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Second law concepts

The second law of thermodynamics is a concept well understood and accepted by all mechanical engineering practitioners. The Kelvin–Planck statement of the second law tells us that *no system whose working fluid undergoes a cycle can receive heat from one source and produce work without rejecting heat to a lower temperature sink.* The interpretation is that if a thermodynamic engine is constructed to convert "heat energy" to shaft (mechanical) energy, some of the input energy must be "wasted" or rejected to a relatively low-temperature sink. The Clausius statement of the second law paraphrased states that *no refrigeration machine whose working fluid undergoes a cycle can receive heat from a low-temperature source and reject heat to a higher temperature receiver unless some external energy (from a level higher than the receiver temperature) is provided into the machine.*

Another well-understood concept by all mechanical engineers and other students of thermodynamics is the statement of the Carnot principle, which sets, in terms of the source and sink temperatures, the maximum effectiveness of either the heat engine or the refrigerating machine. For the heat engine, the efficiency (η) is defined as the shaft work output divided by the heat input from the high-temperature source. The maximum or Carnot efficiency, in turn, is:

$$\eta_c = (T_h - T_s)/T_h$$

where T_h is the absolute temperature of the higher temperature source and T_s is the absolute temperature of the lower temperature sink (see Fig. 27-1).

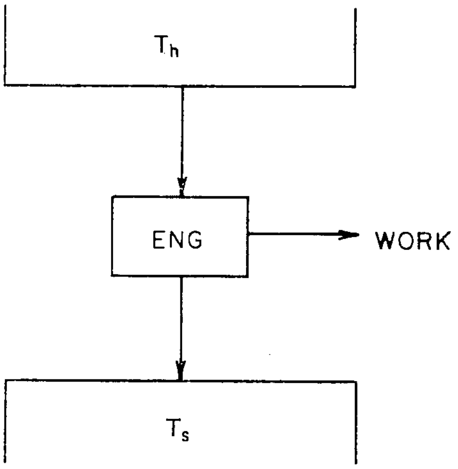

Fig. 27-1. Heat engine.

The effectiveness of the refrigerating machine is generally expressed as a coefficient of performance (COP), defined as the refrigeration effect (heat absorbed from the low-temperature source) divided by the external energy input. If T_s and T_l are the absolute temperatures of the higher temperature receiver and lower temperature source, respectively (Fig. 27-2), the Carnot, or maximum, coefficient of performance is:

$$\mathrm{COP}_C = T_l/(T_s - T_l).$$

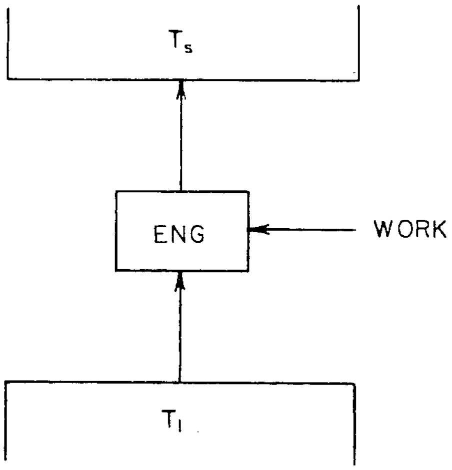

Fig. 27-2. Refrigerating machine.

For engineers, the major use of these Carnot values has been as guidelines in design development. If we want more shaft power per unit of input energy into the heat engine, it becomes immediately evident that we can achieve this by increasing the source temperature, reducing the sink temperature, or both. Similarly, with the refrigerating machine, to reduce the shaft or external energy input, we can raise the source temperature, lower the sink temperature, or both.

Another use is in evaluating the success of a design by comparing its effectiveness to the ultimate or Carnot value. Such a comparative analysis is developed in Chapter 60.

Students of thermodynamics have, however, identified some additional rather interesting aspects of the second law not commonly recognized by engineering practitioners. One of these is that a unit of thermal energy at a high-temperature level can readily be demonstrated to have more potential for heat at a lower level than the heat contained in the high-temperature substance. As an example, consider a flame, resulting from combustion of a fuel, at an average temperature of say 2000 F; it can be demonstrated through a simple second law analysis that many times more than the heating value of the fuel is theoretically available!

Referring to Fig. 27-3 there are three temperature levels, all expressed as absolute temperatures. T_h is the highest temperature source, T_s is a sink less than T_h, and T_l is a low-temperature source lower than T_s. Between T_h and T_s is an ideal or Carnot engine (ENG) that receives heat (Q_h) from the high-temperature source, rejects heat to the medium-temperature sink, and produces shaft work (W). Between T_s and T_l is a Carnot refrigerating machine (REF) that receives heat in the amount Q_l from the low-temperature source, motivated by the shaft work (W) produced by the engine, and rejects heat to the medium-temperature sink.

If the thermodynamic "system" is defined by the dashed boundary in Fig. 27-3, it is seen that there are two inputs, Q_h and Q_l, and two outputs. By combining the above two equations for Carnot efficiency and Carnot coefficient of performance, we can readily develop an expression for the coefficient of performance of the refrigerating machine in terms of the three temperature levels:

$$\mathrm{COP}_C = \frac{T_l}{T_h}\left(\frac{T_h - T_s}{T_s - T_l}\right).$$

This may be recognized as the common form of the ideal COP for absorption refrigeration machinery.

A first law balance on the "system" readily reveals that the rejected heat to T_s is identical to the sum of Q_h and Q_l. Since COP is described as the refrigeration effect divided by high-level energy input, then:

$$\mathrm{COP} = Q_l/Q_h.$$

The heat to the medium-temperature sink, Q_s, is then:

$$Q_s = Q_h + Q_h\,(\mathrm{COP})$$

or

$$Q_s = Q_h\left[1 + \frac{T_l}{T_h}\left(\frac{T_h - T_s}{T_s - T_l}\right)\right].$$

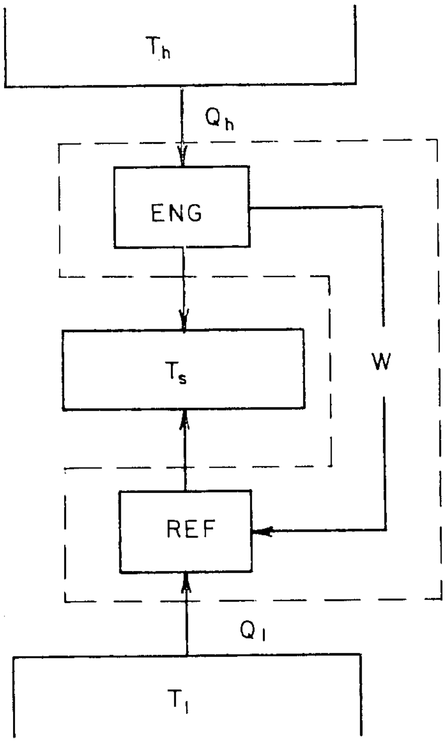

Fig. 27-3. Thermal cycle.

Cite common example

Consider a relatively common situation: T_h is a combustion flame at an average temperature of 2000 F; T_l is the outdoor ambient temperature of say 20 F; T_s is an indoor space temperature of say 70 F; and Q_h is the higher heating value of the fuel. Substituting the absolute temperature values into the above equation reveals:

$$\text{Heat to space} = \text{HHV} \times 8.53.$$

Thus, if the fuel is natural gas with a higher heating value of 1000 Btu per cu ft, the theoretical maximum amount of heat that the fuel could provide to the space under the conditions cited would be not 1000 Btu, but 8530 Btu—all with no wizardry or sleight of hand. This higher value could be referred to as the thermal availability. Further, if this fuel is burned at what would normally be considered 80 percent efficiency (first law basis), the 800 Btu obtained would represent only 9.4 percent of the energy theoretically available through second law conversion!

These concepts were generally developed in the nineteenth century but have been dusted off and reexamined in recent years. Because of technological problems relating to materials, economics, fluids, and the thermal loads themselves, it is recognized as totally impractical to even approach the second law availability value of the heat. But if the concept is kept off the shelf, it may help in more effective utilization of energy resources.