Thermodynamics
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Lecture – 84
Thermodynamics Cycles: Rankine Cycle

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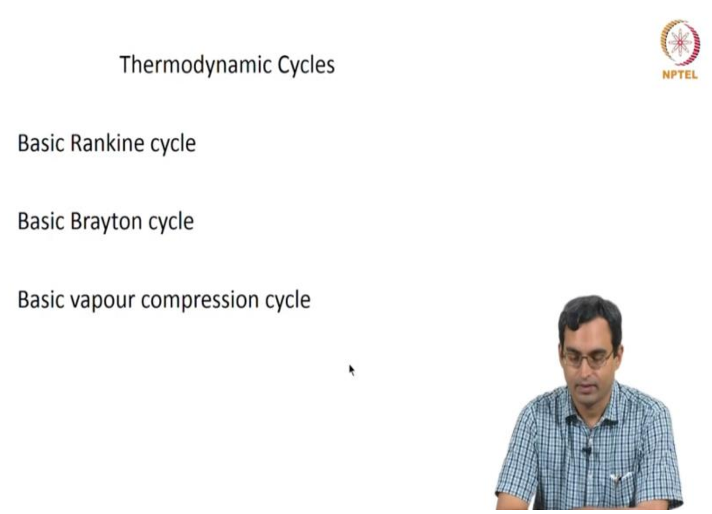

Let’s study the basic Rankine cycle.

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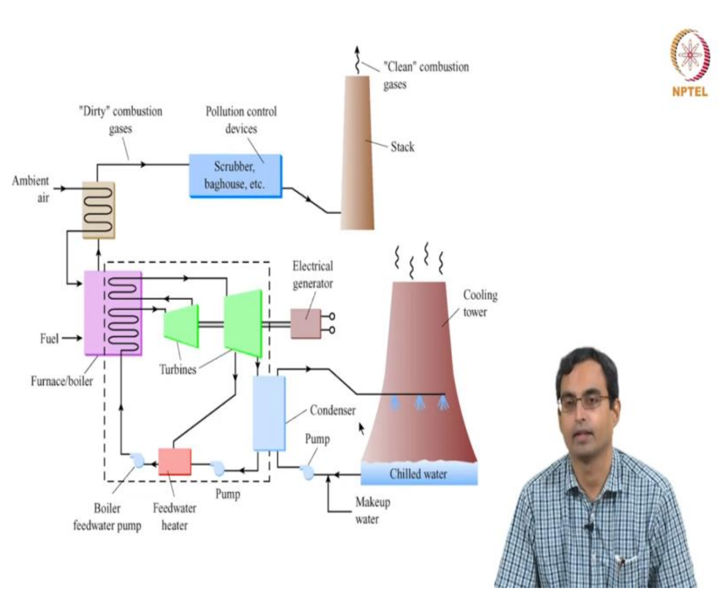

Figure 1.

Figure 1 shows a power plant which employs the Rankine cycle. It has a boiler which takes in air-fuel mixture (fuel could be coal, natural gas, etc). The air-fuel mixture is burned and hot gases form inside the boiler. These hot gases give their heat to water and convert water into steam. The hot gases then, are sent out. In some plants these gases are used to preheat the air entering the boiler for forming air-fuel mixture. These hot gases contain harmful emissions. They are sent to pollution control devices for removing those harmful emissions after which they are sent to stack where they cool. Then, they get out into the environment as clean combustion gases. The steam, after leaving the boiler, enters 1 or 2 turbines. The steam is expanded inside the turbine generating shaft work. The shaft is connected to electrical generator for generating electricity. The steam leaving turbine is at low pressure and low temperature. This low-pressure-low-temperature steam enters a condenser where it condenses back into water. Inside the condenser, chilled water is used to cool down the steam. The steam loses heat to this water which, after leaving the condenser, enters the cooling tower where it is sprayed to cool it down through evaporative cooling. In this process, some water is lost because of evaporation. Hence, we need to add make up water. The condensed water in the condenser is sent back to the boiler through a pump. Sometimes the water entering the boiler is preheated through a feedwater heater, which uses a small quantity of steam from the turbine to heat water.

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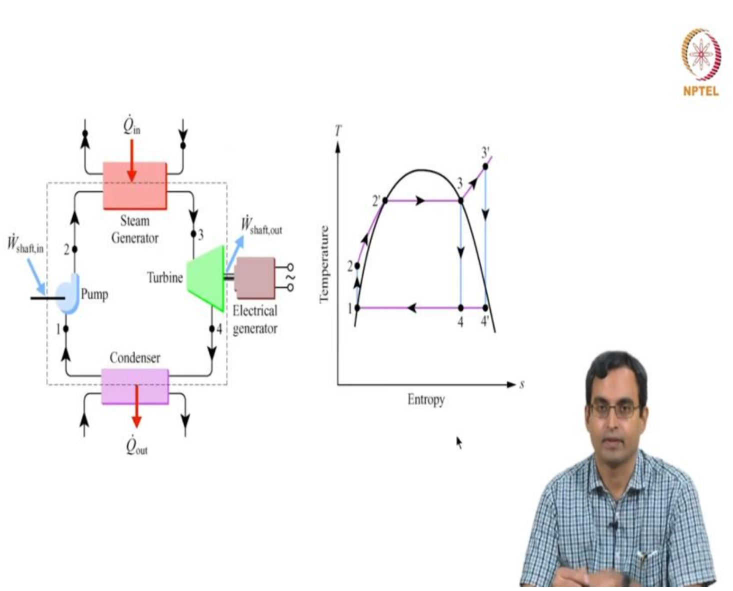

Figure 2.

Essentially, the system consists of 4 components, a boiler (a steam generator), a turbine, a condenser and a pump as shown in Fig. 2. The system here undergoes a cyclic process. The same fluid flows through all the components. The mass of the fluid is constant (in reality, we keep supplying fluid at some places in the cycle as we lose fluid because of some problems or necessities). This system consisting of the four components is a closed system, even though the components individually are open systems as the fluid enters and leaves them at certain mass flow rates. The system interacts with the surroundings through heat and work interactions. We have heat interactions for the boiler and the condenser, and work interactions for the turbine and the pump.

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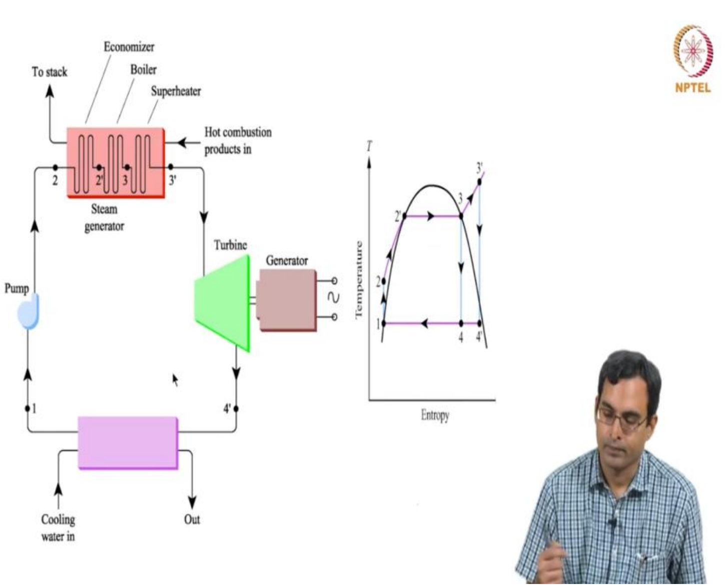

Figure 3.

The pump receives the low temperature low pressure liquid from the condenser and gives out high pressure low temperature liquid. This liquid enters the boiler. The boiler is made of 3 parts, economizer, boiler and superheater (Fig. 3). We will study them in detail later on. The boiler gives out high pressure high temperature steam. This team expands inside the turbine and comes out as low pressure low temperature steam. This steam enters the condenser and comes out as low pressure low temperature liquid, which is sent to the pump, and the cycle continues.

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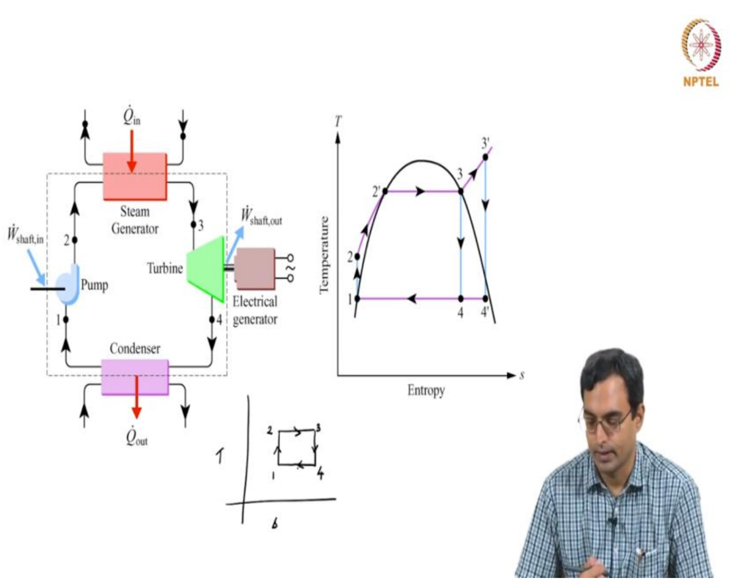

Figure 4.

We know that the Carnot's cycle is the most efficient cycle between a given heat source and a heat sink. The Carnot's cycle consists of two isothermal processes and two isentropic processes. The hand-drawn T-S diagram for the Carnot's cycle is shown in Fig. 4. 1-2 is a reversible adiabatic process which is compression. 2-3 is an isothermal process where we have heat addition. 3-4 is a reversible adiabatic process where we have expansion. 4-1 is an isothermal process where we have heat rejection. So, in the case of the Carnot's cycle, the process 1-2 happens inside a compressor, and the process 3-4 happens inside a turbine. The processes 2-3 and 4-1 happen inside isothermal heat exchangers. But there are practical issues with the Carnot's cycle.

Isothermal heat transfer involving a single phase substance is not achievable. Hence, the processes 2-3 and 4-1 are not achievable for a single phase substance (i.e. for only gas or only liquid). However, as we have seen earlier, isothermal heat transfer is possible during a phase change process inside a liquid-vapor dome. In this process, the temperature and pressure, both remain constant.

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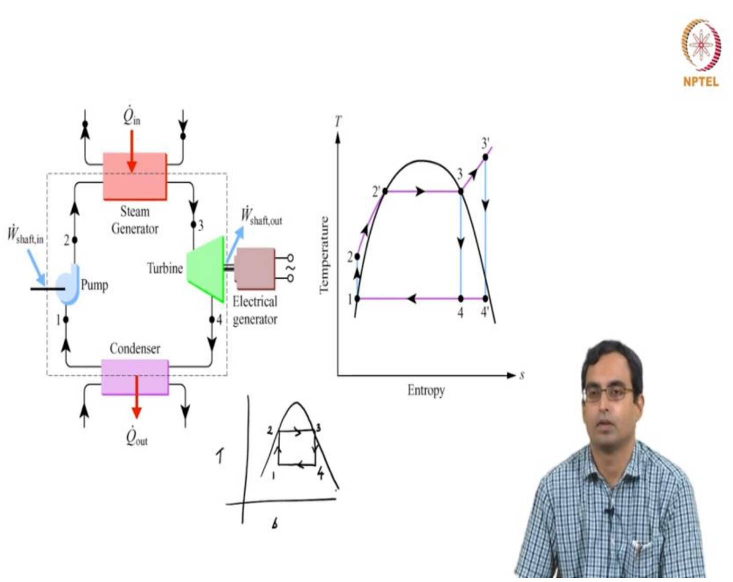

Figure 5.

Figure 5 shows the hand-drawn T-S diagram of the Carnot's cycle inside the liquid-vapor dome. Here, we are dealing with a mixture of liquid and vapor. The process 3-4, which is isentropic expansion, happens in a turbine. It is difficult to design turbine which works with a mixture of liquid and vapor. The turbines rotate at very high speeds. The liquid droplets in a two phase mixture can damage the blades of the turbine. Turbines are designed to work with single phase, i.e., only gases or only liquids.

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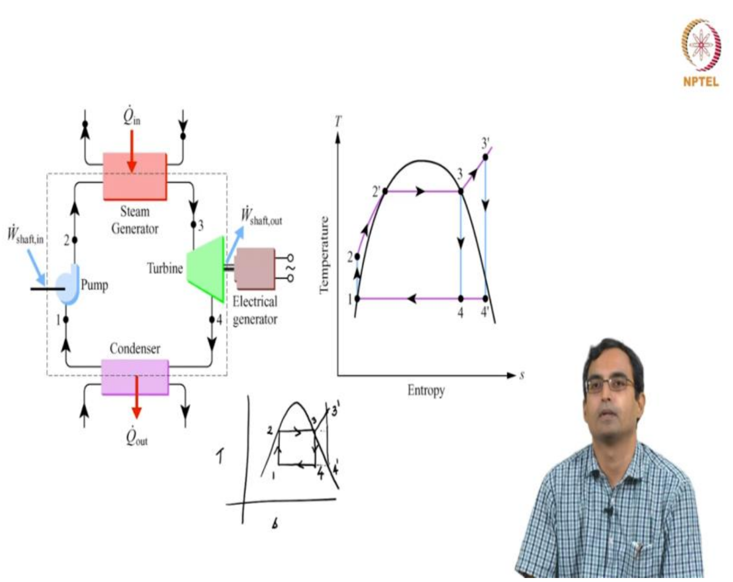

Figure 6.

The solution is to move the process of expansion outside the liquid-vapor dome, where the turbine deals with only a gas phase. The process of heat addition 2-3 is extended till state 3` (Fig. 6). The process 2-3-3` is isobaric. The portion 3-3` cannot be isothermal as it is difficult to achieve isothermal process in a single phase region, as discussed before. Now, the process 3`-4`, which is in a single phase region, happens in the turbine. So, the states 3 and 4 in the Carnot's cycle are changed to 3` and 4`. Hence, the heat rejection process is now from 4` to 1 instead to 4 to 1.

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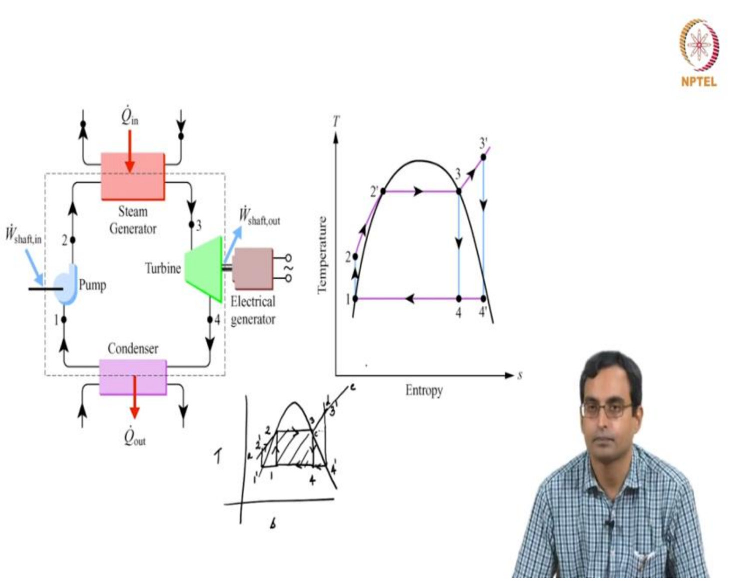

Figure 7.

There is still a problem with the compression process from 1 to 2 (Fig. 7). It is difficult to compress a mixture of liquid and vapor. The compression devices work with only gases or only liquids. Hence, it is logical to let the heat rejection process 4\`-4-1 end at a state on the saturated liquid line, which is 1\` (Fig. 7). Now, we can have a pump compressing the liquid from 1\` to 2\` isentropically. The state 2\` is located at the intersection of isentrope starting at 1\` and the isobar going through states 2, 3 and 3\`. We also know that the compression work for an isentropic pump is given as $|w| = \int v dp$. Since the specific volume of liquid is far smaller than the gas, the work needed for compressing the liquid is significantly small compared to compressing a gas.

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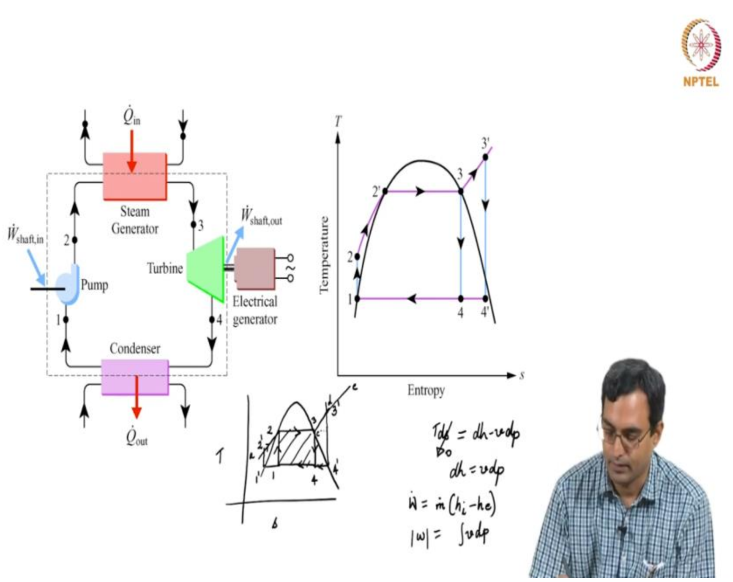

Figure 8.

After incorporating all the changes suggested above, the cycle becomes 1`-2`-2-3-3`-4`-4-1-1`(hand-drawn cycle in Fig. 8). Let's rename state 1` by 1 and erase 1. The Rankine cycle (1-2`-2-3-3`-4`-1) is shown on the T-S diagram in Fig. 8 (top right corner).

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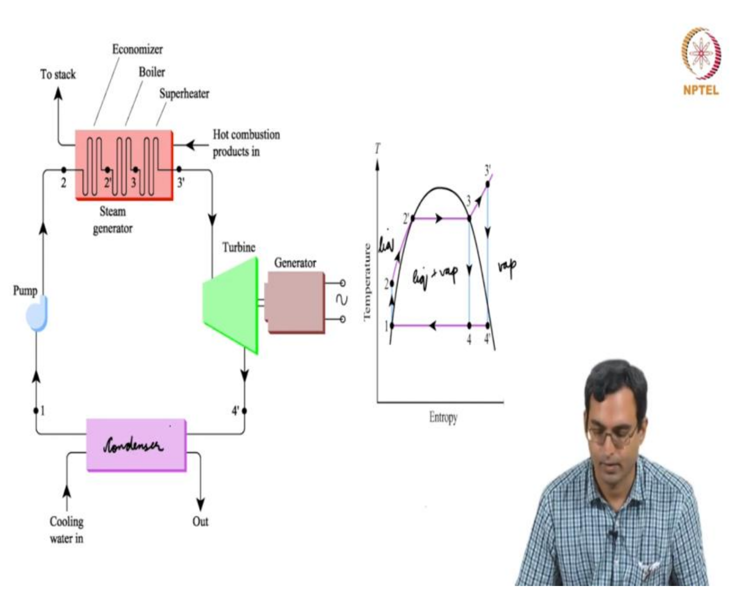

Figure 9.

We have four processes in the Rankine cycle:

1. Process 1-2` – isentropic compression of low pressure low temperature liquid in a pump

2. Process 2`-2-3-3` - constant pressure heat addition in a boiler

The process 2`-2 happens inside the economizer where only liquid is heated at constant pressure (Fig. 9). The process 2-3 happens inside the boiler where heat addition happens at a constant pressure and constant temperature as it is a phase change process (Fig. 9). The process 3-3` happens inside the superheater where only steam is heated at a constant pressure (Fig. 9).

3. Process 3`-4` - isentropic expansion of high pressure high temperature steam in a turbine

4. Process 4`-1 – constant pressure heat rejection in a condenser

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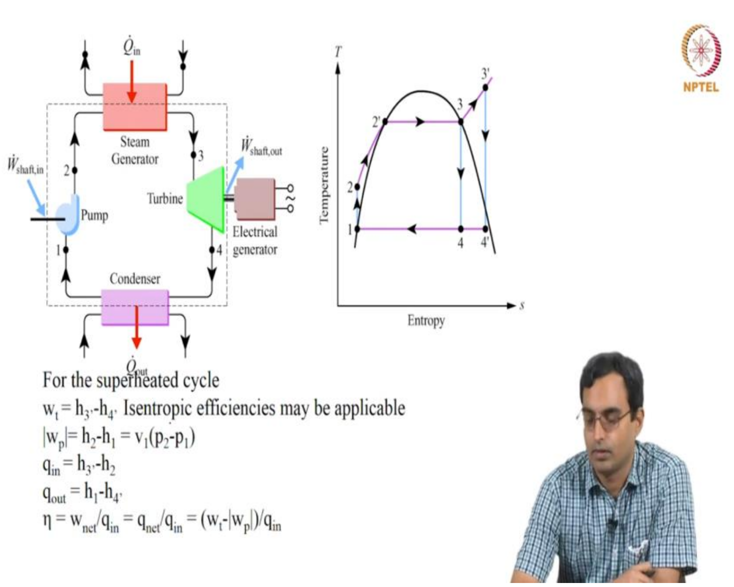

Figure 10.

Figure 10 shows formulae for calculating heat and work interactions for the Rankine cycle on unit mass basis. We have already derived these formulae in previous lectures.

1. Turbine work output: $w_t = h_{3`} - h_{4`}$ (isentropic efficiency needs to be considered if given, which we have discussed in the previous lectures)

2. Work input to pump: $|w_p| = h_2 - h_1 = v_1(p_2 - p_1)$ (isentropic efficiency needs to be considered if given, which we have discussed in the previous lectures)

Work input to a pump is negative as work is being done on the pump. For a non-isentropic process, $|w_p| = v_1(p_2 - p_1)$ is not applicable.

3. Heat transfer in the boiler: $q_{in} = h_{3`} - h_2$ (q_{in} is positive)

4. Heat transfer in the condenser: $q_{out} = h_1 - h_{4`}$ (q_{out} is negative)

5. Efficiency of the cycle, $\eta = \frac{w_{net}}{q_{in}} = \frac{q_{net}}{q_{in}} = \frac{w_t - |w_p|}{q_{in}}$

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