

Module 4 Second Law of Thermodynamics

This module is designed to help you to:

- explain that the inter conversion of heat into work and vice-versa is observed in different sets of conditions;
- explain the general meaning of the term 'heat engine';
- identify the need for the three essential parts of a heat engine;
- discuss that in spite of being permitted by the law of conservation of energy, we cannot have any practical device, working in a cycle, that can convert a given amount of heat energy completely into an equivalent amount of work;
- differentiate between the terms refrigerator and heat pump;
- analyze that the refrigerator is to be viewed as a device that is the inverse of a heat engine;
- explain the meanings of the terms efficiency of a heat engine and coefficient of performance of a refrigerator and do calculations pertaining to the same;
- state the second law of thermodynamics;
- justify why the second law of thermodynamics is regarded as a fundamental law in physics;
- describe the basic details of features of the ideal heat engine, suggested by Sadi Carnot, and, therefore, known as the Carnot engine;
- conclude that even for the Carnot engine - the ideal heat engine - the efficiency cannot be 100%;
- explain that there is no violation of the second law of thermodynamics even in the case of an ideal heat engine;
- explain the difference between reversible and irreversible processes and give practical examples that can (nearly) correspond to each of these two types of processes.

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12.4.1 Introduction

During the process of inter-conversion of heat into work and vice-versa, we observe that in actual practice, it is possible to convert a given amount of mechanical energy completely into heat. However, it is not possible to do so the 'other way'. This implies that, though permitted by the law of conservation of energy, the total conversion of a given amount of heat energy, into mechanical work, is practically not possible.

Why is that so? A simple way of understanding this is to realize that

- (i) conversion of mechanical energy into heat energy can be viewed as going from 'an ordered state' to a 'random (or disordered) state'.
- (ii) conversion of heat into mechanical work can be viewed as going from a random (or disordered) state to an ordered state.

The first process is practically possible and permissible while the reverse process is practically (almost impossible) not permissible.

In the previous module we came across the limitations of the first law of thermodynamics. Here we shall study the second law and see how it accounts for the limitations of the first law.

We shall take a close look at the working of the heat engines, refrigerators, their efficiencies and coefficients of performance. We shall present the Carnot Engine to familiarize you with the concept of an ideal engine and draw linkages with reversible and irreversible processes by revisiting them.

12.4.2 Heat engines

A heat engine is a device by which a system is made to undergo a cyclic process that results in conversion of heat to work. The engine takes heat Q_1 from a hot reservoir at temperature T_1 and uses this to deliver a work W to the surroundings and release a part Q_2 (of the heat 'taken in' by it) to a cold reservoir at temperature T_2 (Fig.12.4.1). The cycle is repeated again and again to get useful work.

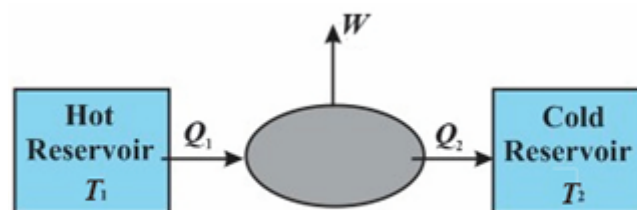


Fig: 12.4.1 Schematic representation of a heat engine

Heat engines, therefore, have a built-in practical limitation. Their efficiency, even under ideal conditions, can never be 100%, i.e., they cannot convert a given amount of heat energy completely into an equivalent amount of mechanical energy. We aim to develop heat engines in which the left over/unused part of the (in taken) heat energy is as low as possible.

The efficiency (η) of a heat engine is defined as

$$\eta = \frac{W}{Q_1} (= 1 - \frac{Q_2}{Q_1}) = \frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1} \quad (12.4.1)$$

(It can be shown that in an ideal situation $\frac{Q_1}{Q_2} = \frac{T_1}{T_2}$)

For $Q_2 = 0$, $\eta = 1$, i.e., the engine will have 100% efficiency of converting heat into work. Experience, however, shows that such an ideal engine (with $\eta = 1$) is never possible.

The actual mechanism of conversion of heat into work varies for different heat engines.

12.4.3 Refrigerators and heat pumps

A refrigerator is the reverse of a heat engine. It uses work to transfer thermal energy from a cold reservoir to a hot reservoir. In such devices (Refrigerator, air conditioners) the working substance extracts heat Q_2 from the cold reservoir at temperature T_2 , has some external work W done on it, and releases heat Q_1 to the hot reservoir at temperature T_1 (Fig.12.4.2).

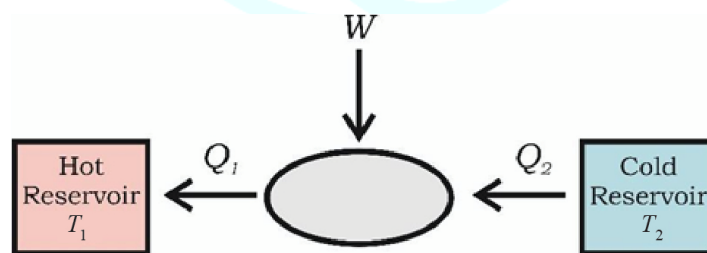


Fig: 12.4.2 Schematic representation of a refrigerator or a heat pump

For example, in the refrigerators used in households, the electrical compressor does work to transfer heat from the food chamber (cold reservoir) to the room environment (hot reservoir).

A heat pump (used to heat up rooms inside during winter in cold countries) is the same as a refrigerator. The only difference is that it does work to transfer heat from the outside environment (cold reservoir) to a given room (hot reservoir).

The coefficient of performance (α) of a refrigerator is given by

$$\alpha = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2} \quad (12.4.2)$$

A refrigerator cannot work without some external work being done on its system, i.e., the coefficient of performance (of a refrigerator) cannot be infinite.

Example 12.4.1 A steam engine delivers 5.4×10^8 J of work per minute and takes in 3.6×10^9 J of heat per minute from its boiler. What is the efficiency of the engine?

Solution:

Consider a Carnot's cycle operating between $T_1 = 500$ K and $T_2 = 300$ K producing 1 kJ of mechanical work per cycle. Find the heats transferred to the engine by the reservoirs.

Hint; $\eta = \frac{200}{500} = \frac{2}{5}$, $Q_1 = \frac{W}{\eta} = \frac{5}{2}W = 2.5 \text{ J / min}$, $Q_2 = Q_1 - W = 1.5 \text{ J/min}$



Let Us Reflect

Q.12.4.1 A refrigerator is to maintain eatables (kept inside it) at 9°C . If room temperature is 36°C , calculate the coefficient of performance.

Q.12.4.2 If a refrigerator's door is kept open, will the room become cool or hot? Explain.

Q.12.4.3 Is it possible to increase the temperature of a gas without adding heat to it? Explain.

Q.12.4.4 In a refrigerator one removes heat from a lower temperature and deposits it to the surroundings at a higher temperature. In this process, mechanical work has to be done, which (in general) is provided by an electric motor. If the motor is of 1 kW power, and heat is transferred from -3°C to 27°C , find the heat taken out of the refrigerator per second assuming that its efficiency is 50% of a perfect engine.

Q.12.4.5 If the coefficient of performance of a refrigerator is 5 and if it operates at room temperature (27 °C), find the temperature inside the refrigerator.



Answers

A.12.4.1

With symbols their usual meanings.

$$T_1 = 9 + 273 = 282 \text{ K}$$

$$T_2 = 36 + 273 = 309 \text{ K}$$

$$\omega = \frac{T_1}{T_2 - T_1} = \frac{282}{309 - 282}$$

$$\therefore \omega = \frac{282}{27} = 10.44$$

A.12.4.2 Under the circumstances, the refrigerator will exhaust more heat into the room than it extracts, and the room will become hotter.

A.12.4.3 Yes, it is possible by way of adiabatic compression. During compression, work is done on the system. So, ΔW is negative. Further, as the process is adiabatic, $\Delta Q = 0$. So, from the first law of thermodynamics, we get, $\Delta U = -\Delta W$ which turns out to be positive, and thus internal energy increases giving rise to increase in temperature.

A.12.4.4

$$\eta_{\text{Carnot Engine}} = 1 - \frac{T_2}{T_1} = \eta, \text{ say}$$

$$\eta_{\text{Refrigerator}} = 50\% \text{ of } 0.1 = 0.05 = \eta', \text{ say}$$

$$\beta = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2} = \frac{\frac{Q_2}{Q_1}}{1 - \frac{Q_2}{Q_1}}$$

$$\therefore \beta = \frac{1-\eta'}{\eta'} = \frac{1-0.05}{0.05}$$

$$\therefore \beta = \frac{0.95}{0.05} = 19$$

$$\therefore Q_2 = 19\% \text{ of } 1 \text{ kW} = 19 \text{ Js}^{-1}$$

A.12.4.5

With symbols having usual meanings.

$$\beta = 5, T_1 = 27 + 273 = 300$$

$$\beta = 5 = \frac{T_2}{T_1 - T_2}$$

$$\therefore 6T_2 = 5T_1$$

$$T_2 = \frac{5}{6}T_1 = 250$$

$$\therefore T_2 = 250 - 273 = -23^\circ\text{C}$$

With this background let us state the Second law of thermodynamics. We have to remember that the law is supposed to cover the limitations of the first law.

12.4.4 Second law of thermodynamics

The following two statements are two (equivalent) concise ways of stating the second law of thermodynamics:

Kelvin-Planck statement

No process is possible whose sole result is the absorption of heat from a reservoir and the complete conversion of this heat into work

Clausius statement

No process is possible whose sole result is the transfer of heat from a colder object to a hotter object

It can be proved that these two statements are completely equivalent.

It follows from the Second Law of Thermodynamics that the efficiency of a heat engine can never be unity and for a refrigerator, the coefficient of performance can never be infinite.

A comment on the second law of thermodynamics

The second law of thermodynamics is essentially an empirical law – a law developed and formulated on the basis of practical experience and experiments. It is not a law that is derived from other fundamental postulates, concepts and laws. However, practical experience leads us to believe that this law is not likely to be violated in any given situation. We, therefore, think of it as an (almost) fundamental law of nature and any conclusion/result, that contradicts it, is regarded as unacceptable. Here we need to remember that thermodynamics is essentially a macroscopic science and these comments are to be viewed as conclusions based on macroscopic observations.

At this point it would be worthwhile revisiting reversible and irreversible processes about which we learnt in Module 2. The concepts will be quite useful in the understanding of the functioning of heat engines.

12.4.5 Reversible and irreversible processes

You may recall that a thermodynamic process (state $i \rightarrow$ state f) is called reversible if the process can be ‘turned back’ such that both the system and the surroundings return to their original states, with no other change anywhere else in the universe.

In a reversible process, there will be no losses of energy due to dissipative effects. These energy losses arise mainly from two causes: (i) many processes (like a free expansion or an explosive chemical reaction) take the system to non-equilibrium states; (ii) most processes involve friction, viscosity and other dissipative effects.

These energy losses occur in all natural processes; hence, natural processes are not reversible. A pure reversible process, you have learnt, is an abstraction. However, it is a useful abstraction because it allows us to understand a variety of practical processes.

It turns out that a heat engine, based on idealized reversible processes, achieves the highest possible efficiency. All other engines, involving irreversibility in any way (as would be the case for practical

engines), have their efficiency lower than this limiting efficiency.



Let Us Reflect

Q.12.4.6 Which of the processes described below are irreversible?

- (a) The increase in temperature of an iron rod by hammering it.
- (b) A gas, in a small container at a temperature T_1 , is brought in contact with a big reservoir at a higher temperature T_2 which increases the temperature of this gas.
- (c) A quasi-static isothermal expansion of an ideal gas in a cylinder fitted with a frictionless piston.
- (d) An ideal gas is enclosed in a (smooth) piston-cylinder arrangement with perfect adiabatic walls. A weight W is made to sit over the piston, resulting in a compression of gas.



Answers

A.12.4.6 (a), (b) and (d), as in case of all of them the intermediate states between the initial and final states are non-equilibrium states.

In case of (c), the intermediate states are approximately departed from equilibrium. So, the process approximates a reversible process

12.4.6 Three essential parts of a heat engine

From our understanding of the working of a heat engine, we realize that a heat engine must have three essential parts;

(i) A heat reservoir as source of heat

This is assumed to be a reservoir that is large enough to remain at the same temperature even when it passes

on a part of its (large) thermal energy content to the ‘working substance’ of the heat engine.

(ii) A working substance/device

This is the substance/device that takes in heat from the heat reservoir/source, converts (maximum possible) part of this heat energy into useful mechanical work and passes on the left over (unconverted) heat energy to the heat sink (or cold reservoir). The useful mechanical work, thus obtained from a heat engine, is an indicator of its efficiency.

(iii) A heat sink/cold reservoir

This is again assumed to be a reservoir that is large enough to remain at the same temperature even when it receives the left over/unused heat energy from the working substance/device of the heat engine. This is also an essential part of the heat engine as its presence ensures that there is a ‘cyclic process’ in the heat engine. The heat engine can keep on working continuously (to convert a part of its ‘in taken heat energy’ into useful mechanical work).

The essence of the second law of thermodynamics is that ‘among heat and work, nature has a preference for energy in heat form’. When we vigorously rub our palms against each other, they become warm, that is energy gets converted from work-form to heat-form so easily, but the converse does not happen so easily. Many more such examples can be cited. This partial preference of nature is the crux of the design of a heat engine. Just get back to the beginning of the sub-section 12.4.6, and you will find that to facilitate performance of the process (i) to (ii), which is what we desire, that is, heat to work, to which nature is unfavorable, we have to create the stage (ii) to (iii), that is, work to heat, to which nature is favorable. Less

the amount of heat energy consumed at the stage (ii) to (iii) for achieving (i) to (ii), more efficient is the engine (Remember that $\eta = 1$ when $Q_2 = 0$).

12.4.7 Carnot engine

Sadi Carnot, a French mechanical engineer, thought of an ideal heat engine in which the heat reservoir and the heat sink are both assumed to be ideal, i.e., their temperatures do not change even when a finite amount of heat is withdrawn from/added to them. He assumed a particular sequence of a set of processes that make up the complete cycle of this ideal heat engine.

The sequence of processes, making up a Carnot cycle, has been shown in the P - V diagram drawn here (Fig 12.4.3). (draw again)

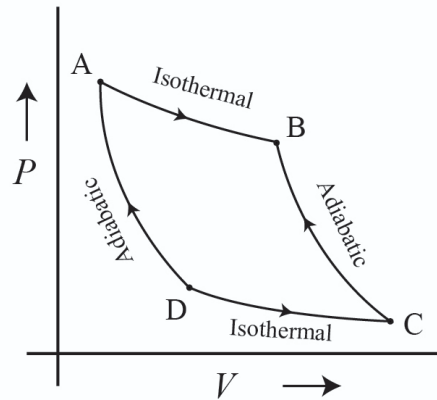


Fig: 12.4.3 PV diagram for Carnot cycle

The working substance (an ideal gas kept in a cylinder fitted with a (smooth) piston) is first made to undergo an isothermal expansion in which the (perfectly conducting) bottom of the cylinder is put in contact with the ‘hot’ reservoir (kept at a temperature T_1 kelvin). Fig.(12.4.4) may be seen. It is then made to undergo an adiabatic expansion in which the bottom of the cylinder is covered with a perfect heat insulator. In the third step, the working substance undergoes an isothermal compression in which the heat insulating cover is again removed from the bottom of the cylinder which is then put in contact with a ‘cold reservoir’ (kept at a temperature T_2 kelvin). Finally the working substance is made to undergo an adiabatic compression (in which the bottom of the cylinder is again covered with a perfect heat insulator). The working substance is thereby brought back to its initial thermodynamic state. This cycle is repeated again and again.

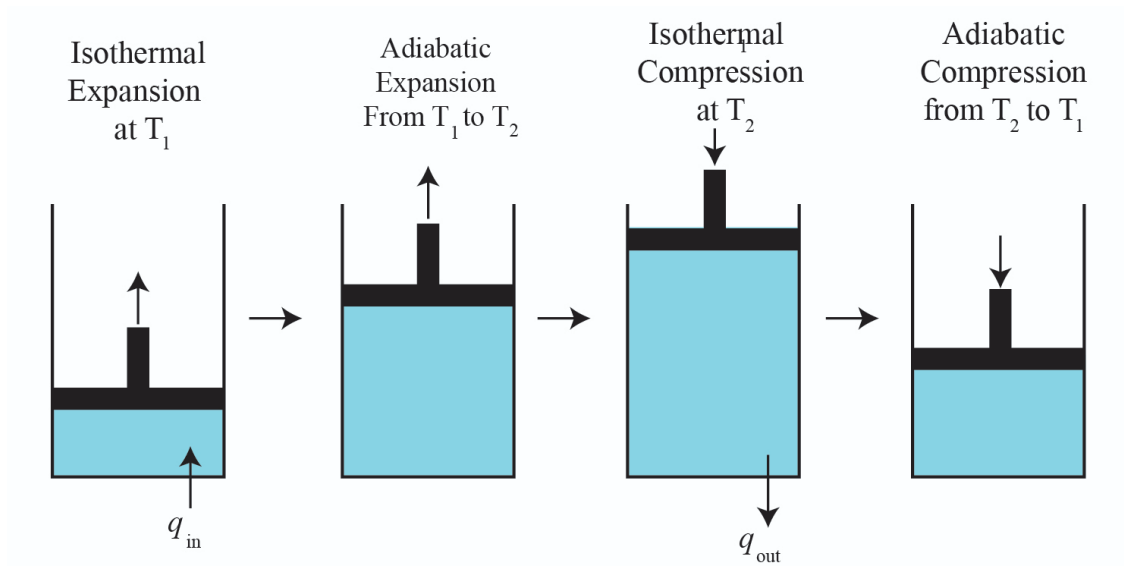


Fig: 12.4.4 Four stages in a Carnot engine

The net work, done by a Carnot engine, in one cycle, equals the area enclosed by its cycle on its P - V diagram. The ratio of this work done, to the heat taken in from the source, gives the efficiency of this heat engine. This efficiency is always less than one. The efficiency can be made to approach one by using a cold reservoir whose temperature approaches the absolute (or kelvin) zero of temperature. Since this temperature can only be approached, and not ‘attained’, the efficiency can only approach unity but never becomes equal to one. This is in accordance with the second law of thermodynamics.

The Carnot engine has the maximum efficiency for a heat engine working between given source and sink temperature. However, because of the ideal nature of all the processes involved in its cycle, it has to work in a quasistatic way. This means that this is an ideal engine with the maximum efficiency but it is also the slowest in its working.

We can think of other cycles/ ‘ways of working’ of an ideal heat engine. However, for given source and sink temperatures, the efficiencies of all such ideal heat engines are one and the same –the efficiency of the corresponding Carnot cycle.

For a Carnot Engine, which follows the Carnot Cycle, it can be shown that,

$$\eta = 1 - T_L/T_H, \quad (12.4.3)$$

where T_L and T_H are lower and higher temperatures of two isothermal processes.

12.4.8 Summary

- A heat engine is a device by which a system is made to undergo a cyclic process that results in conversion of heat to work.
- A refrigerator is the reverse of a heat engine. It uses work to transfer thermal energy from a cold reservoir to a hot reservoir.
- A heat pump (used to heat up rooms inside during winter in cold countries) is the same as a refrigerator. The only difference is that it does work to transfer heat from the outside environment (cold reservoir) to a given room (hot reservoir).
- Second law of thermodynamics

- Kelvin-Planck statement

No process is possible whose sole result is the absorption of heat from a reservoir and the complete conversion of this heat into work

- Clausius statement

No process is possible whose sole result is the transfer of heat from a colder object to a hotter object

- There can be a complete conversion of mechanical energy into heat, the reverse is not the case.
- Carnot engine is ideal in nature and uses two isothermal and two adiabatic processes in one cycle which has efficiency

$$\eta = \frac{\text{Work delivered}}{\text{Heat energy supplied}} = \frac{W}{Q}$$

For Carnot's cycle, $\eta = 1 - T_L/T_H$, where T_L and T_H are lower and higher temperatures of two isothermal processes.

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