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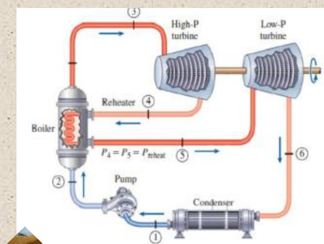
Thermodynamic II

LECTURE 3

An overview of steam, dryness fraction measurements.



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1. Steam

1.1 Introduction

- ***What is steam?*** The English language is a little fuzzy here. Some definitions say that any water vapor (H2O in gaseous form instead of liquid) is steam.

- By that definition, the atmosphere itself is a very low-temperature steam engine.

- Other definitions say that steam is water vapor if the water vapor happens to be boiling. (Which brings up another question: what does "boiling," mean?)

- Finally, a third definition says that steam is "pressurized water vapor", i.e. water vapor at a pressure higher than 1 atmosphere. Those are incompatible definitions, which makes clear thinking difficult.

- ***Steam** is the technical term for the gaseous phase of water*, which is formed when water boils. Technically speaking, in terms of the chemistry and physics.

- Steam is invisible and cannot be seen; however, in common language it is often used to refer to the visible mist or aerosol of water droplets formed as this water vapor condenses in the presence of (cooler) air.

- At lower pressures, such as in the upper atmosphere or at the top of high mountains water boils at a lower temperature than the nominal 100 °C (212 °F) at standard temperature and pressure. If heated further it becomes superheated

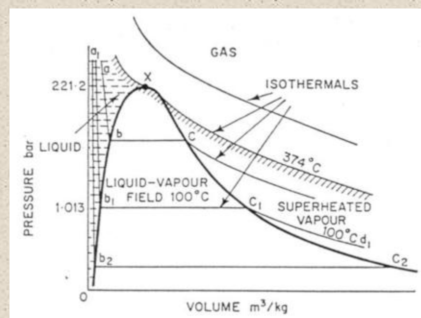
- The enthalpy of vaporization is the energy required to turn water into the gaseous form when it increases in volume by 1,700 times at standard temperature and pressure; this change in volume can be converted into mechanical work by steam engines such as reciprocating piston type engines and steam turbines, which are a sub-group of steam engines.

- Piston type steam engines played a central role to the Industrial Revolution and modern steam turbines are used to generate more than 80% of the world's electricity

- If liquid water comes in contact with a very hot substance (such as lava, or molten metal) it can create a steam explosion. Steam explosions have been responsible for many foundry accidents, and may also have been responsible for much of the damage to the plant in the Chernobyl disaster.

Dryness Fraction

- The figure below shows a typical P-v diagram for steam, which you will all be familiar with by now. On the diagram are shown isothermals (lines of constant temperature).
- Within the Liquid-Vapor mixture region, these lines are horizontal. Any horizontal line on a P-v diagram is an isobar (line of constant pressure).
- It is therefore clear that if the temperature and pressure of wet steam are stated then it is not enough information to completely specify the state of the steam. For we will not know the fraction of it which is liquid and what fraction of it is vapor.



The ratio of the mass of vapor to the mass of mixture is called the dryness fraction, x

$$x = \frac{\text{mass of vapour}}{\text{mass of liquid \& vapour mixture}}$$

How is the dryness fraction of the wet steam actually determined in practice? Well, we use a calorimeter.

1.2 Calorimeters

Calorimeters, in general, are to do with measuring heat. Many, such as the bomb calorimeter, are used to determine the amount of heat generated by burning a certain mass of a certain substance. Here we are concerned with those calorimeters which we might use to determine the dryness fraction of wet steam.

1.2 DETERMINATION OF DRYNESS FRACTION OF STEAM

The dryness fraction of steam can be measured by using the following *calorimeters:*

1. Tank or bucket calorimeter
2. Throttling calorimeter
3. Separating and throttling calorimeter.

1.Tank or Bucket Calorimeter

The dryness fraction of steam can be found with the help of tank calorimeter as follows:

- *A known mass of steam is passed through a known mass of water and steam is completely Condensed.*
- *The heat lost by steam is equated to heat gained by the water.*

Fig. (1) Shows the arrangement of this calorimeter.

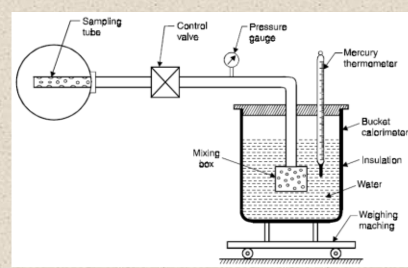


Fig. (1). Tank or bucket calorimeter.

Let,

ps = Gauge pressure of steam (bar),
pa = Atmospheric pressure (bar),
ts = Saturation temperature of steam known from steam table at pressure (*ps* + *pa*),
h_{fg} = Latent heat of steam,
x = Dryness fraction of steam,
Cpw = Specific heat of water,
Cpc = Specific heat of calorimeter,
mc = Mass of calorimeter, kg,
mcw = Mass of calorimeter and water, kg,
mw = (*mcw* – *mc*) = Mass of water in calorimeter, kg,
mcws = Mass of calorimeter, water and condensed steam, kg,
ms = (*mcws* – *mcw*) = Mass of steam condensed in calorimeter, kg,
tcw = Temperature of water and calorimeter before mixing the steam, °C,
tcws = Temperature of water and calorimeter after mixing the steam, °C.

Neglecting the losses and *assuming* that the *heat lost by steam is gained by water and calorimeter*, we have

$$(m_{cws} - m_{cw})\,[xh_{fg} + c_{pw}\,(t_s - t_{cws})] = (m_{cw} - m_c)c_{pw}\,(t_{cws} - t_{cw}) + m_c\,c_{pc}\,(t_{cws} - t_{cw})$$

$$\therefore \quad m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})] = (t_{cws} - t_{cw})\,[m_{cw} - m_c)(c_{pw} + m_c c_{pc}]$$

or

$$m_s[xh_{fg} + c_{pw}\,(t_s - t_{cws})] = (t_{cws} - t_{cw})(m_w c_{pw} + m_c c_{pc})$$

- The *mcCpc* is known as *water equivalent of calorimeter*.
- The value of dryness fraction '*x*' can be found by solving the above equation.
- The value of dryness fraction found by this method involves some *inaccuracy* since losses due to convection and radiation are *not* taken into account.
- The calculated value of dryness fraction neglecting losses is *always less* than the actual value of the dryness.

Example (1)

Steam at a pressure of 5 bar passes into a tank containing water where it gets condensed. The mass and temperature in the tank before the admission of steam are 50 kg and 20°C respectively. Calculate the dryness fraction of steam as it enters the tank if 3 kg of steam gets condensed and resulting temperature of the mixture becomes40°C. Take water equivalent of tank as 1.5 kg.

Solution:

Pressure of steam, P = 5 bar
Mass of water in the tank = 50 kg
Initial temperature of water = 20°C
Amount of steam condensed, ms = 3 kg
Final temperature after condensation of steam = 40°C
Water equivalent of tank = 1.5 kg
Dryness fraction of steam, x =?
At 5 bar. From steam tables, h_f = 640.1 kJ/kg ; h_{fg} = 2107.4 kJ/kg, ts=151.831 °C
Total mass of water, mw = mass of water in the tank + water equivalent of tank
= 50 + 1.5 = 51.5 kg

Also, heat lost by steam = heat gained by water

$$m_s[xh_{fg} + C_{pw}(t_s - t_{cws})] = (t_{cws} - t_{cw})(m_w C_{pw} + m_c C_{pc})$$

$$3[x(2107.4) + 4.18(151.831 - 40)] = (40 - 20)(51.5 * 4.18)$$

Hence dryness fraction of steam = **0.456**

2.Throttling Calorimeter

The dryness fraction of wet steam can be determined by using a throttling calorimeter, which is illustrated diagrammatically in Fig. (2).

The steam to be sampled is taken from the pipe by means of suitable positioned and dimensioned sampling tube. It passes into an insulated container and is throttled through an orifice to atmospheric pressure. Here the temperature is taken and the steam ideally should have about 5.5 K of superheat.

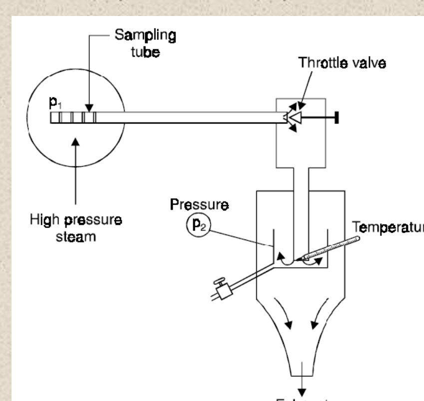


Fig. (2). Throttling calorimeter

- The throttling process is shown on *h-s* diagram in Fig. (3) by the line 1-2.
- If steam initially wet is throttled through a sufficiently large pressure drop, then the steam at state 2 will become superheated.
- State 2 can then be defined by the *measured pressure and temperature*.
- The enthalpy, h_2 can then be found and hence

$$h_2 = h_1 = (h_{f1} + x_1 h_{fg1}) \quad \text{at } p_1$$

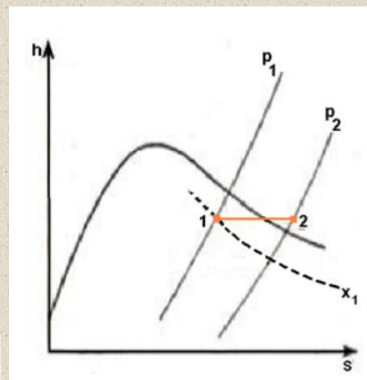


Fig. (3). Throttling process.

$$\text{where } h_2 = h_{f2} + h_{fg2} + c_{ps}\,(T_{sup2} - T_{s2})$$

$$x_1 = \frac{h_2 - h_{f1}}{h_{fg1}}$$

Hence, the dryness fraction is determined and state 1 is defined.

Example (2)

Pressure in the main steam pipe = 10 bar, Pressure after throttling = 1.2 bar, Temperature after throttling = 120°C. Assuming C_p = 2.303 kJ/kg K for steam after throttling. Calculate the Dryness fraction.

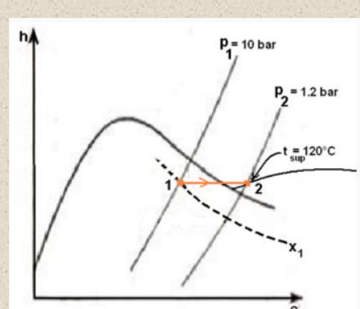
Solution:

Given: Steam at state '1': Pressure in the main steam pipe before throttling, P_1 = 10 bar:

By using steam table (for dry saturated steam):

For state 1, From steam tables for dry saturated steam at P_1 = 10 bar, we have

$h_{f,1}$ = 763 kJ/kg, $h_{fg,1}$ = 2015 kJ/kg



Given: Steam at state '2': Pressure after throttling, p_2 = 1.2 bar; Temperature after throttling, t_2 = 120°C;

By using steam table (for dry saturated steam):

For state 2, From steam tables for dry saturated steam at p_2 = 1.2 bar, we have

$t_{s,2}$ =104.8°C, Given: Steam at state '2': Pressure after throttling, p_2 = 1.2 bar; Temperature after throttling, t_2 = 120°C;

Since, t_2 = 120°C > $t_{s,2}$ =104.8°C the condition of steam at state '2' is superheated. Therefore, $t_{sup,2}$ = t_2 = 120°C

By using steam table (for superheated steam)

For superheated state 2, From steam tables for superheated steam at P_2 = 1.2 bar and $t_{sup,2}$ = 120°C, we have

$h_{sup,2}$ = 2714.81 kJ/kg

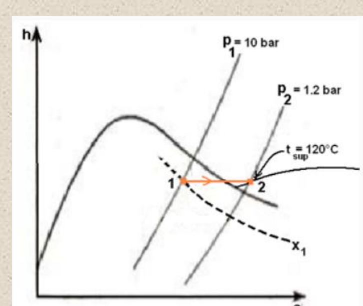
Given: Assuming C_p = 2.303 kJ/kg K for steam after throttling. Calculate the

Determine the dryness fraction of steam in main steam pipe:

During throttling process enthalpy remains constant.

i.e. $h_1 = h_{sup,2}$

$$x_1 = \frac{h_{sup,2} - h_{f,1}}{h_{fg,1}}$$



Answer: Dryness fraction, $x_1 = \frac{h_{sup,2} - h_{f,1}}{h_{fg,1}} = \frac{2714.81 - 763}{2015}$

= 0.9686

3. Separating and Throttling Calorimeter

- If the steam whose dryness fraction is to be determined is *very wet* then throttling to atmospheric pressure *may not be sufficient to ensure superheated steam at exit*. In this case, it is *necessary to dry the steam partially, before throttling*. This is done by *passing the steam sample from the main through a separating calorimeter* as shown in Fig. (4).
  - The steam is made to change direction suddenly, and the water, being denser than the dry steam is separated out.
  - The quantity of water, which is separated out (mw), is measured at the separator, the steam remaining, which *now has a higher dryness fraction*, is passed through the *throttling calorimeter*.

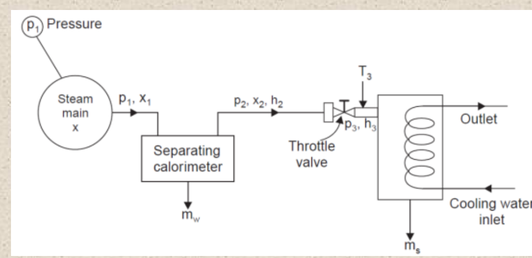


Fig. (4). Separating and throttling calorimeter

With the combined separating and throttling calorimeter it is *necessary* to condense the steam after throttling and measure the amount of condensate (*ms*). If a throttling calorimeter only is sufficient, there is no need to measure condensate, the pressure and temperature measurements at exit being sufficient.

Dryness fraction at 2 is x_2, therefore, the mass of dry steam leaving the separating calorimeter is equal to $x_2 ms$ and this must be the mass of dry vapour in the sample drawn from the main at state 1.

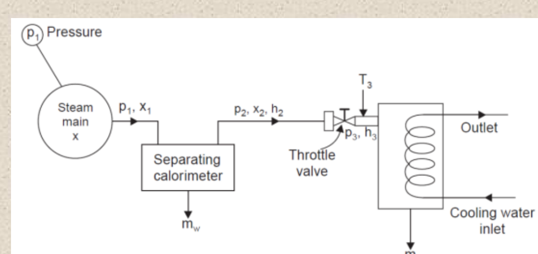


Fig. (4). Separating and throttling calorimeter

$$x_1 = \frac{\text{Mass of dry vapour}}{\text{Total mass}} = \frac{x_2\, m_s}{m_w + m_s}$$

The dryness fraction, x_2, can be determined as follows:

$$h_3 = h_2 = h_{f2} + x_2 h_{fgs} \qquad at\ p_2$$

$$[h_3 = h_{fs} + h_{fgs} + C_{ps}\,(T_{sup3} - T_{s3})\ \text{at pressure}\ p_3]$$

or

$$x_2 = \frac{h_3 - h_{f2}}{h_{fg2}}$$

The values of h_{f2} and h_{fg2} are read from steam tables at pressure p_2. The pressure in the separator is small so that p_1 is approximately equal to p_2. .

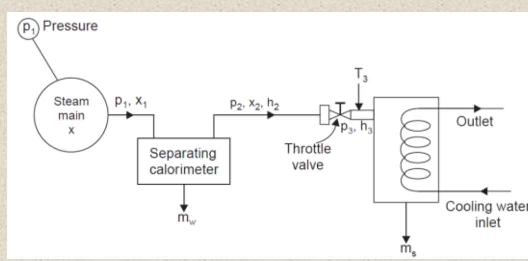


Fig. (4). Separating and throttling calorimeter

Example (3)

The following observations were taken with a separating and a throttling calorimeter arranged in series:
Water separated = 2 kg, steam discharged from the throttling calorimeter = 20.5 kg, temperature of steam after throttling = 110°C, initial pressure = 12 bar abs., barometer= 760 mm of Hg, final pressure = 5 mm of Hg
Estimate the quality of steam supplied.

Solution. Quantity of water separated out, m_w = 2 kg
Steam (condensate) discharged from the throttling calorimeter, m_s = 20.5 kg
Temperature of steam after throttling, t_{sup} = 110°C
Initial pressure of steam, p_1 = 12 bar abs.

Final pressure of steam, $p_3 = 760 + 5 = 765$ mm

$$= \frac{765}{1000} \times 1.3366 \qquad (\because\ 1\ \text{m Hg} = 1.3366\ \text{bar})$$

$$\simeq 1\ \text{bar}$$

From steam tables:
At $P_1 = P_2$ = 12 bar = 1.2 Mpa, **h_{f2} = 798.33 kJ/kg**, **h_{fg2} = 1985.4 kJ/kg**

At P_3 = 1 bar = 0.1 MPa, T_{sup} = 110 °C, **h_3 = 2696.3 kJ/kg**

$h_3 = h_2$ and $h_2 = h_{f2} + x_2\, h_{fg2}$

$h_3 = h_{f2} + x\, h_{fg2}$

$2696.3 = 798.33 + x_2\,(1985.4)$

$$X_2 = \frac{2696.3 - 798.33}{1985.4}$$

X_2 = 0.956

Now, quality of steam supplied,

$$X_1 = \frac{X_2 m_s}{m_w + m_s} = \frac{0.956 \times 20.5}{2 + 20.5} = \mathbf{0.87} \quad Ans.$$

Any Questions???