Thermodynamics
Professor Anand T N C
Department of Mechanical Engineering
Indian Institute of Technology, Madras
Lecture – 86
Thermodynamics Cycles: Brayton Cycle

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Figure 1.

Let's study the Brayton cycle which is used in gas turbine engines. Figure 1 shows a turbofan engine used on aeroplanes, which runs on the Brayton cycle.

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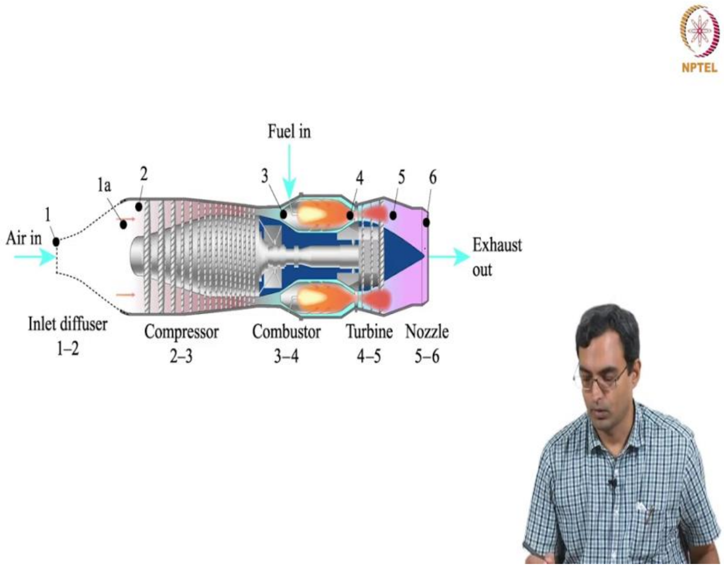

Figure 2.

Figure 2 shows a gas turbine engine on an aeroplane. It consists of a diffuser, a compressor, a combustor, a turbine and a nozzle. The diffuser slows down the flow of air and increases its pressure. Compressor further increases the pressure through multiple stages. In the combustor, a fuel is added to high pressure air and burned, producing hot gases. These high-enthalpy-high temperature-high-pressure gases are expanded partially through the turbine generating work. This work can be used to run the compressor upstream. The gases after coming out of the turbine expand in the nozzle giving thrust. Here, the gas enters and leaves the system. It does not undergo a cyclic process.

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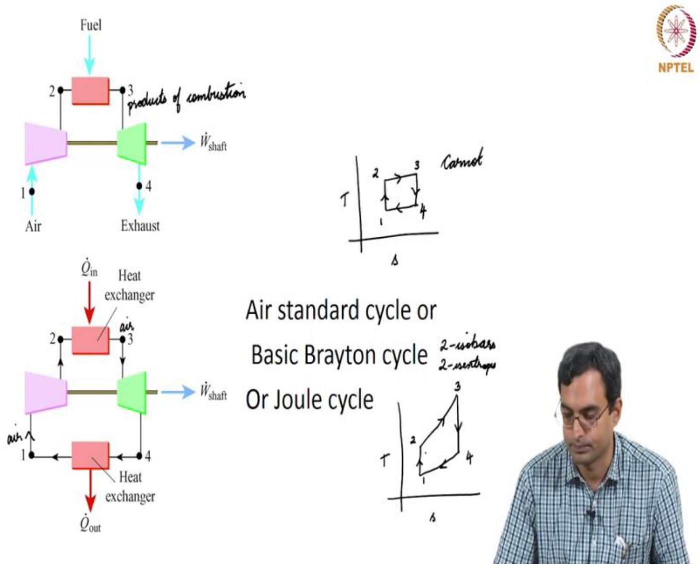

Figure 3.

We replace the actual process (shown in the top left corner of Fig. 3) in the gas turbine engine by a hypothetical one (shown in the bottom left corner of Fig. 3) where air undergoes a cyclic process. This cycle is called air standard cycle or the basic air standard Brayton cycle or the Joule cycle.

The compressor takes in air at low pressure and temperature, compresses it and gives out high pressure and high temperature air. At point 2, this air enters a heat exchanger where heat is added to it at constant pressure (in reality, fuel is added and burned). At point 3, we have high pressure high temperature air. This air enters a turbine, expands and comes out as low pressure low temperature air. During expansion in the turbine, work is produced. Some of that work is used to run the compressor. Depending on the application, the work is used to generate electricity. The low pressure low temperature air at point 4 enters a heat exchanger where it rejects heat at constant pressure, and comes out, at even lower temperature, at point 1, where it enters the compressor and undergoes the cycle again.

To get the maximum work, we would like to have a Carnot's cycle as shown on a T-S diagram in Fig. 3. However, as mentioned before, isothermal heat addition and rejection is not possible if we are dealing with single phase of a substance. Here, the working substance is air. However, isobaric heat transfer is possible. Hence, the processes 2-3 and 4-1, where heat transfers occur, are converted to isobaric processes (Fig. 3). The processes 1-2 and 3-4, where compression and expansion occurs, can remain isentropic. Hence, the basic Brayton cycle consist of two isobaric and two isentropic processes. On a T-S diagram, the isobaric processes, 2-3 and 4-1, diverge from each other (we have discussed this before).

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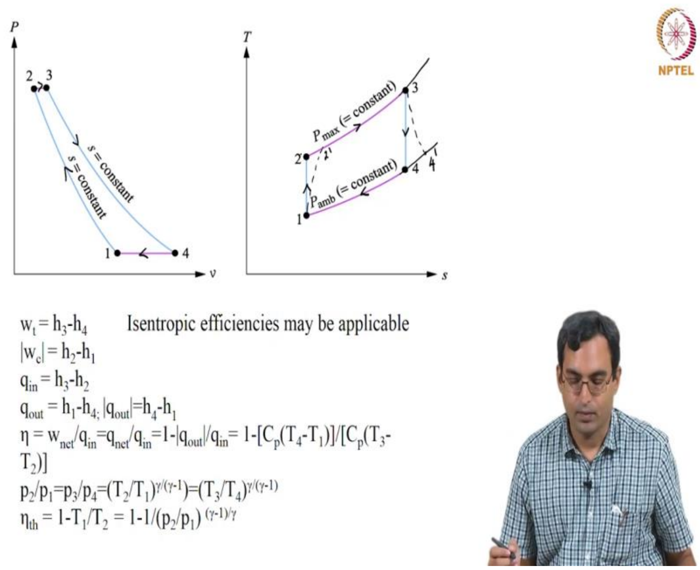

Figure 4.

Figure 4 shows the Brayton cycle on a p-v and a T-s diagram. On the T-s diagram, the length 1-2 is smaller than the length 3-4 as the isobars diverge. We know that the processes 1-2 and 3-4 may not be isentropic. In this case, isentropic efficiencies are given. Non-isentropic processes are shown by dotted lines on the T-s diagram in Fig. 4. Considering non-isentropic processes, the cycle is 1-2`-3-4`-1.

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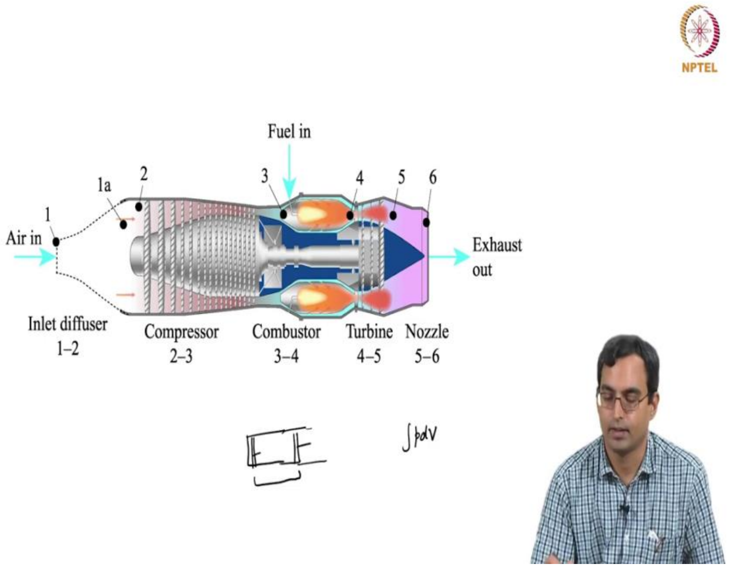

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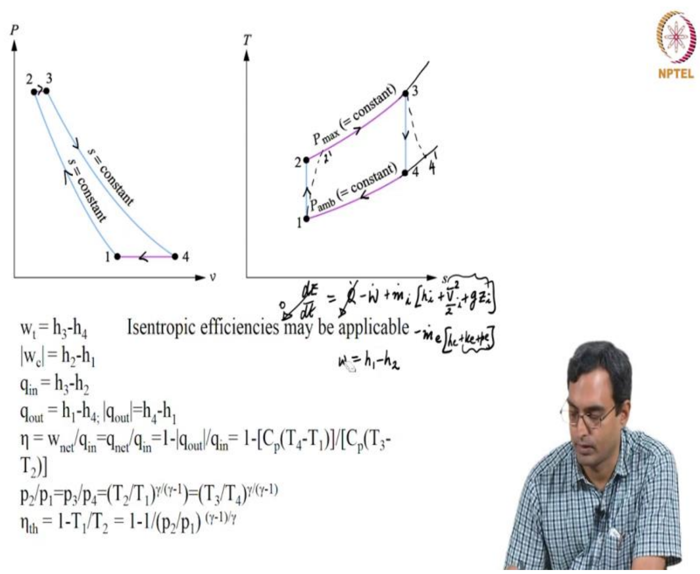

Figure 5.

Figure 5 shows expressions/formulae for work and heat interactions, efficiencies, pressure ratio associated with the Brayton cycle.

The expressions for the work and heat interactions can be derived from the expression of the first law for a control volume (we have already looked at such derivations in the case of a compressor, turbine, heat exchangers, etc.). Below are mentioned those expressions for the Brayton cycle shown in Fig. 5:

1. Turbine work output: $w_t = h_3 - h_4$ (Isentropic efficiencies need to be considered if given)

Assumptions made to arrive at this expression are (a) steady state operation, (b) adiabatic process, (c) kinetic and potential energy changes are negligible, (d) turbine has a single inlet and outlet

2. Compressor work input: $w_c = h_1 - h_2 \; or \; |w_c| = h_2 - h_1$ (Isentropic efficiencies need to be considered if given. The assumptions made here are the same as those for the expression of turbine work output)

3. Heat addition: $q_{in} = h_3 - h_2$

4. Heat rejection: $q_{out} = h_1 - h_4 \; or \; |q_{out}| = h_4 - h_1$

5. Efficiency: $\eta = \frac{w_{net}}{q_{in}} = \frac{q_{net}}{q_{in}} = \frac{q_{in} - |q_{out}|}{q_{in}} = 1 - \frac{|q_{out}|}{q_{in}} = 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)}$ [assuming air as an ideal gas, $|q_{out}| = h_4 - h_1 = C_p(T_4 - T_1)$ and $q_{in} = h_3 - h_2 = C_p(T_3 - T_2)$]

6. Pressure ratio: $\frac{p_2}{p_1} = \frac{p_3}{p_4} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{T_3}{T_4}\right)^{\frac{\gamma}{\gamma-1}}$

1-2 and 3-4 are reversible adiabatic processes. Air is considered as an ideal gas. Using $pv^\gamma = c$ and $pv = RT$, one can derive the above pressure ratio expression.

7. Efficiency of the cycle is also given by, $\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{1}{\left(p_2/p_1\right)^{\frac{\gamma-1}{\gamma}}}$

Students are encouraged to derive this expression (Hint: use expressions in 5 and 6). The expression for the efficiency looks similar to the one for the Carnot's cycle. The efficiency is the function of temperatures at the beginning and end of the compression process.

From 6, taking $\gamma = 1.4$, we can conclude that the pressure ratio is higher than the temperature ratio, i.e., the pressure changes a lot from 1 to 2, but temperature does not change significantly.

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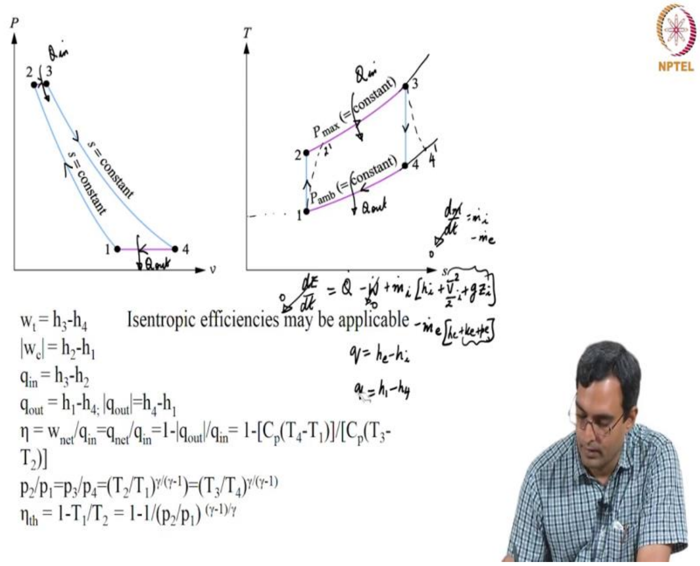

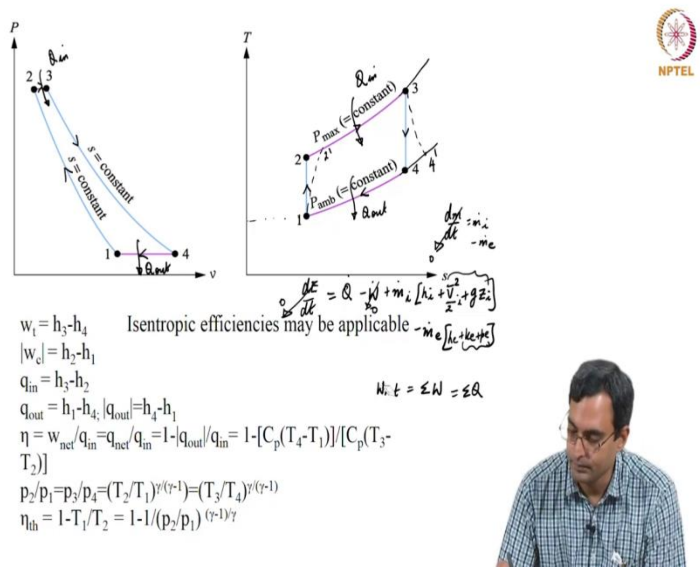

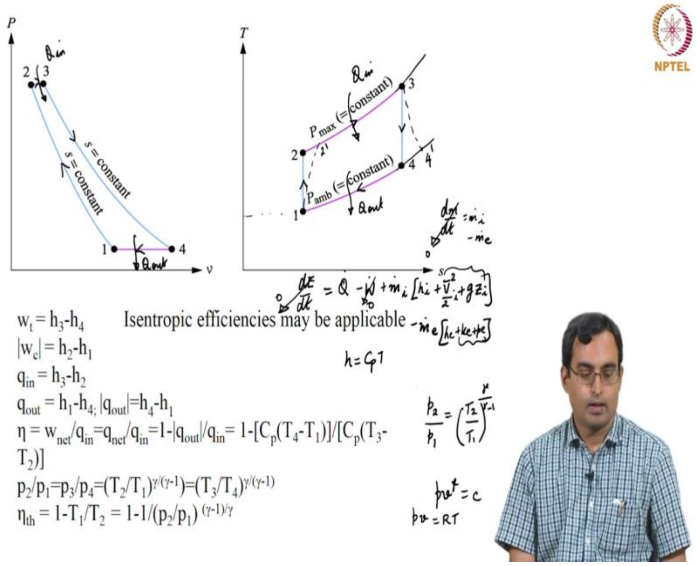

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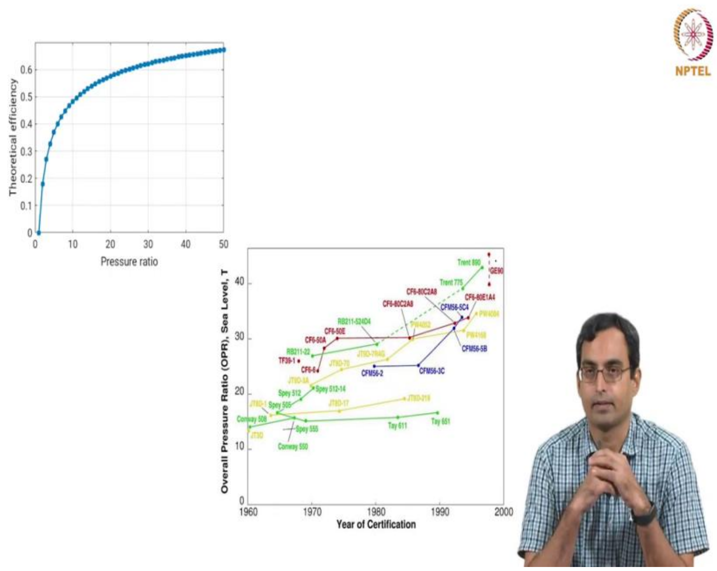

Figure 6.

Figure 6 shows a plot of theoretical efficiency versus pressure ratio for the Brayton cycle. As the pressure increases, the theoretical efficiency increases. We know that the efficiency of such a cycle cannot be 100 %. Figure 6 also shows overall pressure ratios employed in the actual engines on aeroplanes over the years. We can see that with time, attempts are being made to increase the pressure ratio, and hence, the efficiency of the Brayton cycle.