3.2 HEAT ENGINE

The device that does a conversion of heat to some other form of energy continually is called a heat engine. A heat engine must work in a cyclic process for the engine to convert heat to work continuously. Figure 3.1 shows the energy cycle of a heat engine schematically. As shown in this figure, an engine interacts with three external bodies:

1. The engine takes in energy Q_H from a hot bath, such as a furnace.

2. The engine produces work W through some mechanical apparatus, such as turbine which normally converts the mechanical energy to the electrical energy.

3. Finally, the engine gives up energy Q_C to a cold bath, such as cold water, in order to return to the initial state and complete the cycle.

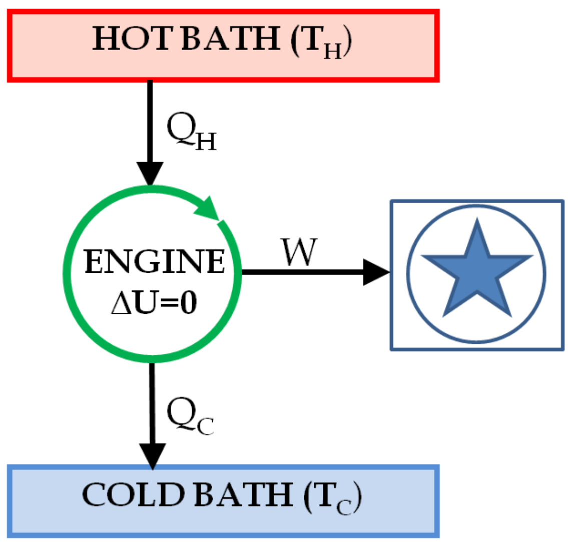

Figure 3.1: Schematics of energy flow in and out of a heat engine.

At the end of each cycle, the engine returns to the initial state, therefore, the net change in the internal energy of the engine would be zero. In each cycle, engine takes up energy Q_H and gives up energy $W + Q_C$. Therefore, the work by the engine would be the difference of heat in and heat out.

$$W = Q_H - Q_C, \tag{3.1}$$

where all quantities are positive. The **efficiency** of a heat engine η is defined as the ratio of the amount of net work W the engine produces in one cycle to the amount of heat Q_H transferred to the engine from the heat source.

$$\boxed{\eta = \frac{W}{Q_H}.} \tag{3.2}$$

Putting the expression of W from Eq. 3.1, the efficiency of a heat engine can he rewritten as follows.

$$\eta = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H}. \tag{3.3}$$

Clearly if all of heat taken (Q_H) is converted into work, i.e. when $Q_C = 0$, the efficiency will be 1, corresponding to a 100% efficient engine. Experience has shown that this is not possible. We will study next an ideal engine called the Carnot engine that puts a limit on the highest possible efficiency of a heat engine.

Example 3.2.1. Efficiency of a Heat Engine. In a steam engine, a fixed amount of water is the working substance which goes through a full cycle, from liquid water at a certain temperature and pressure to steam, and then back to the liquid water at the original temperature and pressure. The heat is put in the working substance, which is water here, in the step when liquid water is converted to steam. In some parts of the cycle the steam expands and the energy comes out of steam when the steam pushes on the blades of a turbine, and in some other parts, the water has to be pumped and compressed, which requires work also. In a certain steam engine, net work done by the working substance of the engine was 2000 J per cycle. If the efficiency of the steam engine is 40%, how much heat must be rejected in the cooling part of the cycle?

Solution. The net work W by the engine and the efficiency η of the engine are given here and we need to find Q_C. From the efficiency η and work W, we can find Q_H, and then using the energy balance, we will find Q_C.

$$\eta = \frac{W}{Q_H} \quad \Longrightarrow \quad Q_H = \frac{W}{\eta} = \frac{2000 \text{ J}}{0.4} = 5000 \text{ J}.$$

Now, from the energy balance over one cycle, we know that in an engine, $W = Q_H - Q_C$. Therefore,

$$Q_C = Q_H - W = 5000 \text{ J} - 2000 \text{ J} = 3000 \text{ J}.$$