

12. Air conditioning plant

Air conditioning is adjusting the temperature and humidity of the air. Refrigeration is used to reduce humidity. It is important to be able to calculate how much refrigeration is required to get the desired air condition. Air to be conditioned is sucked in, cooled down to cause decrease in humidity. This is done by causing a temperature drop to below dew point. The figure shows a schematic diagram of the process.

1 to 2 Work input from fan – a relatively small amount of work due to the low pressure across it.

2 to 3 Heat rejected, mixture saturates, liquid water is drained to 4 – a relatively large amount of thermal energy exchange in the heat exchanger between the refrigerant on the inside of the tubes and the air on the outside of the tubes.

3 to 5 Heat supplied to give desired humidity (ϕ) at temperature T; again a relatively high amount of thermal energy exchange between the heating coil and the air.

Air is heated up after the cooler to make it comfortable before being issued to the room.

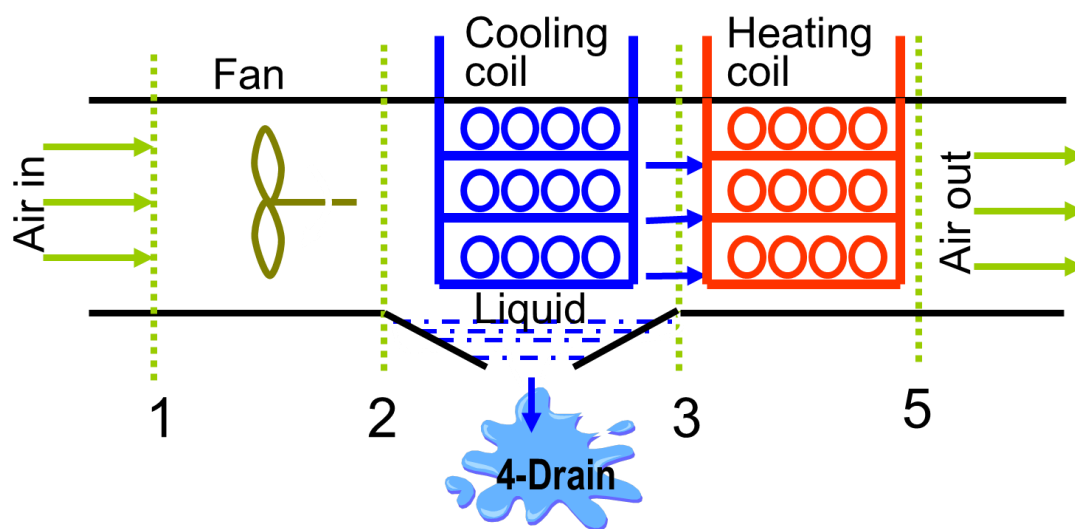


Figure schematic of air conditioning in an air duct

Enthalpy change of the dry air/water vapour mixture between each of the sections is equal to the energy required to cause that change.

Use the steady flow energy equation (SFEE) in order to calculate the energy transfers required to and from the air, but also to and from the refrigerant that is used in the cooling section.

Considering only the cooling section, the SFEE can be written as follows. Thermal energy of moist air entering, plus the heat transfer into the air equals the thermal energy of moist air leaving the section plus the thermal energy of the condensed liquid moisture leaving the section:

$$\dot{m}_{a2}h_{a2} + \dot{m}_{s2}h_{s2} + \dot{Q}_{2-3} = \dot{m}_{a3}h_{a3} + \dot{m}_{s3}h_{s3} + \dot{m}_{c4}h_{c4}$$

Thermo topic 2 Refrigeration and air conditioning

For this section of the air conditioning unit, enthalpy of water vapour plus dry air at section 2, has heat taken out between 2 and 3. At 3, there is the same mass of dry air, but some moisture has fallen out on the cooling unit (fridge coils!) to the drain. So we have same mass of dry air with different enthalpy (calculable by dry air temperature and c_p of dry air in tables), and we have a (smaller) amount of water vapour with the air. We also have an amount of condensate – the condensed water vapour on the cooling coils.

Example: For the cooling section shown in the figure and the following conditions: $\dot{m}_{a,dot}$ is 0.5 kg/s, specific humidity is 0.01 kg/kg air, therefore 0.005 kg/s is $\dot{m}_{s,2}$. Ingoing temperature 30C, what is the heat transfer required to reduce the specific humidity to 0.006 kg/kg air specific humidity? What is p_a and p_s at exit?

The steps are outlined and detailed in the supporting video for this chapter.

A: determine the temperature at point 3:

1. use the specific humidity of point 3 (after dehumidifying) to calculate p_{s3}
2. use the fact of 100% relative humidity meaning that $p_s = p_g = p_{sat,T3}$
3. calculate p_s from the specific humidity formula
4. look up p_{sat} in the saturated water and steam tables (p.2) and find the corresponding temperature
5. realise that temperature is the dew point temperature and it is the temperature at point 3 (find it's between 6 and 7°C)

B: determine the air enthalpy change of dry air between point 1 and point 3

1. enthalpy of dry air is not stated in tables, so use $\Delta H = \dot{m}_a \Delta h = \dot{m}_a c_{p,a} \Delta T$ instead
2. c_p of air is stated in the tables p.16
3. read the c_p of air at T_1 , 30°C or 303 K (take the closest Kelvin value stated which is 300 K)
4. read the c_p of air at T_3 , 280 K (take the closest Kelvin values stated which is 275 K)

N.B. here we've avoided interpolating due to the small differences in values

5. enthalpy change of dry air is $\dot{m}_a c_{p,a} \Delta T$

C: determine the water vapour enthalpy change

1. enthalpy at point 1 of the water vapour is $\dot{m}_s \Delta h_s$
2. h_s is the vapour enthalpy, which is the h_{sat_vap} or h_g of water vapour at T_1
3. find the same for point 3 at temperature T_3

D: find the water condensate enthalpy lost

1. find from the tables h_f for saturated liquid water at T_3 , which is the dew point

2. enthalpy flow rate of the condensate is then $\dot{m}_{cond} h_f$

E: do the sum of the enthalpy changes using the SFEE to find \dot{Q} the heat exchange rate

1. add the change in dry air enthalpy flow to the water vapour enthalpy flow at point 1 minus water vapour enthalpy flow at point 3, and finally take away the condensate enthalpy flow rate; that's \dot{Q}

14. Using the chart to calculate dehumidifying

The alternative method is to use the psychrometric chart, which is much quicker. Plot the two points, the first located by knowing 0.01 specific humidity and the dry bulb temperature (point 1) and the second because of 0.006 specific humidity and knowing it's 100% relative humidity at the dew point (point 3).

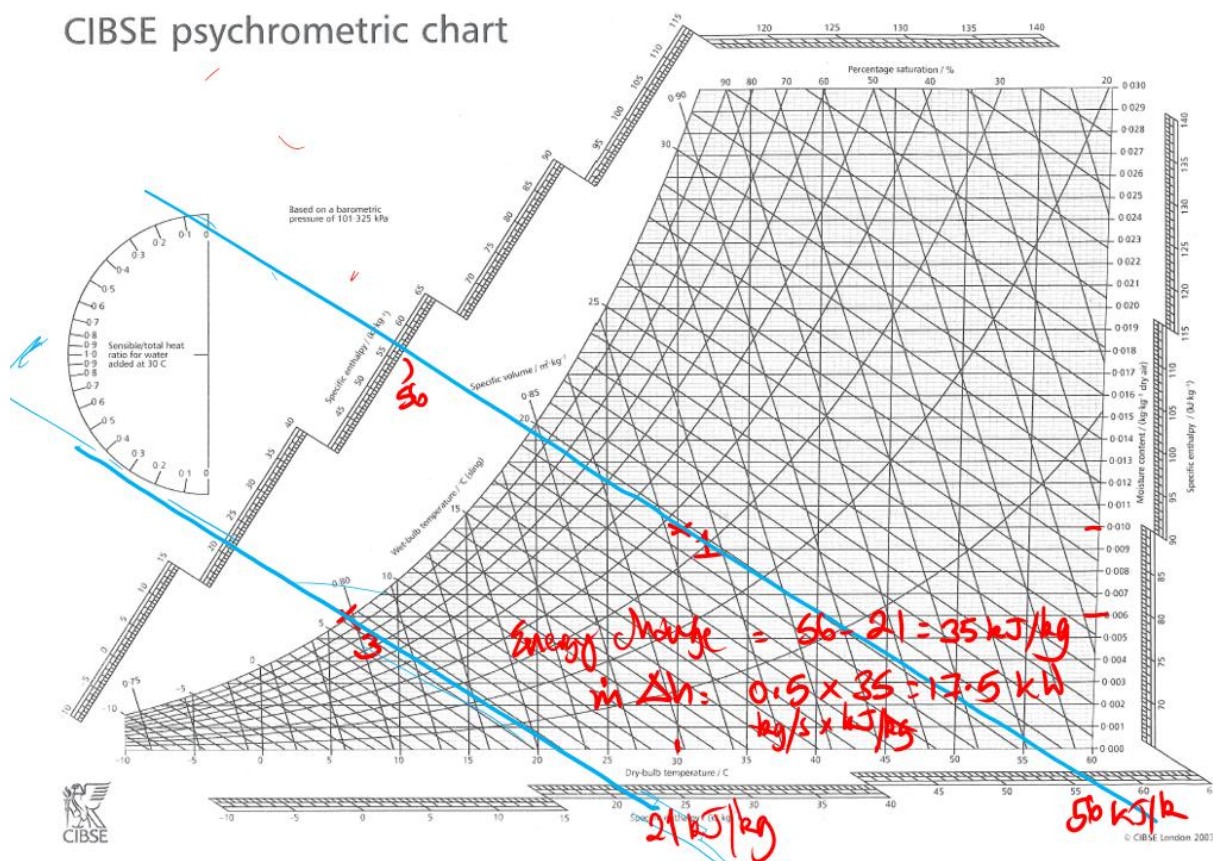


Figure showing psychrometric chart with example plot and energy value readings

the specific enthalpy of the atmospheric air at each of the points is straightaway given by using a ruler over the two points balancing the enthalpy at both ends of the ruler through the point. The difference is the change in enthalpy and multiplied by mass flow rate of the dry air it gives the thermal power extracted by the cooling section heat exchanger, $\dot{Q} = \dot{m}_{dry-air} \Delta h_{atmospheric air}$.

Topic 3. Vapour power cycles – or getting work from steam engines

Aim of this section

Most of the world's power is generated by steam vapour power cycles – whether by traditional coal (which has been burned since day 1 of networked power), gas, nuclear, or concentrated solar thermal. This section introduces the analysis of the basic cycles used and the principles of the thermodynamics underpinning them.

Aim: learn to apply steam state properties into steam power generation cycles

Objectives: understand the principle of work from heat; understand the Carnot cycle principle; understand the metrics of steam power cycles – isentropic efficiency, work ratio, thermal efficiency, specific steam consumption; understand the basic vapour power cycles – Carnot cycle, Rankine cycle and Rankine cycle with superheat; use the Mollier diagram; calculate turbine work, heat into cycle and pump work to derive the metrics of steam power cycles.

1. The 1st Law of Thermodynamics: 'heat is work'.

Steady flow energy equation

$$\dot{Q}_{12} + \dot{W}_{12} = \dot{m} \left(h_2 - h_1 + \frac{C_2^2 - C_1^2}{2} + g(z_2 - z_1) \right)$$

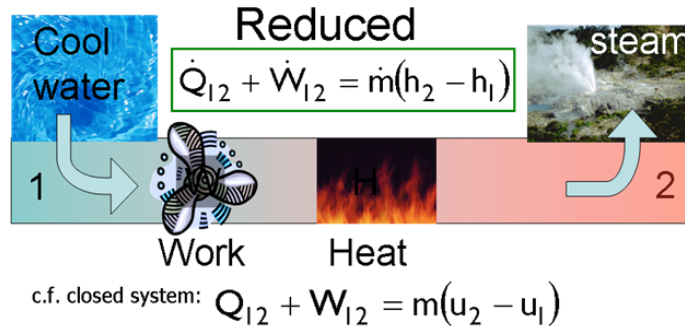


Figure showing first law in the form of steady flow energy equation, with kinetic and potential energy removed, and a schematic of how power can be produced from a condensable vapour circuit

The idea of this schematic and the Steady Flow Energy Equation (SFEE) is to say, heat is equivalent in terms of being an energy quantity, to work. Energy is conserved. The cool water can be worked on to make it flow at a high pressure, where heat can be transferred into it to make steam, and the steam is highly energetic. This is the principle of steam vapour power. The SFEE shows on the left of the formula the heat and work transferred across the system boundaries, and on the right hand side the effect that the heat and work transfer of energy into the system has on the working fluid, in this case water vapour/liquid. In thermodynamic energy generating systems, the kinetic and potential energy terms are negligible, as can be quickly confirmed by working out the energy to lift 100 kg by 100 m (100000 J, or 100 kJ) or accelerating it to 100 ms⁻¹ (500000 J or 500 kJ) compared to raising 100 kg of water to vapour (250,000 kJ).

Comparing the steady flow energy equation (SFEE) with the *Bernoulli* equation $p = \frac{1}{2} \rho U^2 + \rho gz$, which derives from Navier-Stokes equations, it can be seen that there is a velocity head term and a pressure head term in the Bernoulli equation, which in the pressure form of the equation here are directly in the SFEE. That is because they too are forms of energy – kinetic and potential energy. **Heat and work** have to do with **transfers of energy**. That is why they are on the left hand side separately – Q defines the amount of thermal energy transferred to the fluid, and W defines the amount of mechanical work done on the fluid. When these external energy transfers are made, the fluid responds by a thermal energy change (h), a kinetic energy change (C² where C is velocity here) and a potential energy change (z where z is a height). Navier-Stokes equations have an energy equation, which contains these terms as well as their convection and diffusion as in the momentum equation.

Units are: [N·m⁻² = kg·m·s⁻²·m⁻² = kg·m⁻¹·s⁻²] multiply by volume rate and the units become, N·m⁻² × m³·s⁻¹ = Nm·s⁻¹. Units of power, i.e. Fd/t = Nm/s. Therefore the SFEE is the Bernoulli equation with addition of the energy content of the material and whatever energy is transferred across the boundary.

2. Principle of the Second Law of Thermodynamics

A **heat engine** is a system operating in a cycle and producing a net quantity of work from a supply of heat. A heat engine can be presented as:

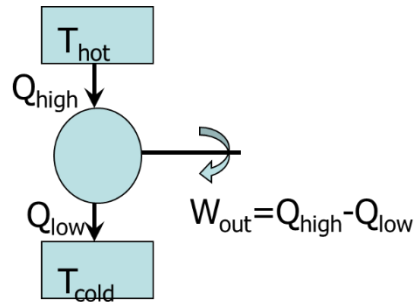


Figure showing schematic of heat engine producing work by using the thermal energy from the hot source and necessarily passing waste heat to the cold sink

The **cycle efficiency** is defined as:

$$\eta = \text{useful energy out/energy supplied} = \text{Work done/Heat supplied} = W_{\text{out}} / Q_{\text{high}} < 1$$

The **2nd law** states that $Q_{\text{low}} > 0$, i.e. some heat must be rejected and η must be $< 100\%$.

Remember that heat transfers across boundaries – if a real engine were not given a place to dump the waste heat, then obviously it would overheat, but ultimately it would stop working, and it wouldn't be able to produce work.

The second law insists on heat being rejected by a real engine.

- If a system is taken through a cycle and produces work, it must be exchanging heat with at least two reservoirs at different temperatures – a heat source and a heat sink.
- If a system is taken through a cycle while exchanging heat with only one reservoir, the work done must be either zero or positive, i.e. work is going into the system – a refrigerator.

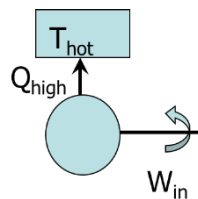


Figure showing a heat engine with work in and only heat exchange to higher temperature

- Since heat can never be converted continuously and completely into work, but the reverse is true, work is a more valuable form of energy transfer than heat.

These statements are about what can be done with the machine due to the system it contains. To produce work you require hot and cold. With only one reservoir you can pass in work, but not out. Hot can be up to whatever you want – in Tokamak fusion reactor 100 million Kelvin. Lower limit is fixed at 0K – at which point nothing moves – all atomic motion ceases.

Thermo topic 3: vapour power cycles
3. Flow processes in real devices

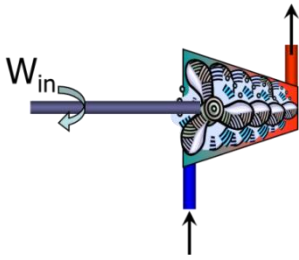


Figure schematic of a compressor for vapour or gas

Compressor – it works by using mechanical work from a motor of some kind to drive a shaft which has on it a number of compressor blades, which spin on the fluid and drive it through successive stages; it is used for gases and vapours. Not liquids. The fluid enters cold and at low pressure and leaves hot and at high pressure.

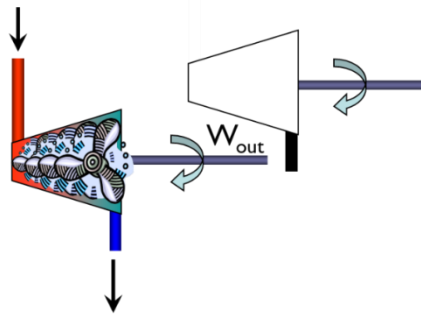


Figure showing schematic of a steam or gas turbine

Turbine works in the reverse sense to a compressor – the vapour or gas enters at high temperature and pressure and leaves at low temperature and pressure. On its way through the turbine it passes over turbine blades which are like windmills in the fluid stream, each one taking successively more energy out of the fluid.

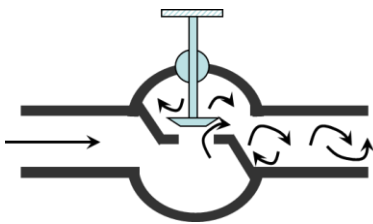


Figure showing schematic of a throttle which reduces pressure in a flow of fluid

Throttle – is a constriction on the flow. It involves a pressure drop but is at flow rate such that kinetic energy change is insignificant – most contained flows which are well away from sonic velocity fit this description. In this case the change of *enthalpy* is negligible – there is an exchange between u and pv internally, but little thermal energy enters as heat due to the small surface area and the *short residence time* (flow time spent in the throttle).

Thermo topic 3: vapour power cycles

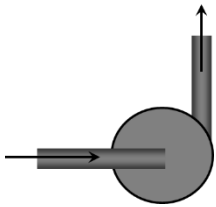


Figure showing schematic of a pump which is for incompressible fluids, i.e. liquids, for raising pressure and producing a volume flow rate at pressure

Pump - Pumps are used to deliver a volume of pressurised liquid. Relatively little thermal energy increase in the liquid (little work done) and the pressure energy for an incompressible fluid is negligible.

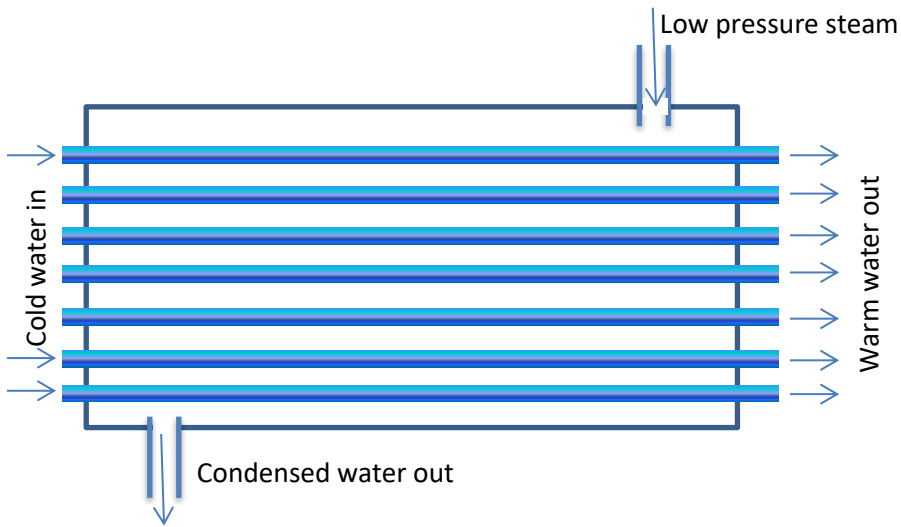


Figure schematic of a condenser heat exchanger – one fluid passes through tubes inside a vessel which contains another fluid; the hotter fluid cools while the cooler heats, in this case there is steam which condenses

Condenser – uses relatively impure water ('cold water in' on diagram) to pass into a sealed heat exchanger, where it exchanges heat with 'low pressure steam' from a vapour power cycle to make it condense to water, which is then fed back into the cycle.

Boiler – heat exchanger for raising steam in tubes which pass back and forth through a hot reactor vessel. Water enters the higher tubes and leaves the lower tubes to reduce temperature gradients. In a power station coal boiler, there are tubes in the walls of the reactor vessel which are used to heat the water, and the tubes across the flow are used to further heat the water to superheated steam.

Thermo topic 3: vapour power cycles

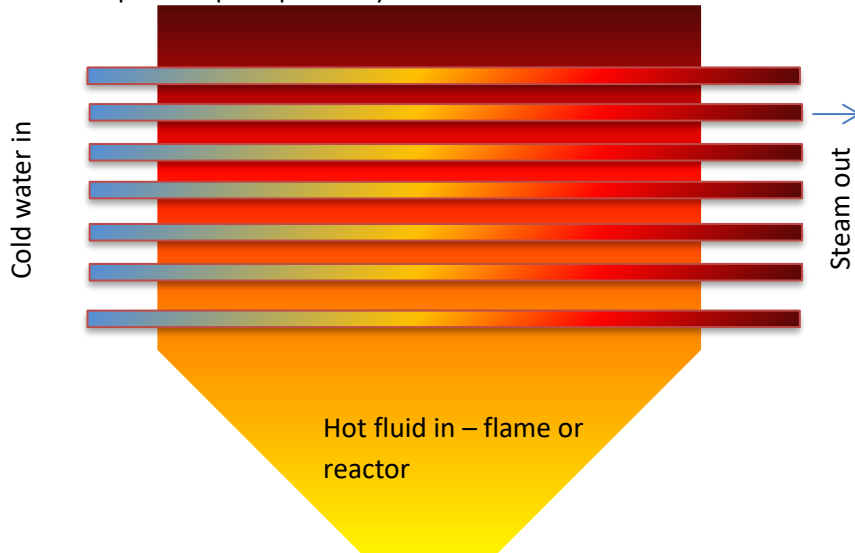


Figure schematic of a boiler heat exchanger: hot gases pass over tubes which contain water that is heated and evaporated

Compressors and turbines are constant *entropy* machines for gas compression or work from expansion. A constant entropy process is one in which there is no heat transfer and no frictional losses – so that it is reversible. The change in enthalpy is the work in for compressor and out for turbine, assuming there is no heat transfer. No heat transfer can be nearly achieved by good insulation, and no friction can be achieved by good design of large scale machines, so mechanical friction is negligibly small compared to work, and so the blade design is optimal for reduction of turbulence. The boiler and condense are heat exchangers allowing two separate and different temperature fluids to exchange heat.

4. Vapour power cycles

The Carnot efficiency is most simply illustrated in Vapour Power Cycles:

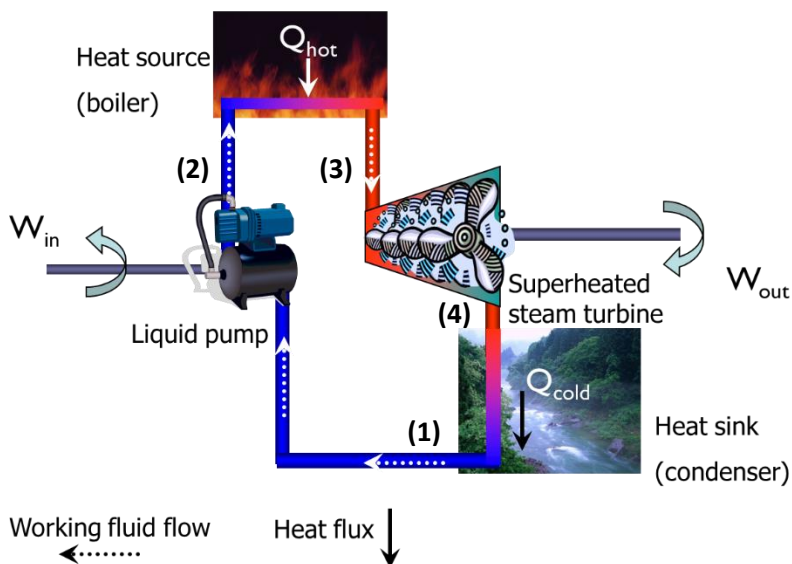


Figure schematic of a vapour power cycle showing the four basic processes: 1-2 pressurise, 2-3 boil, 3-4 expand and extract work, 4-1 condense

5. Entropy

Steven Hawking describes how a drinking glass has low entropy; it is in an ordered state. There are only few ordered states with low entropy. Smashing the glass provides a route to many possible disordered states which have high entropy. To establish an ordered state again would take far more work than the work to produce the disordered state. Entropy defines the amount of disorder in the energy contained by the system. Increasing entropy implies loss of energy to chaotic work and heat which is lost and no longer useful.

Going round a cycle, there will be either no change in the integral (just like all other properties) or there will be a decrease:

$$\oint \frac{\delta Q}{T} \leq 0 \text{ and } \left(\frac{dQ}{T} \right)_{\text{INT,REV}} = dS$$

The change of entropy of a working fluid in an **internally reversible** process is defined as:

$$\Delta s = s_2 - s_1 = \int_1^2 \left(\frac{dQ}{T} \right)_{\text{int,rev}} \quad [\text{J/kgK}]$$

Considering a cycle involving an **irreversible** process, 1-2, and an **internally reversible** process, 2-1:

$$\int_1^2 \frac{dq}{T} + \int_2^1 \left(\frac{dQ}{T} \right)_{\text{int,rev}} \leq 0 \text{ so } \int_1^2 \frac{dq}{T} + s_1 - s_2 \leq 0 \text{ and hence } s_2 - s_1 \geq \int_1^2 \frac{dq}{T}$$

The right hand side is the **entropy transfer** due to the process; there is **entropy generation** in addition to the process entropy. s_{gen} is due entirely to irreversibilities. The inequality shows that there is not only reversible entropy due to heat transfer, but extra entropy s_{gen} due to other disorder in the system.

The property of entropy is defined from the second law

$$dq_{\text{reversible}} = T \cdot ds$$

Consider this to be the heat transfer equivalent of

$$dw_{\text{reversible}} = -P \cdot dv$$

$dq_{\text{reversible}}$ is the minimum heat transfer required to get between two states.

$dq_{\text{reversible}} = Tds$ applies for any reversible process undergone by a closed system.

6. The best efficiency possible – the Carnot efficiency

The 2nd law implies that for a reversible heat engine operating between two reservoirs, the efficiency depends only on the temperature of the reservoirs. Since efficiency, $\eta = W_{\text{out}}/Q_{\text{hot}}$

$$= (Q_{\text{hot}} - Q_{\text{cold}})/Q_{\text{hot}}$$

$$= 1 - Q_{\text{cold}}/Q_{\text{hot}}$$

It follows that $Q_{\text{cold}}/Q_{\text{hot}}$ is a function of these two temperatures only.

Thermo topic 3: vapour power cycles

The choice of function is arbitrary. The one used is

$$T_{\text{cold}}/T_{\text{hot}} = Q_{\text{cold}}/Q_{\text{hot}}$$

in general $T/T_0 = Q/Q_0$, so that

$$\eta = 1 - T_{\text{cold}}/T_{\text{hot}}$$

state '0' is a reference state, and T scale must be absolute, i.e. K, because it is a ratio. This is a very important measure. It is determined by the temperature of each of the reservoirs. It shows that the wider the temperatures are apart the better the efficiency of your machine. The most efficient machine will exchange with absolute zero! This efficiency is called the Carnot efficiency, and represents the maximum work that can be obtained from a pair of thermal reservoirs.

Example: Steam plant, boiler temp = 700K and condenser temp = 300K, what is the Carnot efficiency?

This shows that the maximum ever achievable is quite low. This is the '100%' for this system. The elements of this power producing process are what is in a power generation station.

The lower temperature limit and associated maximum output give rise to the idea of 'availability' of energy. Raising the lower temperature limits the availability of the energy for work. This Carnot efficiency can be used to tell us how much you might get out of your system if you had a perfect process and tells us how available the high temperature thermal energy in the hot thermal reservoir is.

The vapour power cycle deals with the process of power production where:

- a. The working fluid is a condensable vapour
- b. The power cycle consists of a series of steady flow processes; 1-2 pumping, 2-3 boiling and heating; 3-4 turbine expansion for work; 4-1 cooling to condense back to liquid.

The analysis is simplified by the assumption that K.E and P.E changes are negligible compared with the change in enthalpy. SFEE for change of state between points: $Q + W = h_{\text{in}} - h_{\text{out}}$