UNIT 61: ENGINEERING THERMODYNAMICS

Unit code: D/601/1410

QCF level: 5

Credit value: 15

OUTCOME 2
INTERNAL COMBUSTION ENGINE PERFORMANCE

TUTORIAL No. 3 – HEAT ENGINE THEORY

2 **Be able to evaluate the performance of internal combustion engines**

Second law of thermodynamics: statement of law; schematic representation of a heat engine to show heat and work flow

Heat engine cycles: Carnot cycle; Otto cycle; Diesel cycle; dual combustion cycle; Joule cycle; property diagrams; Carnot efficiency; air-standard efficiency

Performance characteristics: engine trials; indicated and brake mean effective pressure; indicated and brake power; indicated and brake thermal efficiency; mechanical efficiency; relative efficiency; specific fuel consumption; heat balance

Improvements: turbo-charging; turbo-charging and inter-cooling; cooling system and exhaust gas heat recovery systems

When you have completed this tutorial, you should be able to do the following.

- Explain the basic idea behind the Second Law of Thermodynamics.
- Define the property called Entropy
- Define an Isentropic process.
- Solve basic problems involving isentropic expansions.
- Explain the Carnot Principle.

1. THE SECOND LAW OF THERMODYNAMICS

The Second Law of Thermodynamics is not something that can be written as a simple statement or formulae. It is a set of observations concerning the way that things flow or run as time progresses forward. It encompasses many observations such as "water normally flows from high levels to low levels" and "heat normally flows from hot to cold". In this module, you must concern yourself only with how the second law relates to heat engines and the efficiency of a heat engine.

In the context of heat engines, the second law may be summed as :

"No heat engine can be 100% efficient".

This should become apparent in the following sections.

1.1 HEAT ENGINES

Nearly all motive power is derived from heat using some form of heat engine. Here are some examples.

- Steam Power Plant.
- Gas Turbines.
- Jet Engines.
- Internal Combustion Engines.

A heat engine requires a source of hot energy. We get this by burning fossil fuel or by nuclear fission. The main sources of natural heat are solar and geothermal. In order to understand the basic theory, it might help to draw an analogy with a hydraulic motor and an electric motor. All motors require a high level source of energy and must exhaust at a low level of energy.

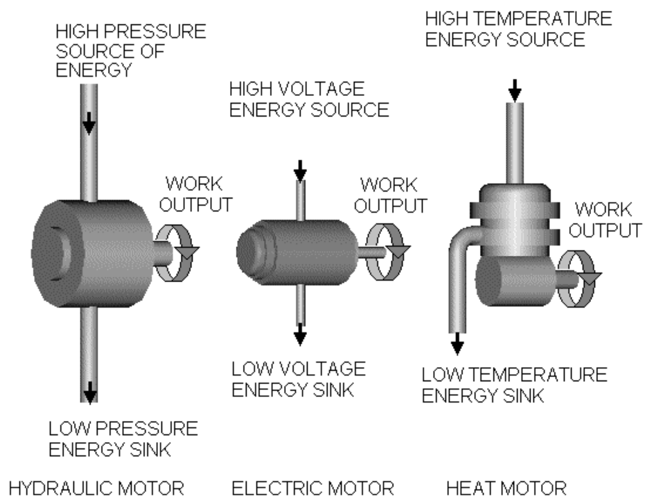

Figure 1

1.1.1 HYDRAULIC MOTOR

Fluid power is transported by the flow Q m^3/s. The energy contained in a volume Q m^3 of liquid at a pressure p is the flow energy given by the expression pQ. The hydraulic motor requires a source of liquid at a high pressure p_1 and exhausts at a lower pressure p_2.The energy supplied is p_1Q and some of this is converted into work. The energy in the low pressure liquid is p_2Q. For a perfect motor with no losses due to friction, the law of energy conservation gives the work output and efficiency as follows.

$$W_{out} = p_1Q - p_2Q = Q(p_1 - p_2)$$

$$\eta = \frac{W_{out}}{Energy\ input} = \frac{W_{out}}{p_1Q} = \frac{Q(p_1 - p_2)}{p_1Q} = \frac{(p_1 - p_2)}{p_1} = 1 - \frac{p_2}{p_1}$$

1.1.2 ELECTRIC MOTOR

Electric power is transported by the current. Electrical energy is the product of the charge Q Coulombs and the electric potential V Volts. The energy input at a high voltage is V_1Q and the energy exhausted at low voltage is V_2Q. For a perfect motor with no losses due to friction, the work output and efficiency are found from the law of energy conservation as follows.

$$W_{out} = V_1Q - V_2Q = Q(V_1 - V_2)$$

$$\eta = \frac{W_{out}}{Energy\ input} = \frac{W_{out}}{V_1Q} = \frac{Q(V_1 - V_2)}{V_1Q} = \frac{(V_1 - V_2)}{V_1} = 1 - \frac{V_2}{V_1}$$

1.1.3 HEAT MOTOR

Temperature is by analogy the equivalent of pressure and electric potential. In order to complete the analogy, we need something that is equivalent to volume and electric charge that transports the energy. It is not difficult to visualise a volume of liquid flowing through a hydraulic motor. It is not impossible to visualise a flow of electrons bearing electric charge through an electric motor. It is impossible to visualise something flowing through our ideal heat engine that transports pure heat but the analogy tells us there must be something so let us suppose a new property called ENTROPY and give it a symbol S. Entropy must have units of energy per degree of temperature or Joules per Kelvin. Entropy is dealt with more fully later on.

The energy supplied at temperature T_1 is T_1S and the energy exhausted is T_2S. For a perfect motor with no losses due to friction, the law of energy conservation gives the work output and efficiency as follows.

$$W_{out} = T_1S - T_2S = S(T_1 - T_2)$$

$$\eta = \frac{W_{out}}{Energy\ input} = \frac{W_{out}}{T_1S} = \frac{S(T_1 - T_2)}{T_1S} = \frac{(T_1 - T_2)}{T_1} = 1 - \frac{T_2}{T_1}$$

1.1.4 EFFICIENCY

In our perfect motors, the energy conversion process is 100% efficient but we may not have converted all the energy supplied into work and energy may be wasted in the exhaust. In the case of the electric motor, the lowest value for V_2 (so far as we know) is ground voltage zero, so theoretically we can obtain 100% efficiency by exhausting the electric charge with no residual energy.

In the case of the hydraulic motor, the lowest pressure we can exhaust to is atmospheric so we always waste some energy in the exhausted liquid.

In the case of the heat motor, the lowest temperature to which we can exhaust is ambient conditions, typically 300K, so there is a lot of residual energy in the exhaust. Only by exhausting to absolute zero, can we extract all the energy.

A model heat engine is usually represented by the following diagram. (Note that the word engine is usually preferred to motor).

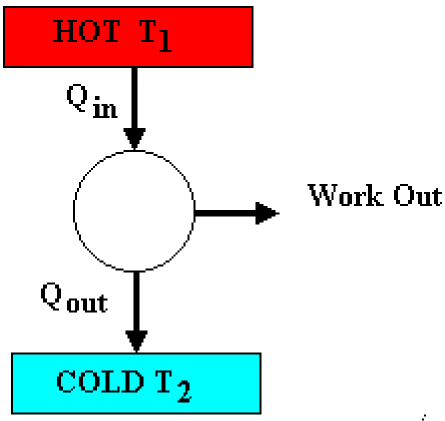

Fig. 2

The energy transfer from the hot source is Q_{in} Joules.
The energy transfer rate from the hot source is Φ_{in} Watts.

The energy transfer to the cold sink is Q_{out} Joules.
The energy transfer rate to the cold sink is Φ_{out} Watts.
The work output us W Joules.
The power output is P Watts.
By considering the total conservation of energy, it follows that the energy converted into work must be $W = Q_{in} - Q_{out}$ Joules or

$P = \Phi_{in} - \Phi_{out}$ Watts

The efficiency of any machine is the ratio Output/Input so the thermal efficiency of a heat engine may be developed as follows.

$$\eta_{th} = \frac{W}{Q_{in}} \qquad \mathrm{W} = Q_{in} - Q_{out} \qquad \eta_{th} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{int}}$$

In terms of energy transfer rates in Watts this is written as

$$\eta_{th} = 1 - \frac{\Phi_{out}}{\Phi_{in}}$$

It follows from our analogy that $Q_{in} = ST_1$ and $Q_{out} = ST_2$ and confirms $\eta = 1 - \frac{T_2}{T_1}$

SELF ASSESSMENT EXERCISE No. 1

1. A heat engine is supplied with 60 MW of energy and produces 20 MW of power. What is the thermal efficiency and the heat lost?
(Answers 33.3% and 40 MW)

2. A heat engine is supplied with 40 kJ of energy that it converts into work with 25% efficiency. What is the work output and the heat lost?
(Answers 10 kJ and 30 kJ)

1.3. PRACTICAL HEAT ENGINE CONSIDERATIONS

Let us consider how we might design a practical heat engine with a piston, connecting rod and crank shaft mechanism. Figure 3 shows how heat may be passed to a gas inside a cylinder causing it to expand. This pushes a piston and makes it do some work. This at first looks like a good way of converting heat into work but the problem is that it works only once and cannot convert heat into work continuously.

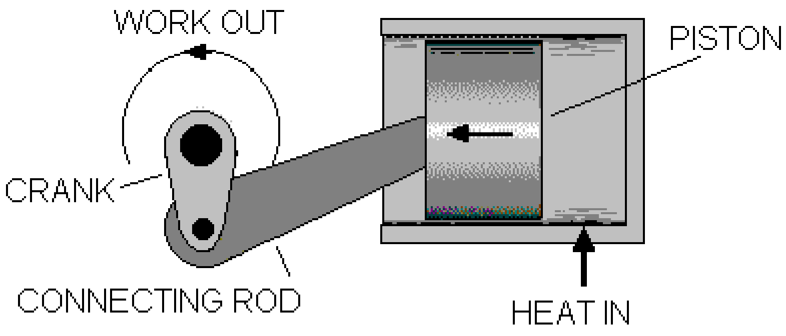

Figure 3

No practical heat engine has ever been invented that continuously converts heat directly into work as supposed in our ideal model. Practical heat engines use a working fluid such as gas or steam. A cycle of thermodynamic processes is conducted on the fluid with the end result being a conversion of heat into work.

First energy is given to the working fluid by use of a heat transfer at a hot temperature. Next we must convert as much of this energy as possible into work by allowing the fluid to expand. Our studies of polytropic expansions tell us that the pressure, volume and temperature all change as the gas or vapour gives up its energy as work. The pressure is vitally important to produce a motivating force on the piston.

Having extracted as much energy as possible from the working fluid, we must return it back to the starting condition in order to repeat the process. To do this, we must raise the pressure of the fluid back to the high level with some form of compression.

A simple reversal of the expansion process would return the fluid back to the original pressure and temperature. However, this would require us to give back all the work we got out so nothing is gained.

The only way we can return the fluid back to a high pressure with less work involves cooling it first. In fact, if it is to be heat engine, we must have a cooling process as indicated in our model.

We have deduced that a practical heat engine must meet the following criteria.

- It must produce work continuously.
- It must return the working fluid back to the same pressure and temperature at the beginning of every cycle.

A model of a practical engine is shown in Fig. 4. This indicates that we need four processes, heating, expansion, cooling and compression. This may be achieved practically using either closed system processes (as in a mechanism with a piston, connecting rod and crank shaft) or open system processes such as with a steam boiler, turbine, cooler and pump).

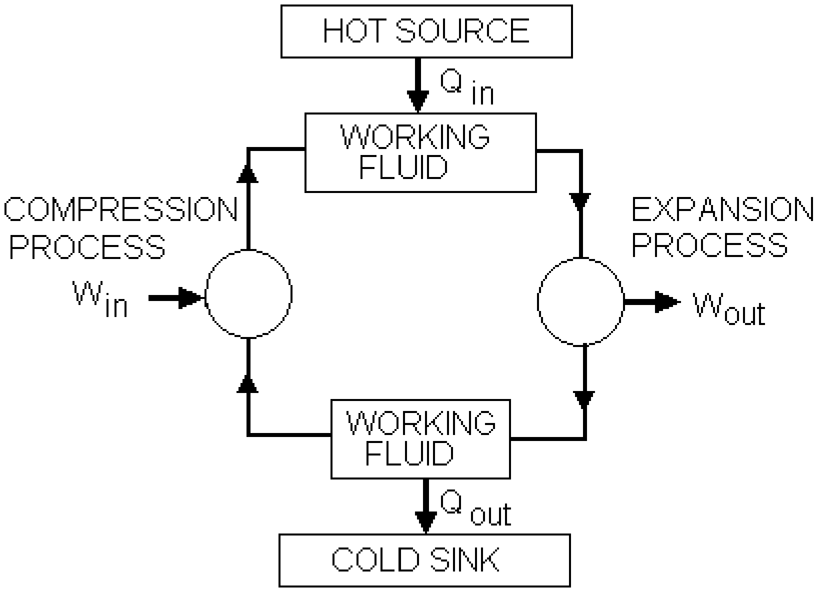

Figure 4

1.4 ENTROPY

We have just discovered that entropy is a property that governs the quantity of energy conveyed at a given temperature such that in our ideal heat engine, the energy is given by the expression Q = ST.

Entropy is a property that is closely associated with the second law of thermodynamics.

In thermodynamics there are two forms of energy transfer, work (W) and heat (Q). You should already be familiar with the theory of work laws in closed systems and know that the area under a pressure - volume diagram gives work transfer. By analogy there should be a property that can be plotted against temperature such that the area under the graph gives the heat transfer. This property is entropy and it is given the symbol S. This idea implies that entropy is a property that can be transported by a fluid. Consider a p-V and T-s graph for a reversible expansion (Fig. 5).

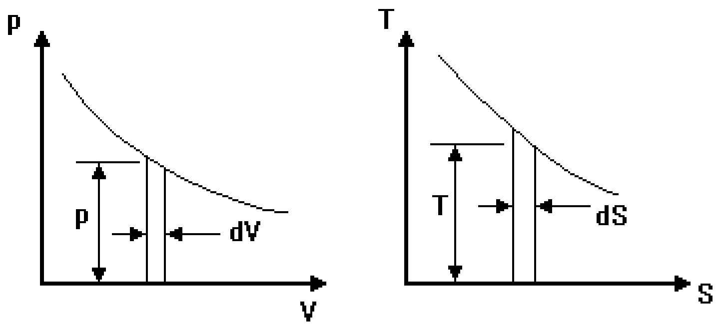

Fig.5

From the p-V graph we have $W = \int pdV$

From the T-S graph we have $Q = \int Tds$

This is the way entropy was developed for thermodynamics and from the above we get the following definition **dS = dQ/T**

The units of entropy are hence J/K. Specific entropy has a symbol s and the units are J/kg K

It should be pointed out that there are other definitions of entropy but this one is the most meaningful for thermodynamics. A suitable integration will enable you to solve the entropy change for a fluid process. For those wishing to do studies in greater depth, these are shown in appendix A.

Entropy values for steam may be found in your thermodynamic tables in the columns headed s_f, s_{fg} and s_g.

s_f is the specific entropy of saturated liquid.
s_{fg} is the change in specific entropy during the latent stage.
s_g is the specific entropy of dry saturated vapour.

1.4.1 ISENTROPIC PROCESSES

The word ISENTROPIC means constant entropy and this is a very important thermodynamic process. It occurs in particular when a process is reversible and adiabatic. This means that there is no heat transfer to or from the fluid and no internal heat generation due to friction. In such a process it follows that if dQ is zero then dS must be zero. Since there is no area under the T-S graph, the graph must be a vertical line as shown.

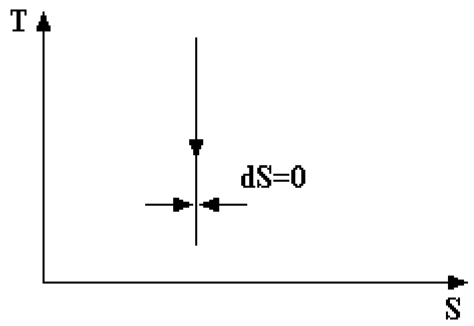

Fig. 6

There are other cases where the entropy is constant. For example, if there is friction in the process generating heat but this is lost through cooling, then the net result is zero heat transfer and constant entropy. You do not need to be concerned about this at this stage.

1.4.2 TEMPERATURE - ENTROPY (T-s) DIAGRAM FOR VAPOURS.

If you plot the specific entropy for saturated liquid (s_f) and for dry saturated vapour (s_g) against temperature, you would obtain the saturation curve. Lines of constant dryness fraction and constant pressure may be shown (Figure 7).

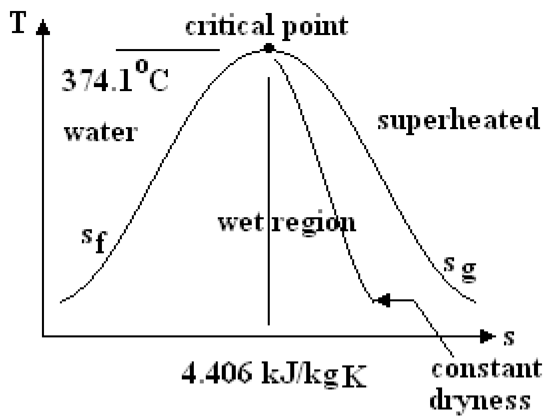

Fig. 7

1.4.3 SPECIFIC ENTHALPY-SPECIFIC ENTROPY (h-s) DIAGRAM.

This diagram is especially useful for steady flow processes (figure 8). The diagram is obtained by plotting h_g against s_g and h_f against s_f to obtain the characteristic saturation curve. The two curves meet at the critical point C. Lines of constant pressure, temperature and dryness are superimposed on the diagram. This is an extremely useful chart and it is available commercially. If any two coordinates are known, a point can be obtained on the chart and all other relevant values may be read off it. h –s charts are especially useful for solving isentropic processes because the process is a vertical line on this graph.

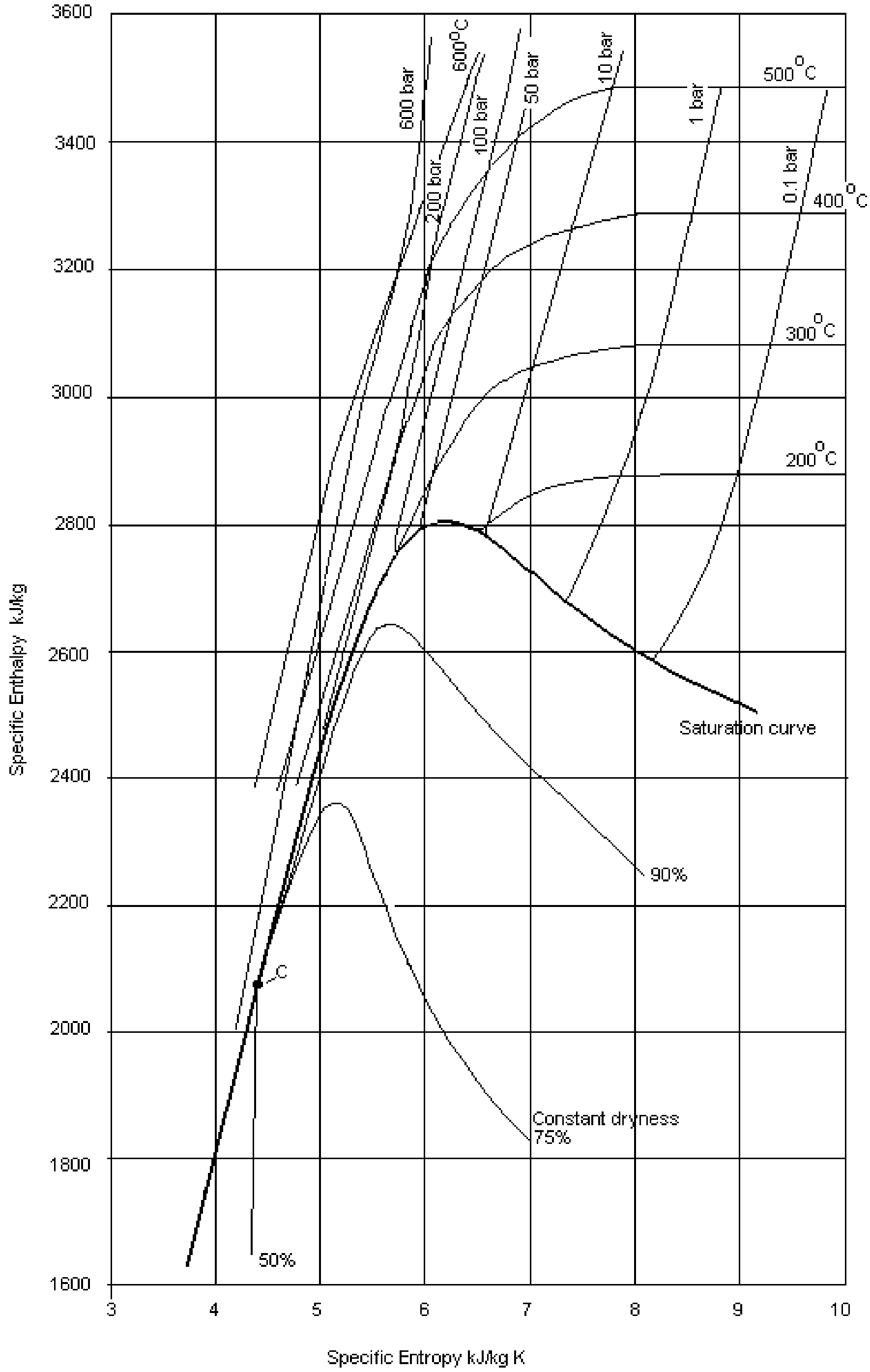

Fig. 8

Entropy values can be used to determine the dryness fraction following a steam expansion into the wet region when the process is isentropic. This is a very important point and you must master how to do this in order to solve steam expansion problems, especially in the following tutorials where steam cycles and refrigeration cycles are covered. The following examples show how this is done.

WORKED EXAMPLE No.1

Steam at 2 bar and 150°C is expanded reversibly and adiabatically to 1 bar. Calculate the final dryness fraction and the enthalpy change.

SOLUTION

Let suffix (1) refer to the conditions before the expansion and (2) to the conditions after.

h_1 at 2 bar and 150°C = 2770 kJ/kg

s_1 at 2 bar and 150°C is 7.280 kJ/kg K.

Because the process is adiabatic and reversible, the entropy remains the same.

s_2 at 1 bar and assumed wet is $s_f + xs_{fg} = s_1$

$7.280 = 1.303 + x(6.056)$

$x = 0.987$

h_2 at 1 bar and 0.987 dry = $h_f + x\,h_{fg}$

$h_2 = 417 + 0.987(2258) = 2645.6$ kJ/kg

$\Delta h = 2645.6 - 2770 = -124.4$ kJ/kg

Being ale to solve the changes in enthalpy enable us to apply the first law of thermodynamics to solve problems with steam turbines. The next example shows you how to do this.

WORKED EXAMPLE No.2

A steam turbine expands 60 kg/s from 40 bar and 300°C to 4 bar reversibly and adiabatically (isentropic). Calculate the theoretical power output.

SOLUTION

$\Phi + P = \Delta E$ per second (SFEE)

The process is adiabatic. $\Phi = 0$ and the only energy term to use is enthalpy.

$P = \Delta H$ per second.

h_1 at 40 bar and 300°C = 2963 kJ/kg

s_1 at 40 bar and 300°C is 6.364 kJ/kg K.

s_2 at 4 bar and assumed wet is $s_f + xs_{fg} = s_1$

$6.364 = 1.776 + x(5.121)$

$x = 0.896$

h_2 at 4 bar and 0.896 dry $= h_f + x\,h_{fg}$

$h_2 = 605 + 0.896(2134) = 2517$ kJ/kg

$P = \Delta H$ per second $= 60(2517-2963) = -26756$ kW (out of system)

SELF ASSESSMENT EXERCISE No.2

1. A turbine expands 40 kg/s of steam from 20 bar and 250^oC reversibly and adiabatically to 0.5 bar. Calculate the theoretical power output.
(Answer 25.2 MW)

2. A turbine expands 4 kg/s of steam from 50 bar and 300^oC reversibly and adiabatically to 0.1 bar. Calculate the theoretical power output.
(Answer 3.8 MW)

3. A turbine expands 20 kg/s of steam from 800 bar and 400^oC reversibly and adiabatically to 0.2 bar. Calculate the theoretical power output.
(Answer 11.2 MW)

4. A turbine expands 1 kg/s of steam reversibly and adiabatically. The inlet conditions are 10 bar and dry saturated. The outlet pressure is 3 bar. Calculate the theoretical power output.
(Answer 218.5 MW)

2. THE CARNOT PRINCIPLE

A man called Sadi Carnot deduced that if the heat transfers from the hot reservoir and to the cold sump were done at constant temperature (isothermal processes), then the efficiency of the engine would be the maximum possible.

The reasoning behind this is as follows. Consider heat being transferred from a hot body A to a slightly cooler body B. The temperature of body A falls and the temperature of body B rises until they are at the same temperature.

If body B is now raised in temperature by heat transfer from the surroundings, it becomes the hotter body and the heat flow is reversed from B to A. If body A returns to its original temperature then the net heat transfers between A and B is zero. However body B is now hotter than its original temperature so there has been a net heat transfer from the surroundings. The heat transfer process is hence not reversible as external help was needed to reverse the process.

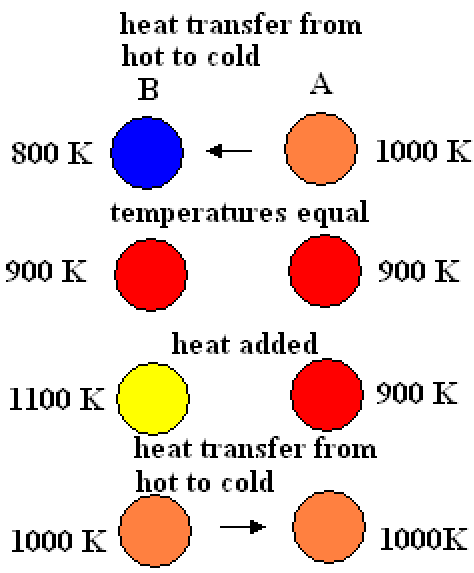

Figure 9

If it were possible to transfer heat with no temperature difference from A to B then it could be reversed with no external help. Such a process is an ISOTHERMAL process. Isothermal heat transfer is possible, for example evaporation of water in a boiler is isothermal.

Carnot devised a thermodynamic cycle using isothermal heat transfers only so by definition, the efficiency of this cycle is the most efficient any engine could be operating between two temperatures. Engine cycles are covered in the next tutorial but the following shows how the Carnot cycle might be conducted. In practice, it is not possible to make this cycle work.

2.1.1 CLOSED SYSTEM CARNOT CYCLE.

The cycle could be conducted on gas or vapour in a closed or open cycle. The cycle described here is for gas in a cylinder fitted with a piston. It consists of four closed system processes as follows.

1 to 2. The fluid is compressed isentropically. Work is put in and no heat transfer occurs.

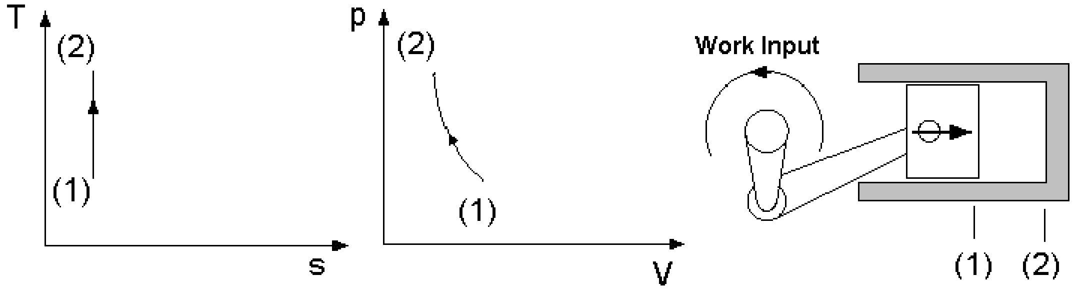

Fig. 10

2 to 3. The fluid is heated isothermally. This could only occur if it is heated as it expands so there is work taken out and heat put in.

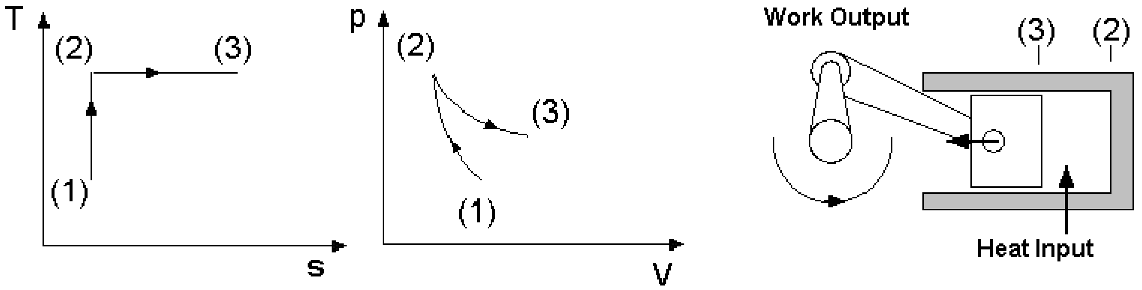

Fig. 11

3 to 4. The fluid continues to expand isentropically with no heat transfer. Work output is obtained.

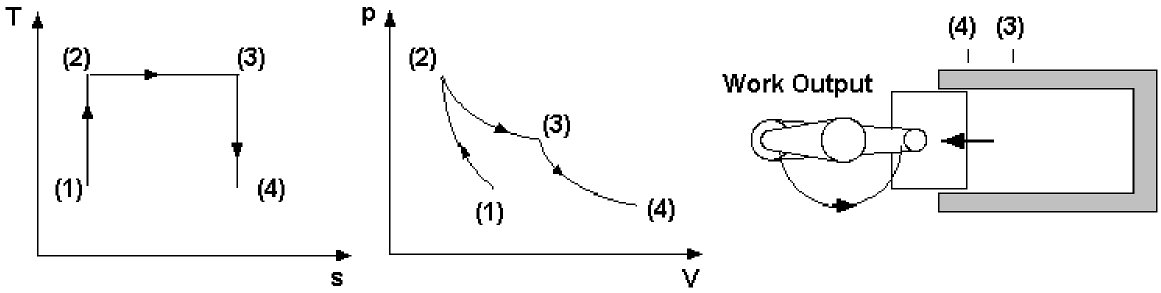

Fig.12

4 to 1 The fluid is cooled isothermally. This can only occur if it cooled as it is compressed, so work is put in and heat is taken out. At the end of this process every thing is returned to the initial condition.

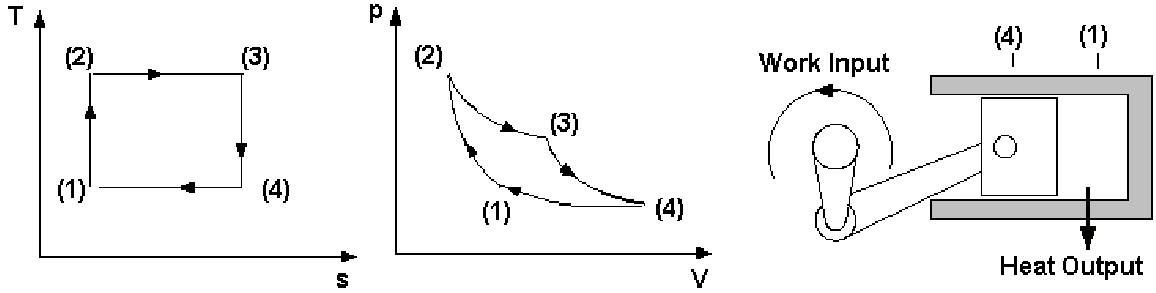

Fig.13

The total work taken out is W_{out} and the total work put in is W_{in}.

To be an engine, W_{out} must be larger than W_{in} and a net amount of work is obtained from the cycle. It also follows that since the area under a p-V graph represents the work done, then the area enclosed by the p-V diagram represents the net work transfer. It also follows that since the area under the T-s graph is represents the heat transfer, and then the area enclosed on the T-s diagram represents the net heat transfer. This is true for all cycles and also for real engines.

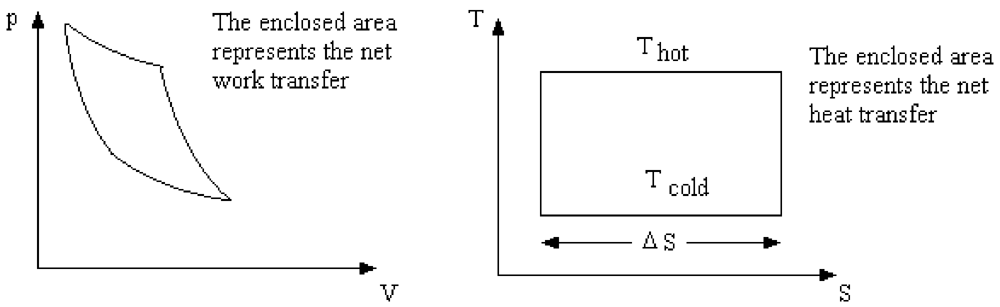

Fig.14

Applying the first law, it follows $\mathbf{Q_{nett} = W_{nett}}$

For isothermal heat transfers $Q = \int T\,ds = T\Delta S$ since T is constant.

The efficiency would then be given by $\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{T_{cold}\Delta s_{cold}}{T_{hot}\Delta s_{hot}}$

It is apparent from the T-s diagram that the change in entropy Δs is the same at the hot and cold temperatures. It follows that $\eta_{th} = 1 - \frac{T_{cold}}{T_{hot}}$

This expression, which is the same as that used for the ideal model, gives the CARNOT EFFICIENCY and it is used as a target figure that cannot be surpassed (in fact not even attained).

WORKED EXAMPLE No.3

A heat engine draws heat from a combustion chamber at 300°C and exhausts to atmosphere at 10°C. What is the maximum possible thermal efficiency that could be achieved?

SOLUTION

The maximum efficiency possible is the Carnot efficiency. Remember to use absolute temperatures.

$$\eta_{th} = 1 - \frac{T_{cold}}{T_{hot}} = 1 - \frac{273 + 10}{273 + 300} = 1 - \frac{283}{573} = 0.505 \text{ or } 50.6\%$$

SELF ASSESSMENT EXERCISE No.3

1. A heat engine works between temperatures of 1100° C and 120°C. It is claimed that it has a thermal efficiency of 75%. Is this possible?
   (Answer the maximum efficiency cannot exceed 71%)

2. Calculate the efficiency of a Carnot Engine working between temperatures of 1200°C and 200° C.
   (Answer 67.9%)