ing 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.

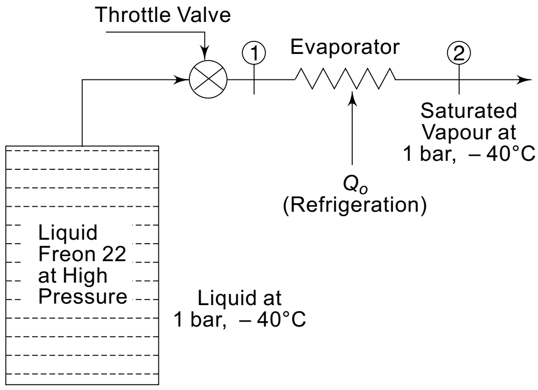

Fig. 2.6 A process: Producing refrigeration while $W = 0$

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.

Figure 2.7 illustrates the manner of application of heat engine *E*, heat pump *H* and refrigerating machine *R*. It implies that the same machine can be used either for cooling or for heating. When used for cooling, it is called a refrigerating machine and when used for heating it is called a heat pump.

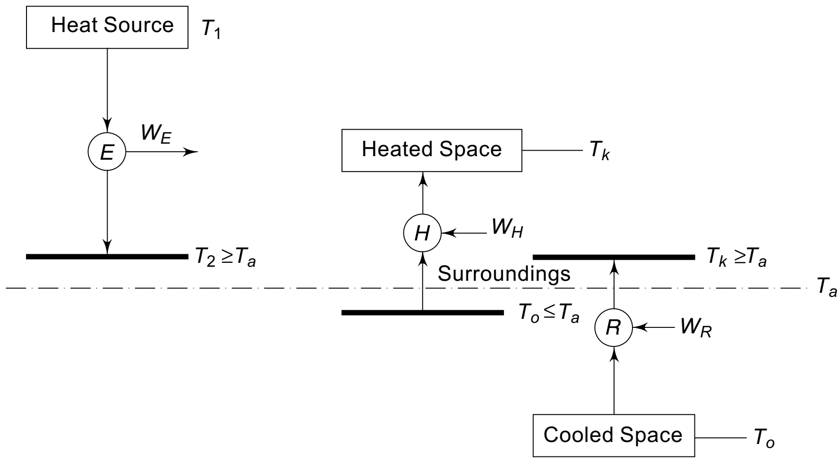

Fig. 2.7 Comparison of heat engine, heat pump and refrigerating machine

The main difference between the two is in their operating temperatures. A refrigerating machine operates between the ambient temperature $T_a \approx T_k$ and a low temperature T_o. A heat pump operates between the ambient temperature $T_a \approx T_o$ and a high temperature T_k. The heat engine operates between the heat source temperature T_1 and ambient temperature $T_a \approx T_2$.

Another essential difference is in their useful function. In a refrigerating machine, the heat exchanger that absorbs heat is connected to the conditioned space. In a heat pump, instead, the heat exchanger that rejects heat is connected to the conditioned space. The other heat exchanger in each case is connected to the surroundings. Thus if a refrigerating machine, that is used for cooling in summer, is to be used as a heat pump for heating in winter, it will be necessary, either

(i) to rotate the machine by 180° to interchange the positions of the two heat exchangers between the space and the surroundings, or

(ii) to exchange the functions of the two heat exchangers by the operation of valves, e.g., a four-way valve in a window-type air conditioner.

Such an operation of a refrigerating machine is termed as *reversed cycle heating*.

2.3.1 Energy Ratios or Coefficients of Performance

The performance of a heat engine is described by its thermal efficiency. The performance of a refrigerating machine or a heat pump is expressed by the ratio of useful heat to work, called the *energy ratio* or *coefficient of performance* (COP). Thus we have for a refrigerating machine:

Cooling energy ratio, or COP for cooling

$$\mathcal{E}_c = \frac{Q_o}{W} = \frac{Q_o}{Q_k - Q_o} = \frac{1}{\dfrac{Q_k}{Q_o} - 1} \tag{2.1}$$

And we have for a heat pump:

Heating energy ratio, or COP for heating

$$\mathcal{E}_h = \frac{Q_k}{W} = \frac{Q_k}{Q_k - Q_o} = \frac{1}{1 - \dfrac{Q_o}{Q_k}} \tag{2.2}$$

An idea about the approximate magnitude of the numerical values of these coefficients can be had from the following approximate calculations. The thermal efficiency of a heat engine is of the order of 30 per cent (say) so that

$$\eta_{\text{th}} = \frac{Q_k - Q_o}{Q_k} = 0.3$$

Then, if the engine is reversed in operation to work as a refrigerator or a heat pump with operating conditions unchanged (although in actual practice the operating temperatures will be different), we should have

$$\mathcal{E}_c = \frac{Q_o}{Q_k - Q_o} = \frac{1 - \eta_{\text{th}}}{\eta_{\text{th}}} = 2.33$$

and

$$\mathcal{E}_h = \frac{Q_k}{Q_k - Q_o} = \frac{1}{\eta_{\text{th}}} = 3.33$$

For vapour compression systems, $\mathcal{E}_c$ is of the order of 3 for water-cooled and 2 for air-cooled air-conditioning applications and 1 for domestic refrigerators.

For air cycle refrigeration systems, $\mathcal{E}_c \approx 1$ and for vapour absorption systems, it is well below unity. Steam ejector machines have still lower values.

However, the latter two are heat-operated refrigerating machines, and the definition of their coefficients of performance is altogether different. Hence, no comparison need be made at this stage.

2.3.2 Power Consumption of a Refrigerating Machine

Power consumption $\dot{W}$ of a refrigerating machine is determined in terms of kW. However, the power consumption of the motors is sometimes rated in horsepower (HP). We have

$$\text{HP} = \frac{\dot{W}}{0.746}$$

where $\dot{W}$ is in kW.

A quantity which is frequently used for comparison is horsepower per ton refrigeration. It is determined as follows:

$$\text{HP/kW refrigeration} = \frac{\dot{W}}{0.746\ \dot{Q}_o}$$

where $\dot{Q}_o$ is the refrigerating capacity in kW. Then, since 1 TR = 3.5167 kW,

$$\text{HP/TR} = \frac{\dot{W}}{0.746\ \dot{Q}_o}\ (3.5167)$$

$$= \frac{4.71\ \dot{W}}{\dot{Q}_o}$$

$$= \frac{4.71}{\mathcal{E}_c} \tag{2.3}$$

Thus HP/TR is inversely proportional to COP for cooling. In the above derivation, imperial horsepower has been used. If the horsepower is metric, then

$$\text{HP} = \frac{\dot{W}}{0.736}$$

$$\text{HP/TR} = \frac{4.78}{\mathcal{E}_0}$$

2.3.3 Heat Pump vs. Electric Resistance Heater

It may be seen from the simple transposition of Eqs. (2.1) and (2.2) that

$$\frac{Q_k}{W} = 1 + \frac{Q_o}{W}$$

$$\mathcal{E}_h = 1 + \mathcal{E}_c \tag{2.4}$$

The above relationship expresses a very interesting feature of a heat pump. According to Eq. (2.4), COP for heating is always greater than unity. It is so since Q_k is always greater then Q_o by the amount W.

Thus for the purpose of heating, it is far more economical to use a heat pump rather than an electric-resistance heater. For example, if W is the energy consumption of an electric resistance heater, the heat released to the space will be W only. But if this electrical energy W is utilized in a heat pump, the heat pumped to the space will be

$$Q_k = \mathcal{E}_h\, W = (1 + \mathcal{E}_c)\, W$$

Therefore, whatever is the value of $\mathcal{E}_c$ (even zero), Q_k will always be greater than or equal to W. The value of $\mathcal{E}_h$ for air-conditioning applications is of the order of 3. Then the heat pumped will be 3 W in a heat pump unit while the power consumption is only W. The heat pump, therefore, is a definite advancement over the simple electric-resistance heater. Only the cost of the heat pump (which is a refrigerating machine also) is prohibitive. But when an air-conditioning plant is already installed for cooling in summer, it would always be prudent to use it for heating as well in winter, operating as a heat pump.

Suppose a room loses $\dot{Q}_k$ kW of heat during winter. Then, it requires an equal amount of heat addition to maintain it at a desired temperature. Figure 2.8 illustrates the two methods for heating the room:

(i) Using electric resistance heater. The power consumption is

$$\dot{W} = \dot{Q}_k$$

(ii) Using heat pump. The power consumption is

$$\dot{W} = \frac{\dot{Q}_k}{\mathcal{E}_h} \cong \frac{1}{3}\dot{Q}_k$$

if $\mathcal{E}_h = 3$. Thus, power consumption of the heat pump is very much lower.

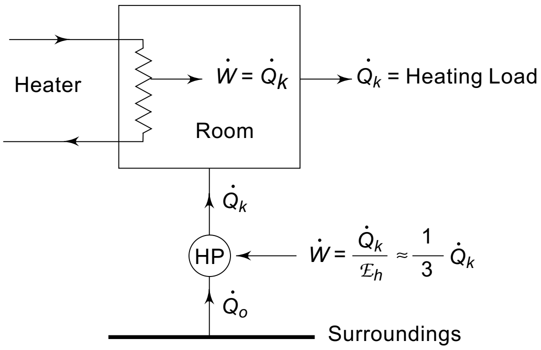

Fig. 2.8 Heating of a room by electric heater and heat pump

2.4 BEST REFRIGERATION CYCLE: THE CARNOT PRINCIPLE

It is possible to show that the cooling energy ratio of a refrigeration cycle working between two temperatures will be maximum when the cycle is a reversible one. For the purpose, consider a reversible refrigerating machine R and another irreversible refrigerating machine I, both working between two heat reservoirs at temperatures T_k and T_o, and absorbing the same quantity of heat Q_o from the cold reservoir at T_o as shown in Fig. 2.9 (a).

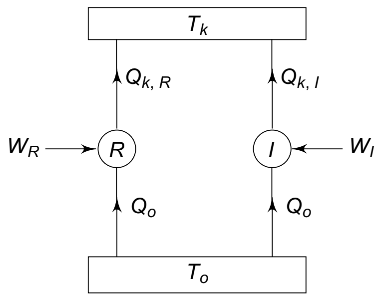

Fig. 2.9 (a) Reversible and irreversible refrigerating machines

Now, to prove the contrary, let us assume that the COP of the irreversible machine is higher than that of the reversible machine, viz., $\mathcal{E}_I > \mathcal{E}_R$. Hence

$$\frac{\dot{Q}_o}{W_I} > \frac{\dot{Q}_o}{W_R}$$

$$W_R > W_1$$

And since

$$Q_{k,R} = Q_o + W_R$$

$$Q_{k,I} = Q_o + W_I$$

we have

$$Q_{k,R} > Q_{k,I}$$

and

$$Q_{k,R} - Q_{k,I} = W_R - W_I = W_{net}$$