UNIT 6 HEAT ENGINES - SECOND LAW OF THERMODYNAMICS

Structure

6.1 INTRODUCTION

Although the first law of thermodynamics explains clearly the relationship existing between heat and work it does not deal with the actual conversion of work to heat and vice versa. These conversions are indeed very important in engineering practice. In this unit the working principles of a few devices that actually convert heat to work and work to heat are explained. Also explained are the performance characteristics of such devices. It is further explained that the performance limits are bound by the constraints imposed by the second law of thermodynamics.

Objectives

After a study of this Unit you should be able to

* explain the concept of heat engines,
* distinguish between direct and reversed heat engines,
* calculate the efficiency of a direct heat engine and COP of a reversed heat engine, and
* state, explain and apply the Kelvin-Planck and Clausius statements of the second law of thermodynamics.

6.2 LIMITATIONS OF THE FIRST LAW OF THERMODYNAMICS

The First Law of Thermodynamics has certain limitations. Although it gives the relationship that exists between heat and work it does not say anything about the conversion of heat to work and vice versa. For example, a thermodynamic cycle in which the heat transferred to the system is completely converted to an equivalent magnitude of work does not violate the first law of thermodynamics, but experience shows that such a cycle is an impossibility.

Now, suppose several hypothetical processes have to be analysed for their feasibility or otherwise and determine the direction of all feasible processes. This task cannot be comprehensively and conclusively accomplished with the help of the first law of thermodynamics alone. As an example let two systems at different temperatures be brought in communication with each other. As a result of this communication there occurs a non-cyclic process of heat interaction between the two systems. This is a natural process that occurs to bring about equilibrium between the two communicating systems. It is spontaneous in nature and the direction of the process is fixed (heat is transferred from the high temperature system to the low temperature system only). However, in such a situation of two systems at different temperatures being brought in communication with each other, if it is said that heat is spontaneously transferred from the low temperature system to the high temperature system it does not violate the first law. All that first law wants to make sure is that the magnitude of heat transferred from the low temperature system is equal to the magnitude of heat transferred to the high temperature system so that energy is conserved. But such a process is impossible.

To cite a second example, consider air flowing steadily through a horizontal, insulated, variable area duct. Suppose the measurements made at two different locations A and B along the length of the duct give the following information:

Location	Pressure (kPa)	Enthalpy (kJ/kg)	Velocity (m/s)
A	120	50	150
B	100	30	250

Under these conditions what would be the direction of the flow of air - is it from A to B or from B to A ?. According to the first law of thermodynamics both directions are possible.

Suppose the flow is assumed to be from A to B. From SFEE,

$$Q - W_x = \Delta\left(h + \frac{V^2}{2} + gZ\right) \quad \text{where } Q = 0,\ W_x = 0\ \&\ \Delta gZ = 0$$

$$\therefore\ \Delta\left(h + \frac{V^2}{2}\right) = 0 \text{ or } h_B - h_A = \left(\frac{V_A{}^2 - V_B{}^2}{2}\right)$$

By substituting the values for each term in the above relation, taking due care of the units of each quantity, we find that $h_B - h_A = -20$ kJ / kg and also

$$\left(\frac{V_A{}^2 - V_B{}^2}{2}\right) = -20 \text{ kJ/ kg.}$$

Thus, if the direction of flow is assumed to be from A to B, the first law is satisfied. Does this mean that in actual practice the flow is from A to B ? Not necessarily because even when the flow is assumed to be from B to A we arrive at the same result that the first law is satisfied. In such a case the first law reduces to $h_A - h_B = \left(V_B{}^2 - V_A{}^2\right) / 2$, the value of each side being equal to + 20 kJ/kg. Thus, according to the first law of thermodynamics both directions of flow are possible but in actual practice the flow is possible under the given conditions in only one particular direction. The possible direction is only from B to A and not from A to B. This can be confirmed by the second law analysis using the 'principle of increase of entropy ' (discussed later in Unit 8 on Entropy), according to which the adiabatic flow is possible only in the direction of increase of entropy.

In many chemical reactions it is very essential to know the direction of their occurrence. As an example, suppose the simple chemical reaction represented by $2\ CO + O_2 \rightarrow 2\ CO_2$ is considered. Experience shows that this reaction cannot take place in the forward direction beyond a certain pressure and temperature. Yet the first law of thermodynamics does not impose any such restriction on the process.

Many such hypothetical processes can be cited as examples which although do not violate the first law of thermodynamics in principle, cannot proceed in the cited direction.

It is the second law of thermodynamics (and its corollaries) which not only deals with all aspects of conversion of heat to work and vice versa but also throws light on the criteria for the feasibility of processes and their directions. For a process, cyclic or non-cyclic, to be feasible, in addition to the first law of thermodynamics, the second law of thermodynamics must also be satisfied. Before the second law of thermodynamics is stated a few practical devices that convert heat to work and vice versa are considered here.

6.3 A STEAM POWER PLANT

A schematic of the steam power plant is given in Fig.6.1. A steady flow of water, at high pressure, enters the boiler. Heat transferred (Q_1) from the combustion products (generated by burning fuel and air in a furnace and led to the boiler) causes the water to boil. The high pressure steam thus generated leaves the boiler steadily to enter the turbine.

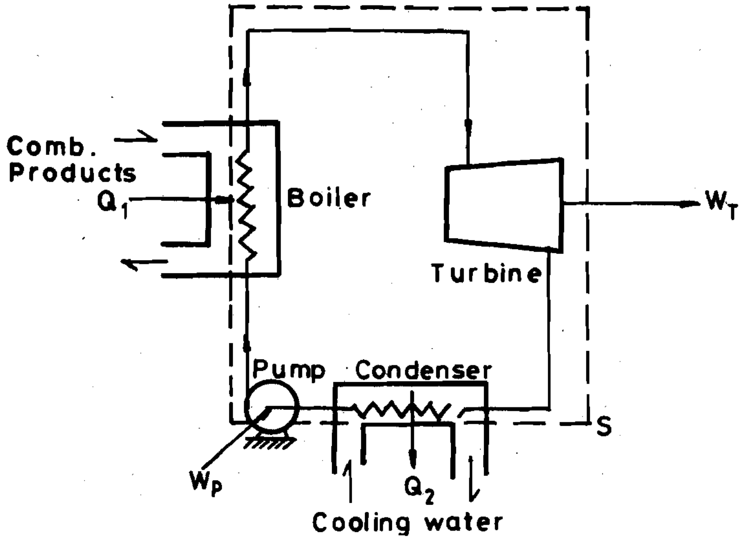

Fig.6.1 : Schematic of steam power plant

The steam expands in the turbine to deliver the shaft work (W_T). The low pressure steam leaving the turbine enters the water cooled condenser where it is condensed because of heat transfer (Q_2) to the cooling water. A steady flow of condensate (water) enters the pump. To complete the cycle of events the pump delivers water at high pressure to the boiler. The work supplied to the pump (W_P) is usually very small in comparison to other interactions and hence unless otherwise mentioned it is customary to neglect the magnitude of this work in the analysis of the steam power plant.

Although each of the four devices in the plant (Boiler, Turbine, Condenser and Pump) is a steady flow device, all these four devices together enable the water to undergo a thermodynamic cycle. The system (water) that undergoes the thermodynamic cycle is shown enclosed by the boundary S in Fig.6.1. A careful perusal of the figure reveals that during the cycle there are four interactions across this system boundary namely, (i) Q_1, the heat transfer to the system , (ii) W_T, the work output from the system, (iii) Q_2, the heat transfer from the system and (iv) W_P, the work input to the system. By the sign convention employed in this book while Q_1 and W_T are positive Q_2 and W_P are negative.

Applying the first law of thermodynamics to the system executing the cycle,

$$Q_1 + \left(-Q_2\right) = W_T + \left(-W_P\right)$$

or

$$Q_1 - Q_2 = W_T - W_P. \tag{6.1}$$

The performance of any device is usually evaluated by its **efficiency** (η) which is defined as the ratio of the output to the input (or the ratio of **what we want to what we are paying for**). The output from the steam power plant is the net work (W_T - W_P) and the input is the heat transfer in the boiler (Q_1). Hence, the **thermal efficiency** or the **cycle efficiency** of the plant is given by,

$$\eta = \frac{(W_T - W_P)}{Q_1} \tag{6.2}$$

Also, in a thermodynamic cycle,from the first law of thermodynamics, net work (W_T - W_P), is equal to net heat transfer ,(Q_1 - Q_2). Therefore it is obvious from equations (6.1) and (6.2) that the efficiency of the cycle is also given by

$$\eta = \frac{(Q_1 - Q_2)}{Q_1} = 1 - \left(\frac{Q_2}{Q_1}\right) \tag{6.3}$$

Caution: It is worth recalling here that in equations (6.1) to (6.3) the directions of heat and work interactions are already included and hence while using these equations for computations, only the magnitudes of the interactions have to be used. This is illustrated in Example 6.1.

In a steam power plant while the work output is around (1/3) Q_1 the heat rejected in the condenser is around (2/3) Q_1. The heat rejected goes as waste to the cooling water which cannot be recovered. It can hence be said that all the heat transfer (Q_1) to this thermodynamic cycle is not completely converted to work. In other words it may be stated that no steam power plant can be 100 % efficient. This fact is highly unpalatable to an engineer who would want to have all the heat transfer converted to work.

On a second thought one may feel that in a steam power plant all the heat transfer to the system could have been converted to work provided no heat was rejected in the condenser. This would be possible if the steam discharged from the turbine, without being condensed in the condenser, is directly compressed by some means and made to enter the boiler as high pressure liquid. Such a process is practically impossible (theoretically it can be shown that in such a process work required will be more than the work output of the turbine and hence the plant, as a whole, cannot produce any net positive work at all) and experience has shown that the plant will never operate without the condenser. Hence Q_2 is unavoidable.

Before generalising the observations made on the steam power plant, the working of a closed cycle gas turbine power plant will be explained next.

6.4 CLOSED CYCLE GAS TURBINE POWER PLANT

Figure 6.2 shows the schematic of a closed cycle gas turbine power plant. Compressed air from the compressor is heated steadily in the heater by the heat transfer (Q_1) from the combustion products. High temperature high pressure air is then expanded steadily as it flows through a turbine. As a result of this expansion process the turbine delivers shaft work (W_T) and the air leaves the turbine at low pressure and low temperature. The low pressure air from the turbine is then cooled in the cooler by heat transfer (Q_2) to the cooling water passing through the cooler. Air from the cooler in turn is sucked in to the compressor to be compressed and delivered to the heater again. The turbine and the compressor are normally mounted on the same shaft so that the work required for compression (W_C) is provided directly by the turbine. The net work output of the plant is thus (W_T - W_C).

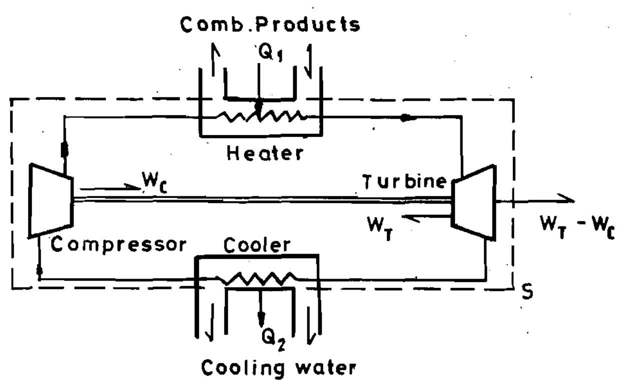

Fig.6.2 : Schematic of closed cycle gas turbine power plant

As in the steam power plant it can be seen that air (inside the boundary S in Fig.6.2) in the closed cycle gas turbine power plant undergoes a cyclic process with two heat interactions and two work interactions. Hence equations (6.1) to (6.3), with W_P being replaced by W_C, hold good in this case also. It may be pointed out here that in the closed cycle gas turbine power plant, unlike in the steam power plant, W_C is of a sizable magnitude and hence can never be neglected in computations.

It is evident that the closed cycle gas turbine power plant, working in a thermodynamic cycle, is also unable to convert all the heat transfer to the system (Q_1) to net work (W_T - W_C). Q_2 is always rejected as waste to the surroundings. In the absence of the cooler, where Q_2 is rejected, the plant will not operate.

All thermodynamic cycles, delivering net work, give the same information and hence it can be generalised that **it is impossible to have a thermodynamic cycle in which all the heat transferred to the system is completely converted to work**; in other words, it is impossible for any device operating in a thermodynamic cycle to operate with 100 % efficiency. As will be seen later this fact forms the basis for the Kelvin - Planck statement of the second law of thermodynamics.

SAQ 1

Make an attempt to understand the operation of an open cycle gas turbine power plant. Identify the major difference between this plant and the steam power plant or a closed cycle gas turbine power plant.

6.5 REFRIGERATOR

Figure 6.3 shows the schematic of a domestic refrigeration system that operates in a thermodynamic cycle. The working substance that undergoes the cycle is referred to as the 'refrigerant'. Heat (Q_2) is transferred to the refrigerant in the evaporator to maintain at a low temperature (In actual practice this is the heat transferred from the articles stored in the refrigerator to the refrigerant flowing through the coils across the freezer situated inside the cabinet at the top).

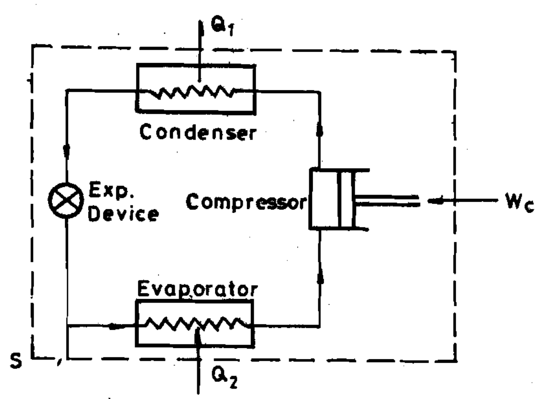

Fig.6.3 : Schematic of a refrigerator/heat pump

As a consequence of this heat transfer, the liquid refrigerant coming from the expansion device gets vaporised in the evaporator and the low pressure, low temperature vapour leaves the evaporator to enter the compressor. Work W_C supplied to the compressor from electrical mains increases the pressure and temperature of the refrigerant vapour as it passes through the compressor. This compressed vapour passes to the air cooled condenser (situated behind but outside the refrigerator cabinet) where it is steadily condensed to liquid at high pressure. In the condenser, heat (Q_1) is transferred from the refrigerant to the surrounding air which is at a temperature higher than the temperature inside the refrigerator cabinet. The high pressure liquid refrigerant is then throttled through an expansion device before it enters the evaporator as low pressure low temperature liquid (actually after throttling the refrigerant will be a mixture of liquid and vapour with a high percent of the former) to complete the cycle of events. It can be noted that heat is transferred to the refrigerant at low temperature while heat is rejected from the refrigerant at a higher temperature and work is supplied to the system. Thus all the interactions are opposite in direction to those in either the steam power plant or the closed cycle gas turbine power plant.

In the type of refrigerator described above it has been possible to transfer heat from a low temperature region to a high temperature region only because of the work input to the compressor. In the absence of the compressor it would be impossible to carry out the above heat transfer. This fact embodies the Clausius' statement of the second law of thermodynamics.

It has been explained earlier that the performance of a work producing cycle is evaluated by its efficiency. However, it is customary to evaluate the performance of a work absorbing cycle, such as the refrigerator, by its COEFFICIENT OF PERFORMANCE which is abbreviated as COP. Similar to efficiency, COP is also the ratio of what we want to what we are paying for.

Application of the first law of thermodynamics to the refrigeration cycle gives,

$$\sum Q = \sum W \tag{6.4}$$

For the refrigerant undergoing the cycle, Q_2 the heat interaction at the evaporator (what is wanted for providing refrigeration) is positive, Q_1 the heat interaction at the condenser is negative and the work input to the compressor W_C (what is to be supplied) is negative. Hence from equation (6.4)

$$-Q_1 + Q_2 = -W_C$$

or

$$Q_1 - Q_2 = W_C \tag{6.5}$$

By definition

$$(\text{COP})_{\text{Ref}} = \frac{Q_2}{W_C} \tag{6.6}$$

or

$$(\text{COP})_{\text{Ref}} = \frac{Q_2}{(Q_1 - Q_2)} \tag{6.7}$$

Caution: In equations (6.5) to (6.7) the directions of heat and work interactions are already incorporated. Thus while using these equations for computations, only the magnitudes of the interactions will have to be considered.

6.6 HEAT PUMP

A refrigerator provides a low temperature region by transferring continuously the heat from the region to be cooled to the surroundings at a relatively high temperature. A refrigerator, or a window air-conditioner which also operates on a cycle similar to that of the domestic refrigerator, is a necessity in hot climates. In cold climates it may be necessary to provide a relatively high temperature region like a heated room. This can be achieved by a HEAT PUMP, whose operation is exactly similar to that of a refrigerator. Figure 6.3 is also schematic of a heat pump. In a heat pump one is interested in Q_1, the heat transfer to the high temperature region. To maintain the high temperature region heat is continuously transferred to it from the low temperature surroundings with the help of work supplied to the compressor. It may be imagined that a domestic refrigerator can be used as a heat pump by installing it in such a manner that with its door open the cabinet is exposed to the cold weather outside the room and the condenser coil is exposed to the room air to be heated. It is needless to mention again that a heat pump is also a work absorbing cycle.

While equation (6.5) holds good for a heat pump also its coefficient of performance is given by,

$$(\text{COP})_{\text{hp}} = \frac{Q_1}{W_C} = \frac{Q_1}{(Q_1 - Q_2)} \tag{6.8}$$

It may be deduced from equations (6.7) and (6.8) that

$$(\text{COP})_{\text{hp}} = 1 + (\text{COP})_{\text{Ref}} \tag{6.9}$$

Example 6.2 is meant to explain how computations have to be made while dealing with refrigerators and heat pumps.

6.7 HEAT ENGINE

Many thermodynamicists prefer to define a HEAT ENGINE as **a continuously operating thermodynamic system across the boundary of which there are only heat and work interactions.** In other words a heat engine is nothing but a system undergoing a thermodynamic cycle.

However, the concept of heat engine does not put a restriction on the directions of heat and work transfers. Thus a refrigerator and a heat pump cycle in which the heat and work interactions are in opposite directions to those in the earlier two cases are also heat engines. DIRECT HEAT ENGINE and REVERSED HEAT ENGINE are the two terms generally used to distinguish between the work producing and work absorbing cycles.

6.7.1 Direct Heat Engine

A heat engine which delivers work, by receiving heat from a high temperature reservoir and rejecting heat to a low temperature reservoir, is called a DIRECT HEAT ENGINE (A reservoir is a system at constant temperature). Accordingly the steam power plant and the closed cycle gas turbine power plant are Direct Heat Engines.

6.7.2 Reversed Heat Engine

A heat engine which transfers heat from a low temperature reservoir to a high temperature reservoir, by receiving work from its surroundings, is a REVERSED HEAT ENGINE. Accordingly, the refrigerator and the heat pump are Reversed Heat Engines.

6.7.3 Symbolic Representation of Heat Engines

By now it is very clear that a direct heat engine is one in which the working substance undergoes a thermodynamic cycle to produce work while heat is transferred to the working substance from a high temperature system and the working substance in turn transfers out heat to a low temperature system. Thus, it can be said that a heat engine operates between two systems at different temperatures. The HIGH TEMPERATURE SYSTEM AT A FIXED TEMPERATURE with which the heat engine engages in heat transfer is usually referred to as HIGH TEMPERATURE RESERVOIR (or as a SOURCE by a few authors). Similarly the LOW TEMPERATURE SYSTEM AT FIXED TEMPERATURE with which the heat engine engages in heat transfer is usually called a LOW TEMPERATURE RESERVOIR (or as a SINK by a few authors).

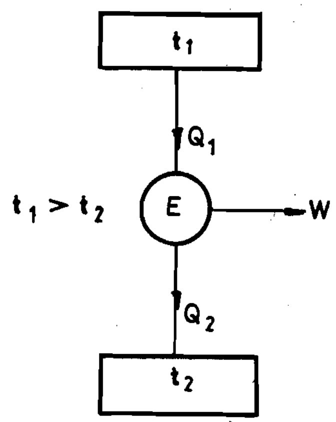

Fig.6.4 :Symbolic representation of direct heat engine

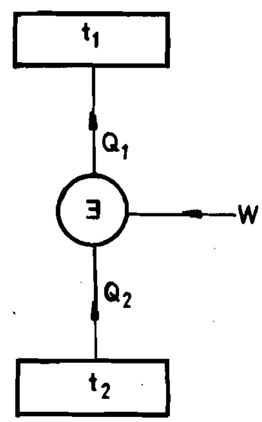

Fig.6.5 : Symbolic representation of a reversed heat engine

Figure 6.4 shows how a direct heat engine can be represented symbolically. In this figure the circle with the letter *E* at the center represents the heat engine. The top block represents the high temperature reservoir at t_1. The bottom block represents the low temperature reservoir at t_2. The arrows indicate the directions of heat and work interactions. While Q_1 is the magnitude of heat interaction with the high temperature reservoir, Q_2 is the magnitude of heat interaction with the low temperature reservoir and *W* is the magnitude of the net work interaction. Similarly Fig.6.5 shows the symbolic representation of a reversed heat engine, either a refrigerator or a heat pump.

SAQ 2

A heat engine, either direct or reversed, is nothing but a system undergoing a thermodynamic cycle. Is this statement true or false ?

SAQ 3

Assume that the efficiency of the heat engine shown in Fig.6.4 is 0.5. If this engine operates as a refrigerator between the same two temperatures with the same magnitudes of heat and work interactions what would its COP be ? Identify the correct answer from among the following: (a) 2, (b) 1, (c) -1 , (d) 0.

SAQ 4

Consider the reversed heat engine in Fig.6.5. Here, while Q_1 and W are negative, Q_2 is positive. Hence its COP as a refrigerator, according to equation (6.6), is negative and its COP as a heat pump ,according to equation (6.8), is +ve. Do you agree with this ?

6.8 SECOND LAW OF THERMODYNAMICS

Based on the observations made hitherto we are now in a position to state the second law of thermodynamics. The two classical statements of the second law are given below:

6.8.1 Kelvin-Planck Statement

It is impossible for a device operating in a thermodynamic cycle to produce work while having heat interaction with a single system at fixed temperature.

Mathematically it may be stated as $\oint\limits_{\substack{\text{single const.}\\ \text{temp. system}}} \delta W \leq 0$

This statement of the second law is made with respect to the observations made on the direct heat engines. In brief it means that a heat engine shown symbolically in Fig.6.6 cannot operate. In such a case there is no heat rejection and hence according to first law, $Q_1 = W$ and therefore the efficiency of the engine , which is given by the ratio W/Q_1, is equal to

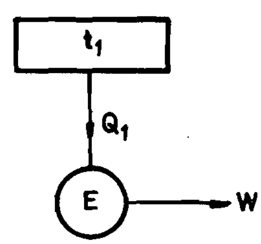

Fig. 6.6 : Impossible direct heat engine (PMM II or 100% efficient engine)

100 %. Such an engine which is impossible is referred to as PERPETUAL MOTION MACHINE OF THE SECOND KIND (PMM II). (Incidentally a PMM I is a device that contradicts the first law of thermodynamics. It is a continuously operating adiabatic system that produces positive work). Thus the gist of the Kelvin-Planck statement is that a 100 % efficient heat engine or a PMM2 is an impossibility. In other words no heat engine can completely and continuously convert heat to work. It is worth pointing out here that although it is impossible to completely and continuously convert heat to work, experiments have shown that it is possible to convert work transferred to a system to an equal quantity of heat transfer out of it. It is because of this directional dependence of the conversion of one

to another a great effort was made in the earlier chapters to clearly distinguish between the heat and work interactions.

6.8.2 Clausius' Statement

It is impossible for any device operating in a thermodynamic cycle to accomplish as its sole effect the transfer of heat from a low temperature region to a high temperature region. This statement is made with respect to the observations made that a reversed heat engine cannot operate unless work is supplied to it from outside. Thus a heat pump shown symbolically in Fig.6.7 is an impossibility. If such a heat pump were to be

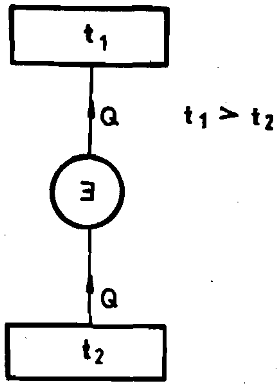

Fig.6.7 : Impossible reversed heat engine (heat pump with infinite COP)

possible the COP ($= Q / W$) of the heat pump would be infinite as $W = 0$. Thus, the gist of the Clausius' statement is that no reversed heat engine (a refrigerator or a heat pump) can operate without work being supplied to it. In other words it is impossible to have a heat pump of infinite COP.

The second law derives its validity through experimental evidence only. Until this day it has not been possible to construct any practical device that contradicts the second law. Thus, every experiment, directly or indirectly, verifies the second law.

The two statements of the second law although appear to be different, in reality the two are equivalent. As a matter of fact they have to be so. This is elaborated below:

6.8.3. Equivalence of Kelvin-Planck and Clausius Statements

A simple method by which the equivalence can be shown is by making use of the fact that any two statements are equivalent if the violation of one statement implies the violation of the other and vice versa. Let it now be assumed that a heat pump violates the Clausius statement. As shown in Fig. 6.8 let this heat pump Ǝ transfer heat from low temperature reservoir at t_2 to the high temperature reservoir at t_1 without any work being supplied to it. Let the heat interaction with the reservoir at t_2 be Q_2 and that with the reservoir at t_1 be Q_1. Ǝ is working in a cycle. Hence, by the first law $\sum Q = \sum W$ for this reversed engine. As per the assumption made, $\sum W = 0$. Therefore $\sum Q = 0$, and hence, $Q_2 - Q_1 = 0$,or in other words $Q_1 = Q_2$. Assume now that a direct heat engine E, which works in accordance with the Kelvin-Planck statement, operates between the same two temperature limits and that heat supplied to it, from the reservoir at t_1, is Q_1.

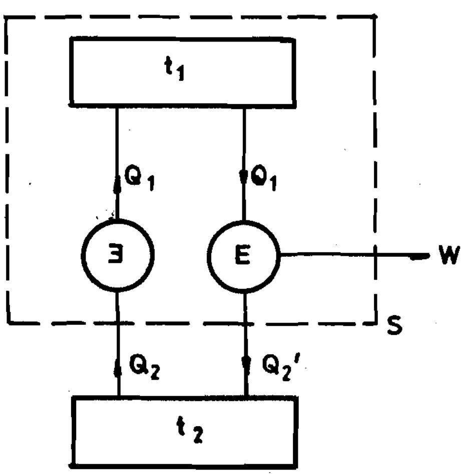

Fig.6.8 : Equivalence of Clausius and Kelvin-Planck statements

Let the work produced by this engine be W and the heat rejected by it to the low temperature reservoir at t_2 be Q_2'. This engine does not voilate the second law. Now consider the system S enclosed by the dotted boundary. This system is also undergoing a cyclic process as it consists of three sub-systems, each undergoing a cyclic process. It may be pointed out here that inclusion of the high temperature reservoir inside the boundary does not pose any problem as this reservoir experiences no change whatsoever with time because the heat transfer by it to E is equal to the heat transfer to it by Ǝ, both being equal to Q_1 in magnitude. The net work output of this system W, according to the first law, is equal to $(Q_1 - Q_2')$. The system identified by the dotted boundary, while operating in a cycle, has heat interaction with only the low temperature reservoir. It can also be seen from figure 6.8 that the net heat transfer to the system from the reservoir at t_2 is equal to $Q_2 - Q_2'$ where Q_2 is shown to be equal to Q_1. Hence,

$$\text{Net } Q = Q_1 - Q_2' \text{ and}$$

$$\text{Net } W = Q_1 - Q_2'. \text{ Therefore } \eta = \frac{W}{Q} = 100\ \%.$$

Hence, this system working in a thermodynamic cycle converts all the heat transfer to it from a single reservoir to an equal quantity of work. This amounts to the violation of the Kelvin-Planck statement as it turns out to be a 100 % efficient engine (PMM2). Thus it may be concluded that violation of Clausius statement leads to the violation of Kelvin-Planck statement.

To complete the exercise let it now be assumed that there exists a heat engine E that operates violating the K-P statement. As shown in Fig.6.9 let heat transfer from the high temperature reservoir to this heat engine be Q_1. As no heat is rejected by this engine to the low temperature region, the work output of the engine is W and by first law $W = Q_1$. Let this work be supplied to the heat pump Ǝ which receives Q_2 from the low temperature reservoir and transfers Q_3 to the high temperature reservoir. It can be seen that the heat pump is operating in accordance with the Clausius statement and the first law of thermodynamics dictates that $Q_3 = W + Q_2 = Q_1 + Q_2$. Thus the net heat transfer to the high temperature reservoir is $(Q_3 - Q_1) = (Q_1 + Q_2) - Q_1 = Q_2$. Consider the heat pump and the engine together as a system. This system shown enclosed in the dotted

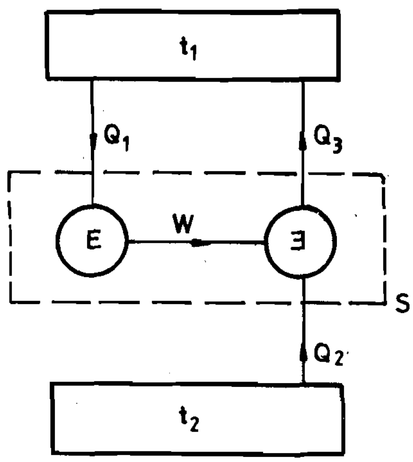

Fig. 6.9 : Equivalence of Kelvin-Planck and Clausius statements.

boundary also undergoes a thermodynamic cycle during which Q_2 is transferred from the low temperature reservoir to the high temperature reservoir without the requirement of any work from outside the system. This is a violation of the Clausius statement. Therefore a violation of the Kelvin-Planck statement also leads to the violation of the Clausius statement. Hence, the equivalence of the two statements is proved as the violation of any one statement leads to the violation of the other.

6.9 ILLUSTRATIVE PROBLEMS

Example 6.1 :

In a steam power plant the work output of the turbine is 100 kJ while heat supplied at the boiler is 300 kJ. Given that during the same period work input to the pump is 0.5 kJ find the heat rejected at the condenser and thermal efficiency of the plant.

Solution :

Refer to Fig.6.1.

$$Q_1 - Q_2 = W_T - W_P \qquad (6.1)$$

From Data, substituting the magnitudes of Q_1 (= 300 kJ), W_T (= 100 kJ) and W_p(= 0.5 kJ) in equation (6.1),

$$300 - Q_2 = 100 - 0.5$$

$\therefore\ Q_2$ = Heat rejected at the condenser = 200.5 kJ.

$$\eta = \frac{(W_T - W_P)}{Q_1} \qquad (6.2)$$

$$= \frac{(100 - 0.5)}{300} = 0.33 \text{ or } 33\ \%$$

Alternatively, $\eta = 1 - \dfrac{Q_2}{Q_1}$ (6.4)

$$= 1 - \frac{200.5}{300} = 0.33 \text{ or } 33\ \%.$$

Example 6.2 :

A refrigerator with a COP of 4.0 transfers heat at a rate of 0.5 kJ/s at the condenser. Find the rate of heat transfer at the evaporator and the power input to the compressor. Also calculate the COP if the refrigerator were to operate as a heat pump with same heat and work interactions.

Solution :

'Refer to Fig. 6.5.

From data $(COP)_{Ref} = 4.0$ and $Q_1 = 0.5$ kJ/s.

$$(COP)_{Ref} = \frac{Q_2}{W_C} \qquad (6.6)$$

$$\therefore\ Q_2 = 4.0 W_C \qquad (i)$$

From the I law, $Q_1 - Q_2 = W_C$ (6.5)

$$\therefore\ 0.5 - Q_2 = W_C \qquad (ii)$$

From (i) and (ii) $W_C = 0.1$ kJ/s

Substituting for W_C in (i),

Q_2 = rate of heat transfer through the evaporator

= 0.4 kJ/s.

$$(COP)_{hp} = \frac{Q_1}{W_C} = \frac{0.5}{0.1} = 5. \qquad (6.8)$$

Alternatively, $(COP)_{hp} = 1 + (COP)_{Ref}$ (6.9)

$$= 1 + 4 = 5.$$

Example 6.3 :

The properties of the working substance (air) at different locations in a closed cycle gas turbine power plant are as follows:

Location	Temperature (°C)	Velocity (m/s)
Between cooler and compressor	35	95
Between compressor and heater	240	35
Between heater and turbine	t_3	220
Between turbine and cooler	525	110

The heat transfer to air in the heater is 640 kJ/kg air. Assume no heat loss from any component to atmosphere. Calculate (a) t_3, (b) heat transfer in the cooler, (c) net work output and (d) thermal efficiency of the plant. Assume that enthalpy of air is a function of its temperature only and that c_p = 1.005 kJ/kg.K .

Solution:

Refer to Fig. 6.2. From the data:

$t_1 = 35^\circ$ C, $V_1 = 95$ m/s, $t_2 = 240^\circ$ C, $V_2 = 35$ m/s,

$t_3 = ?$, $V_3 = 220$ m/s, $t_4 = 525^\circ$ C and $V_4 = 110$ m/s.

$Q_1 = 640$ kJ/kg air.

Heal loss from all components to the atmosphere = 0. As c_p is a function of temperature only and that it is a constant, $h_2 - h_1 = c_p\,(t_2 - t_1)$.

Applying SFEE to the adiabatic compressor,

$$-W_C = \left[(h_2 - h_1) + \left(\frac{V_2^{\,2} - V_1^{\,2}}{2}\right)\right]$$

$$= \left[c_p\left(t_2 - t_1\right) + \left(\frac{V_2^{\,2} - V_1^{\,2}}{2}\right)\right]$$

$$\therefore\ W_C = -\left[1.005\ (240 - 35) + \left(\frac{35^2 - 95^2}{2000}\right)\right] = -202 \text{ kJ/kg}$$

Applying SFEE to Heater,

$$Q_1 = 640 = \left[\left(h_3 - h_2\right) + \left(\frac{V_3^{\,2} - V_2^{\,2}}{2}\right)\right]$$

$$= \left[c_p\ \left(t_3 - t_2\right) + \left(\frac{V_3^{\,2} - V_2^{\,2}}{2}\right)\right]$$

$$= \left[1.005\ (t_3 - 240) + \left(\frac{220^2 - 35^2}{2000}\right)\right]$$

$$\therefore\ t_3 = 853.3^\circ \text{ C.}$$

Applying SFEE to the adiabatic turbine,

$$-W_T = \left[\left(h_4 - h_3\right) + \left(\frac{V_4^{\,2} - V_3^{\,2}}{2}\right)\right]$$

$$= \left[c_p\ \left(t_4 - t_3\right) + \left(\frac{V_4^{\,2} - V_3^{\,2}}{2}\right)\right]$$

$$W_T = -\left[1.005\,(525 - 853.3) + \left(\frac{110^2 - 220^2}{2000}\right)\right] = 348 \text{ kJ/kg}$$

Applying SFEE to cooler,

$$Q_2 = \left[\left(h_1 - h_4\right) + \left(\frac{V_1^{\,2} - V_4^{\,2}}{2}\right)\right]$$

$$= \left[c_p\left(t_1 - t_4\right) + \left(\frac{V_1^{\,2} - V_4^{\,2}}{2}\right)\right]$$

$$= \left[1.005\ (35 - 525) + \left(\frac{95^2 - 110^2}{2000}\right)\right] = 494 \text{ kJ/kg}$$

$\therefore$ (a) t_3 = temp.of air after the heater = 853.3°C.

(b) Q_2 = heat rejected at the condenser = 494 kJ/kg

(c) net work out put = W_T - W_C = 348 - 202 = 146 kJ/kg

(d) Thermal efficiency $= \frac{(W_T - W_c)}{Q_1} = \frac{146}{640} = 0.228$. Also, alternatively,

efficiency $= \frac{(Q_1 - Q_2)}{Q_1} = \frac{(640-494)}{640} = 0.228$

Example 6.4 :

A heat engine is used to drive a heat pump. The heat transfers from the heat engine and the heat pump are used to heat the water circulating through the radiators of a building. It is given that the efficiency of the heat engine is 30 % and the COP of the heat pump is 4. How much heat is transferred to the radiator water for every kJ heat transferred to the heat engine.

Solution:

Refer to Fig.6.10.

Efficiency of the heat engine $= \left(1 - \frac{Q_2}{Q_1}\right) = 0.3$

$$\therefore \quad \frac{Q_2}{Q_1} = 0.7$$

$(COP)_{hp} = 4 = \frac{Q_4}{W}$ where $W =$ eff. of $E \times Q_1 = 0.3\, Q_1$,

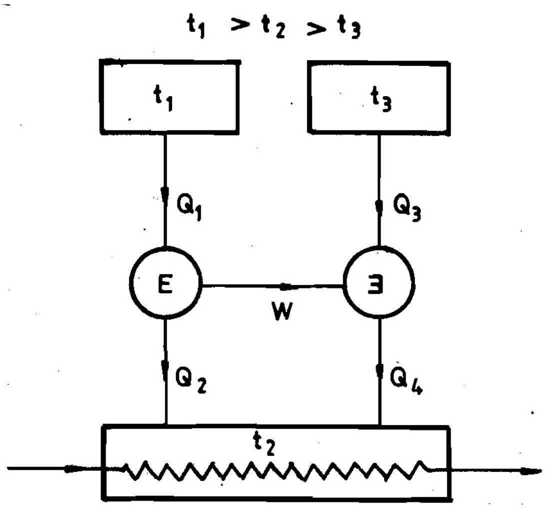

Fig.6.10 : Heat pump driven by the heat engine

$$\frac{Q_4}{0.3\, Q_1} = 4 \quad \text{or} \quad \frac{Q_4}{Q_1} = 0.3 \times 4 = 1.2.$$

Total heat transfer to the radiator water $= Q_4 + Q_2$

Heat transfer to the heat engine $= Q_1$

$\therefore$ Heat transfer to radiator water for every kJ added to heat engine $= \frac{(Q_4 + Q_2)}{Q_1}$

$$= \left(\frac{Q_2}{Q_1}\right) + \left(\frac{Q_4}{Q_1}\right) = 0.7 + 1.2 = 1.9 \text{ kJ}.$$

Example 6.5 :

An internal combustion engine produces net work while having heat interaction only with the surroundings at a fixed temperature. Does this mean that the internal combustion engine violates the second law of thermodynamics ?

Solution :

In an internal combustion engine a steady flow of fuel and air enters the engine. The fuel air mixture is burnt in the piston cylinder mechanism of the engine and subsequently the combustion products expand to do work on the piston. This causes the engine to deliver shaft work. Because of the combustion process there will be an increase in temperature of the engine and hence the engine exchanges heat with the surroundings. Also a steady flow of combustion products leaves the engine through the exhaust pipe. From the operation of the internal combustion engine it becomes evident that it does not work in a thermodynamic cycle as the working substance is not returned to its original state after each cycle of mechanical events. In fact there is a steady flow of material into and out of the engine. Hence an internal combustion engine is not a heat engine and as such Kelvin - Planck statement of the second law of thermodynamics cannot be applied to comment on its violation or otherwise of the second law. An internal combustion is a practically feasible engine - it could not have been so if it were to violate the second law of thermodynamics. It shall be explained later that the processes, such as those occurring in internal combustion engine, are also bound by the corollaries of the second law of thermodynamics.

6.10 SUMMARY

Heat engine is a system undergoing a thermodynamic cycle with heat and work interactions.

In a direct heat engine heat (Q_1) is transferred to the system from a high temperature reservoir (t_1), work (W) is transferred out of the system and heat (Q_2) is transferred from the system to a low temperature reservoir (t_2).

The efficiency of a direct heat engine is given by

$$\eta = \left(\frac{Q_1 - Q_2}{Q_1}\right) = \frac{W}{Q_1}$$

In a reversed heat engine the heat and work interactions are in opposite directions compared with the direct heat engine.

Heat pump and refrigerator are reversed heat engines.

The coefficient of performance of a reversed engine is calculated using

$$(\text{COP})_{hp} = \left(\frac{Q_1}{Q_1 - Q_2}\right) = \frac{Q_1}{W} \quad \text{and}$$

$$(\text{COP})_{ref} = \left(\frac{Q_2}{Q_1 - Q_2}\right) = \frac{Q_2}{W}$$

$$\text{Also,} \qquad (\text{COP})_{hp} = 1 + (\text{COP})_{ref}.$$

The gist of the Kelvin-Planck statement of the second law of thermodynamics is " it is impossible to have an 100 % efficient heat engine".

According to the Clausius statement of the second law "it is impossible to have a heat pump of infinite COP".

6.11 ANSWERS/SOLUTIONS TO SAQs

SAQ 1

In the open cycle gas turbine power plant there is a steady flow of fuel and air to the engine and a steady flow of combustion products out of the engine. Because of the combustion process involved, the chemical aggregation of the system is changing and hence these engines are not working in thermodynamic cycles.

SAQ 2

True

SAQ 3

COP = 1.

SAQ 4

No. The COP, a measure of the system performance, can only have +ve value. Thus in evaluating the COP only magnitudes of Q and W have to be considered and not their directions.

6.12 GLOSSARY

Heat Engine	:	A system operating in a thermodynamic cycle
Direct Heat Engine	:	A heat engine in which net work is positive
Refrigerator		A reversed heat engine maintaining a body or space at a temperature lower than that of the surroundings.
Heat Pump	:	A reversed heat engine maintaining a body or space at a temperature higher than that of the surrounding.
Kelvin-Planck Statement	:	Statement of a second law of thermodynamics according to which 'it is impossible for a direct heat engine to produce work while having heat transfer with a single reservoir at a fixed temperature'.
Clausius' Statement	:	Statement of a second law of thermodynamics according to which 'it is impossible for a reversed heat engine to transfer heat from a low to a high temperature region in the absence of external work'.
PMM 2	:	Perpetual motion machine of the second kind (a 100% efficient or impossible direct heat engine).