# 2

# Refrigerating Machine and Reversed Carnot Cycle

## 2.1 REFRIGERATING MACHINES

There are essentially two categories of thermal plants. These are:

(i) Thermal power plants or *work producing plants*.

(ii) Refrigeration/heat pump plants or *work consuming plants*.

The work producing plants or *heat engines* lead to the conversion of heat to work. The work consuming plants, viz., *refrigerators/heat pumps*, are not those which are in any way related to the conversion of work into heat. No ingenuity at all is required for the conversion of work into heat. In fact, all work (mechanical/electrical energy) that is consumed in machinery is ultimately dissipated as heat to the environment. The objective of work consuming plants, actually, is to lead to the flow of heat from a low temperature body to a high temperature body. The work is consumed to achieve this.

Examples of common work consuming plants, viz., refrigerators are the following:

Cold storages. Central air conditioning plants. Domestic refrigerators. Room air conditioners. Ice Plants. Food freezing and freeze-drying plants. Air liquefaction plants. etc.

Heat pumps are heating plants. But they operate in the same way as refrigerators.

Refrigeration equipment, in general, is relatively smaller in size as compared to work producing plants. The capacity of a power plant is in MW, whereas the capacity of a refrigeration system is in kW or even less. A very large super cold storage or a central air conditioning plant for a multistoreyed building may consume power in the range of 2000 to 5000 kW. A window-type room air conditioner may consume only 2.5 kW of power, and a domestic refrigerator just 100 to 250 W only.

## 2.2 A REFRIGERATING MACHINE—THE SECOND LAW INTERPRETATION

A *refrigerating machine* is a device which will either cool or maintain a body at a temperature below that of the surroundings. Hence, heat must be made to flow from a body at low temperature to the surroundings at high temperature.

However, this is not possible on its own. We see in nature that heat *spontaneously* flows from a high temperature body to a low temperature body.

The reverse process to complete the thermodynamic cycle, in which heat Q will flow back from the low temperature body to the high temperature body, is not possible. Thus, we see that a thermodynamic cycle involving heat transfer alone as shown in Fig. 2.1 cannot be devised. The logical conclusion is that there must be a process in which some work is done.

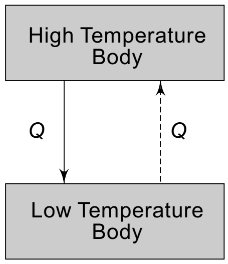


**Fig. 2.1** A thermodynamic cycle involving heat transfer alone: Not possible

The second law of thermodynamics, like the first law, is based on the observations of actually existing processes and devices in nature. Figure 2.2 shows the schematic diagram of an actual refrigeration system which works on the well-known *vapour compression cycle*. Most refrigeration devices/plants, including air conditioners and refrigerators such as the ones illustrated in Chap. 1, work on this cycle only.

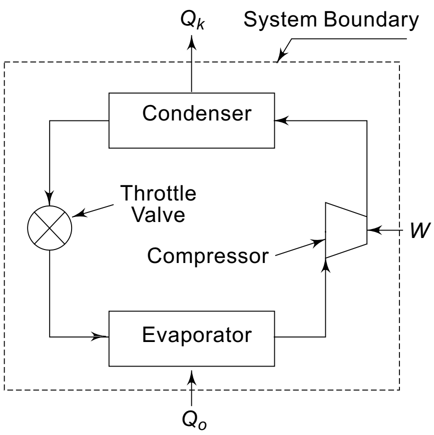


**Fig. 2.2** Illustration of an actual refrigerator/heat pump: The simple vapour compression system

The heat and work interactions of the processes of the cycle are as follows:

(i) Heat $Q_0$ is absorbed in the evaporator by the evaporation of a liquid refrigerant at a low pressure $p_0$, and corresponding low saturation temperature $T_0$.

(ii) The evaporated refrigerant vapour is compressed to a high pressure $p_k$ in the compressor consuming work $W$. The pressure after compression is such that the corresponding saturation temperature $T_k$ is higher than the temperature of the surroundings.

(iii) Heat $Q_k$ is then rejected in the condenser to the surroundings at high temperature $T_k$.

The application of the first law, $\oint \delta Q = \oint \delta W$, to the cycle gives:

$$-Q_k + Q_o = -W$$
$$Q_k - Q_o = W$$

This, also, represents an *energy balance* of the system in Fig. 2.2 obtained by drawing a boundary around it.

There are two statements of the second law of thermodynamics, the *Kelvin-Planck statement*, and the *Clausius statement*. The Kelvin-Planck statement pertains to heat engines such as E represented in Fig. 2.3.

The Clausius statement pertains to refrigerators/heat pumps R. The above observation from illustration of actually existing refrigerators/heat pumps leads to the Clausius statement which is as follows:

"*It is impossible to construct a device which will operate in a cycle and produce no effect other than the transfer of heat from a low temperature body to a high temperature body*".

The statement implies that a refrigerator R of the type shown in Fig. 2.4 which will absorb heat $Q_o$ from a low temperature body and transfer it to a high temperature body is impossible.

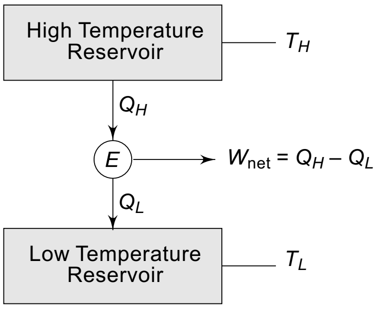


**Fig. 2.3** Schematic representation of a heat engine

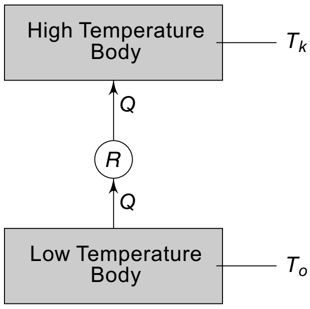


**Fig. 2.4** Refrigerator without any Work Input: Impossible

The only alternative is that there must be some work input $W_{in}$. Accordingly, we obtain a schematic representation of a refrigerating machine/heat pump as shown in Fig. 2.5, and from the first law $W_{in} = Q_k - Q_o$. Accordingly, heat transferred $Q_k$ is more than heat absorbed $Q_o$ by the amount of work input $W_{in}$.

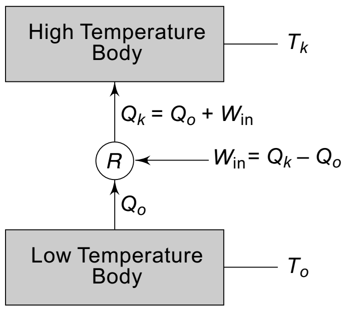


**Fig. 2.5** Schematic representation of a refrigerator/heat pump

Now, the stress on the words 'operating in a cycle' is significant. For, in a single process, it may be possible to obtain removal of heat from a low temperature body without doing external work, e.g., by the evaporation of a refrigerant, for instance liquid Freon 22 after throttling expansion to, say, 1 bar corresponding to a saturation temperature of –40°C as shown in Fig. 2.6. However, this could not happen continuously. This process could continue only if one had an infinite supply of high pressure Freon 22 liquid in the cylinder. But that is not possible in nature. To obtain refrigeration continuously, the refrigerant vapour after evaporation at low pressure will have to be brought back to the initial state of high pressure liquid again. That will mean forming a complete thermodynamic cycle.

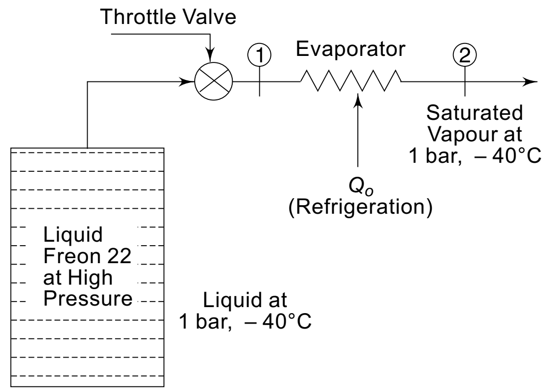


**Fig. 2.6** A process: Producing refrigeration while $W = 0$

The Clausius statement eliminates the possibility of obtaining refrigeration without doing work. The statement necessitates a further clarification regarding heat-operated refrigerating machines such as the vapour absorption type or ejector type, using heat directly to produce refrigeration. Such systems may be considered as a combination of a heat engine and a refrigerating machine. The heat engine part of the system utilizes heat from a body at a higher temperature than the surroundings and delivers the required mechanical work, *within the system*, which is directly used by the refrigerating machine part. Thus the usual process of the conversion of thermal energy, first into work (or electrical energy) and then its utilization in a refrigerating machine, is replaced by a combined process.

## 2.3 HEAT ENGINE, HEAT PUMP AND REFRIGERATING MACHINE

It may be concluded from the preceding discussion that a reversible heat engine may be converted into a refrigerating machine by running it in the reversed direction. Schematically, therefore, a refrigerating machine is a reversed heat engine which can be seen by comparing Figs. 2.5 and 2.3.

As for the *heat pump*, there is no difference in the cycle of operation between a refrigerating machine and a heat pump. The same machine can be utilized either

(i) to absorb heat from a cold body (a cooled space) at temperature $T_o$ and reject it to the surroundings at temperature $T_k \geq T_a$, or

(ii) to absorb heat from the surroundings at temperature $T_o \leq T_a$ and reject it to a hot body (a heated space) at temperature $T_k$,

where $T_a$ is the temperature of the surroundings.