

Thermodynamics
Professor Anand T N C
Department of Mechanical Engineering
Indian Institute of Technology, Madras
Lecture 60

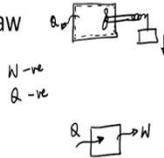
Second Law of Thermodynamics: Direct and Reverse Heat Engine

(Refer Time Slide: 00:13)



- Direct and Reverse heat engines

- Joule's experiment → First law
 - W and Q negative



- For W and Q to be positive, a direct heat engine is required e.g.:



- To transfer heat from low to high temperature, a reverse heat engine (heat pump) is required e.g.:



We discussed Joule's experiment when we introduced the first law of thermodynamics. A falling mass rotates a shaft having a fan at its one end. The fan churns fluid inside a rigid closed chamber. The temperature of the fluid increases after the process. Here, the system consists of the fluid inside the rigid chamber. The work is done on the system. Hence, the work interaction is negative for the system. The system also loses heat and comes back to its original state. Thus, heat interaction is also negative for the system. Here, both the interactions, work as well as heat, are negative.

A system for which both the interactions, heat as well as work, are positive is called a direct heat engine. This engine takes in heat and gives out work. A piston-cylinder assembly where a piston is free to move can be a direct heat engine. We can heat the gas inside this system. The gas expands and moves the piston doing work on the surroundings. Here, heat and work interactions are positive.

A reverse heat engine transfers heat from a source at low temperature to a source at high temperature using negative work interaction (work is done on the engine here). Refrigerators and

heat pumps are examples of a reverse heat engine. In refrigerators, heat is taken out of the region which needs to be kept cold (insides of the refrigerator) and it is rejected to the surroundings which is at higher temperature.

In a direct heat engine, we give in heat and get work out, whereas in a reverse heat engine, we give in work and extract heat out.

(Refer Time Slide: 05:07)

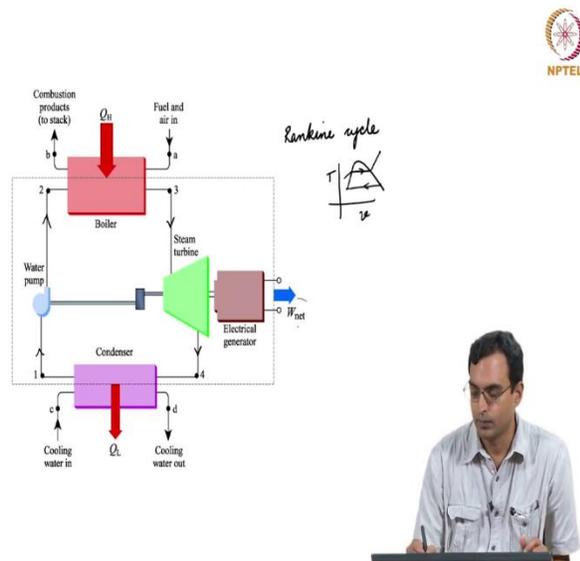
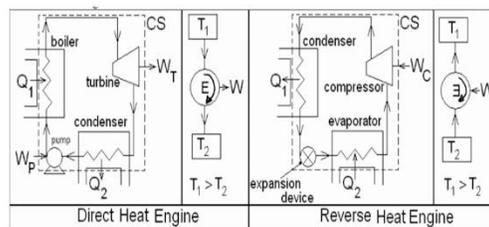


Figure 1.

A power plant is a direct heat engine. Figure 1 shows components of a steam power plant. It runs on a Rankine cycle which will be discussed in detail later in the course. There is boiler which takes in high pressure water coming from the pump. The boiler is a heat exchanger where high pressure water is heated by hot gases (which are generated by burning air and fuel) and converted into high pressure superheated steam. This superheated steam enters turbine where it expands and produces power. This power is used to run an electric generator to produce electricity. The steam comes out of the turbine at low pressure and low temperature and enters a condenser (which is also a heat exchanger). In the condenser, the steam is converted back to liquid water. This water then, is sent to the pump which pressurizes it. The high pressure water again enters the turbine and the cycle continues.

Here, the boiler takes in Q_H amount of heat. The turbine generates some amount of work. A fraction of that work is used to run the pump. The remaining is the net work output of the turbine, W_{net} . In the condenser, as the steam converts back into water, some heat is given out which is represented as Q_L . This heat equals latent heat of vaporization. So, we have heat input as Q_H , heat output/rejection as Q_L ($Q_H > Q_L$), and net work output as W_{net} . Hence, a steam power plant is a direct heat engine.

(Refer Time Slide: 08:58)



Thermal efficiency and COP

$$\eta = \frac{W_{net}}{Q_1}$$

Heat engine

$$COP_{HP} = \frac{Q_2}{W_{net}}$$

Coeff. of performance for Heat pump

$$COP_{Ref} = \frac{Q_1}{W_{net}}$$

Coeff. of performance for Refrigerator



Figure 2.

Figure 2 shows schematics representing a direct and reverse heat engines. In a direct heat engine (e.g. a steam power plant), the boiler takes in heat Q_1 at high temperature (T_1). The turbine produces work W_T . The pump takes in work W_P . The net work produced is $W = W_T - W_P$. The condenser gives out heat Q_2 at low temperature (T_2). So, the direct heat engine takes in some heat (Q_1) from a high temperature source/reservoir at T_1 , gives out net work W , and rejects some amount heat (Q_2) to the low temperature reservoir at T_2 . Also, $Q_2 < Q_1$. The heat engine shown here, runs in a cyclic process.

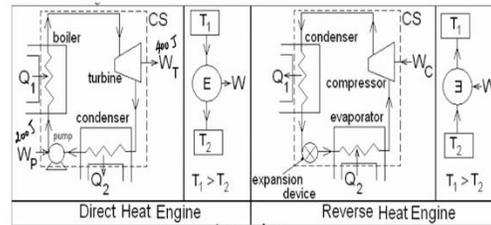
Similarly, we have a reverse heat engine where some amount of heat is absorbed from a low temperature reservoir, work is done on the heat engine and some amount of heat (which is greater than what is absorbed) is rejected to a high temperature reservoir. In Fig. 2, components

of a refrigerator are shown. The evaporator takes in Q_2 amount of heat from a low temperature reservoir at T_2 . Because of this, the refrigerant inside the evaporator vaporizes. The compressor takes in W_C amount of work to compress the refrigerant vapor to high pressure and temperature. The condenser rejects Q_1 amount of heat to a high temperature reservoir at T_1 . Because of this, the refrigerant converts into liquid. The expansion device cools the refrigerant (no work interaction is involved for the expansion device). Then, it enters the evaporator and the cycle repeats. We will discuss this refrigeration cycle in more detail later. So, a reverse heat engine takes in heat Q_2 from a low temperature reservoir at T_2 , takes in some work W (for a compressor), and rejects heat Q_1 to a high temperature reservoir at T_1 .

The efficiency of a direct heat engine is defined as what we want or we are interested in divided by what we need to give. For a direct heat engine, the efficiency $\eta = \frac{W_{net}}{Q_1}$ (Fig. 2). The purpose of a heat engine is to produce net work by taking in heat.

For a reverse heat engine, we have coefficient of performance (COP). Similar to the efficiency of a heat engine, COP is defined as what we want or what we are interested in divided by what we need to give. However, it depends on a device. For example, for heat pumps which are used in cold countries to heat insides of homes, we are interested in the amount of heat given by the heat pump (which is a reverse heat engine). For giving out some amount of heat, we need to give in some work (W_{net} or compressor work). Hence, for a heat pump, $COP_{HP} = \frac{Q_1}{W_{net}}$ (Fig. 2). For a refrigerator, we are interested in the amount heat it takes in (or removes) from the region to be kept cold. For removing that heat, we need to give in some work (W_{net} or compressor work). Hence, for a refrigerator, $COP_R = \frac{Q_2}{W_{net}}$ (Fig. 2).

(Refer Time Slide: 16:52)



First law $\oint \delta W = \oint \delta Q \Rightarrow \Sigma \delta W = \Sigma \delta Q$

$$Q_1 + (-Q_2) = W_T + (-W_P) \quad \text{turbine + pump}$$

$$Q_1 - |Q_2| = W_T - |W_P| = W_{net}$$

$$-Q_1 + Q_2 = -W_C$$

$$Q_1 - |Q_2| = W_C$$

$$\Sigma \delta W = 500 + (-300) \quad \Sigma \delta W = 400 - [200]$$

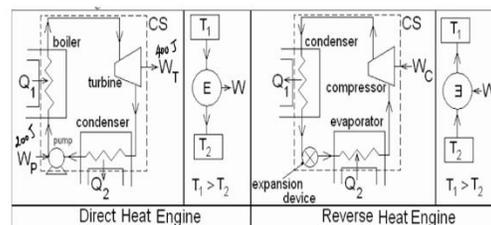
$$500 - 300$$



Figure 3.

For a direct heat engine, which runs in a cyclic process, as shown in Fig. 3, the first law states $\oint \delta Q = \oint \delta W$. Hence, $Q_1 + (-Q_2) = W_T + (-W_P)$ considering the sign conventions for heat and work transfer. We can also write it as $Q_1 - |Q_2| = W_T - |W_P| = W_{net}$ (we have taken out the negative sign already).

(Refer Time Slide: 21:18)



First law $\oint \delta W = \oint \delta Q \Rightarrow \Sigma \delta W = \Sigma \delta Q$

$$Q_1 + (-Q_2) = W_T + (-W_P) \quad \text{turbine + pump}$$

$$Q_1 - |Q_2| = W_T - |W_P| = W_{net} \quad \text{Heat engine}$$

$$-Q_1 + Q_2 = -W_C$$

$$Q_1 - |Q_2| = |W_C| \quad \text{Heat pump}$$



Figure 4.

Similarly for a reverse heat engine which runs in a cyclic process as shown in Fig. 4, the first law reduces to $-Q_1 + Q_2 = -W_C$. Multiplying by -1, we get, $Q_1 - Q_2 = W_C$. It can also be written as $|Q_1| - Q_2 = |W_C|$.

(Refer Time Slide: 23:36)

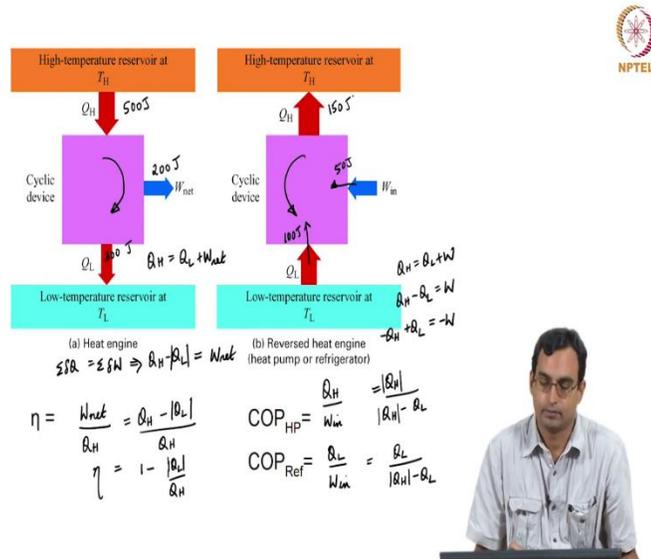


Figure 5.

Figure 5 shows the schematics of a direct heat engine and a reverse heat engine (running in a cycle). For a direct heat engine, $\eta = \frac{W_{net}}{Q_H} = \frac{Q_H - |Q_L|}{Q_H} = 1 - \frac{|Q_L|}{Q_H}$, where Q_L and Q_H are the heat rejected to the low temperature reservoir at T_L and the heat absorbed from the high temperature reservoir at T_H , respectively. Here, according to the first law for a cyclic process, $W_{net} = Q_H - |Q_L|$.

For a heat pump (which is a reverse heat engine), $COP_{HP} = \frac{Q_H}{W_{in}} = \frac{|Q_H|}{|Q_H| - Q_L}$, where Q_H is the heat rejected to the high temperature reservoir at T_H , Q_L is the heat absorbed from the low temperature reservoir at T_L , W_{in} is the work input to the heat pump.

For a refrigerator (which is a reverse heat engine), $COP_R = \frac{Q_L}{W_{in}} = \frac{Q_L}{|Q_H| - Q_L}$.

(Refer Time Slide: 29:16)



$$W = \int p dV$$
$$W = p \int dV = p(V_2 - V_1)$$



Second Law of thermodynamics

- Kelvin-Planck statement
- Clausius statement



Correction: p_2 should be equal or lower than p_1

The heat engine essentially converts heat into work. This work, then, can be converted into, for example, electricity. The electricity can be used to do work, for example, run household electrical appliances.

Why do we have to run the heat engine in a cycle?

Consider a piston-cylinder arrangement containing gas where the piston is free to move. If we give in some amount of heat Q , the gas expands moving the piston and we get work W . If we need a large quantity of work, we need to give in large amount of heat and the displacement of the piston has to be large, because we know that the displacement work is given by $\int p dV$. The change in volume has to be large if we want a large quantity of work (assume that the process is a constant pressure process). Giving in large amount of heat is possible. However, for the change in volume to be large, the cylinder length has to be large. Such a long cylinder is difficult to manufacture and expensive.

The solution for this problem is to run the engine in a cycle. Give in some amount of heat initially. Let the piston move and extract some work W . Now, bring the piston back to initial location (by extracting out heat maybe). Give in some heat again, let the piston move, extract work and bring the piston back to its initial location. This is a cyclic process. This way we do not need a long cylinder to extract a large quantity of work.

Hence, a direct and a reverse heat engine run in a cycle.

(Refer Time Slide: 33:08)



High-temperature reservoir at T_H

$Q_H = 500\text{ J}$

Cyclic device

$W_{net} = 200\text{ J}$

Low-temperature reservoir at T_L

$Q_L = 300\text{ J}$

$Q_H = Q_L + W_{net}$

(a) Heat engine

$\oint \delta Q = \oint \delta W \Rightarrow Q_H - Q_L = W_{net}$

$\eta = \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H}$

$\eta = 1 - \frac{Q_L}{Q_H}$

High-temperature reservoir at T_H

$Q_H = 160\text{ J}$

Cyclic device

$W_{in} = 50\text{ J}$

Low-temperature reservoir at T_L

$Q_L = 110\text{ J}$

$Q_H - Q_L = W$

$-Q_H + Q_L = -W$

(b) Reversed heat engine (heat pump or refrigerator)

$COP_{HP} = \frac{Q_H}{W_{in}} = \frac{Q_H}{|Q_H - Q_L|}$

$COP_{Ref} = \frac{Q_L}{W_{in}} = \frac{Q_L}{|Q_H - Q_L|}$



(Refer Time Slide: 33:23)





$W = \int p dV$

$W = p \Delta V = p(V_2 - V_1)$



Second Law of thermodynamics

- Kelvin-Planck statement
- Clausius statement



(Refer Time Slide: 33:30)



- K-P: It is impossible for a device operating in a thermodynamic cycle to produce work while having heat interaction with a single reservoir at any T
- Such an impossible engine is called PMM2 – perpetual motion machine of 2nd kind
- Efficiency $(\eta) < 1$



Knowing this we can on to the Kelvin-Planck and Clausius statements of the second law of thermodynamics.

The Kelvin-Planck statement says it is impossible for a device operating in a thermodynamic cycle to produce work while having heat interaction with a single reservoir at any temperature.

(Refer Time Slide: 33:58)



- Clausius: It is impossible for any device operating in a thermodynamic cycle to transfer heat from a low T region to a high T region without the help of work interaction from the surroundings
- COP cannot be infinite



The Clausius statement says it is impossible for any device operating in a thermodynamic cycle to transfer heat from a low temperature region to a high temperature region without the help of work interaction from the surroundings.

(Refer Time Slide: 34:20)



$$W = \int p \, dV$$
$$W = p \, \Delta V = p(V_2 - V_1)$$



Second Law of thermodynamics

- Kelvin-Planck statement
- Clausius statement



We will look at these in detail in the next lecture.

Let's look at the concept of a perpetual motion machine of the first kind. The first law tells us that energy is conserved. It can neither be created nor destroyed, but you can transform it from one form to another.

Consider a hypothetical machine which keeps generating energy out of nothing. Such a machine would violate the first law, because the first law says energy cannot be created or destroyed. The machine which violates the first law of thermodynamics is called a perpetual motion machine of the first kind (PMM1). Such a machine can keep on producing energy forever.