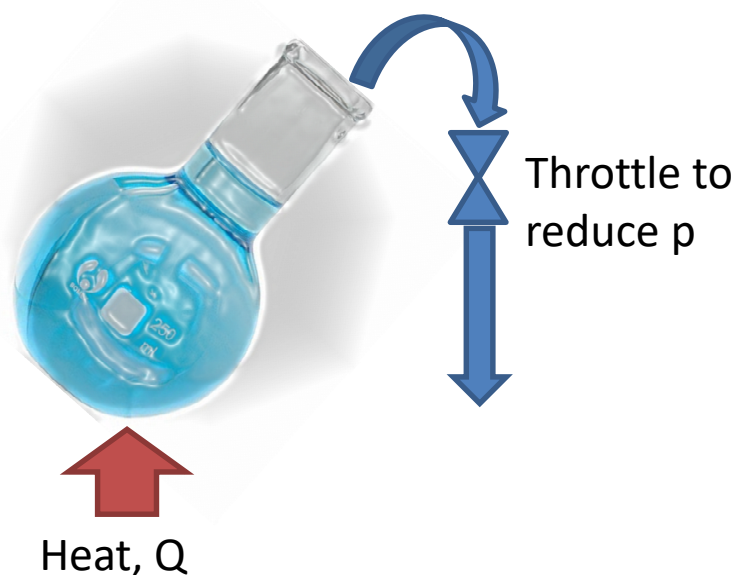
Thinking about this unusual pressure vessel, what would happen if an amount of water was put in the bottom of it and heat were applied to make it boil, and the pressure valve were set at 1 bar (which is 0.1MPa)? The water would gradually boil off until there were no liquid water left in the bottom of the vessel, only steam at the temperature of the vessel.

But if heat were applied beyond this point, what then? Because there is no water liquid in the vessel, there is now no restriction on the temperature in the vessel, and the steam in the vessel, being dry, can warm up like a gas. This is then **superheated steam**.

MMME2047 Thermodynamics, 21-22

Thermo topic 1, Thermodynamic and transport properties of fluids

A rigid walled pressure vessel has a pressure sensitive valve set to 1 MPa (which is 10 bar). Water in the vessel is boiled away until there is just steam in the vessel, and yet more heat is transferred into the vessel. What is the saturation temperature of water, and what is its specific enthalpy, at 1MPa?

Further heat is added until the temperature is 200°C. The difference between the saturation temperature and the actual temperature is called the amount of superheat. What is the amount of superheat? And what is now the specific enthalpy of the vapour, which is now called superheated vapour?

Interpolating superheated tables

The principle of interpolating tabulated data described previously is very useful with superheated steam, when later on it becomes a puzzle to work out what changes have occurred in a steam cycle.

What is the enthalpy of steam at 4MPa (40 bar) and at 525°C?

What is the entropy of the steam at 4MPa and 525C?

If the entropy is kept at this value, but a process is done to the steam, which reduces its pressure to 0.4 MPa, use interpolation to find the *enthalpy* of the steam at 0.4MPa and at the same entropy as the steam at 4MPa and 525C.