Basics of Mechanical Engineering-3

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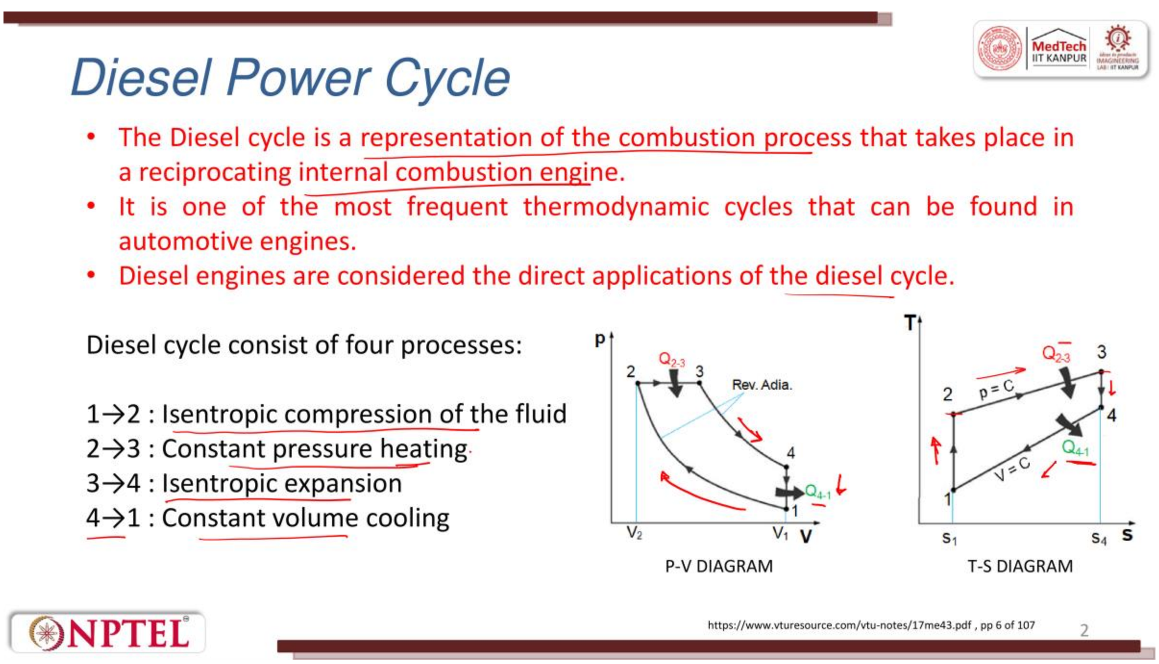
Week 05

Lecture 21: Tutorial 4 Power Cycles, Part 2 of 2

Welcome back to the course Basics of Mechanical Engineering 3. I am discussing the tutorial on the power cycles. I have discussed in the third tutorial of this course the Otto power cycle in the previous part. This is the second part of the third tutorial, where I will discuss the Diesel power cycle.



To recall the concept of the Diesel power cycle, the Diesel cycle is just like the Otto cycle, another representation of the combustion process that takes place in reciprocating internal combustion engines.

The Otto power cycle was a typical spark-ignition piston engine. Diesel power is a reciprocating internal combustion engine. One of the most frequent thermodynamic cycles that can be found in automotive engines. Diesel engines are considered the direct applications of the Diesel cycle. The Diesel cycle consists of four processes.

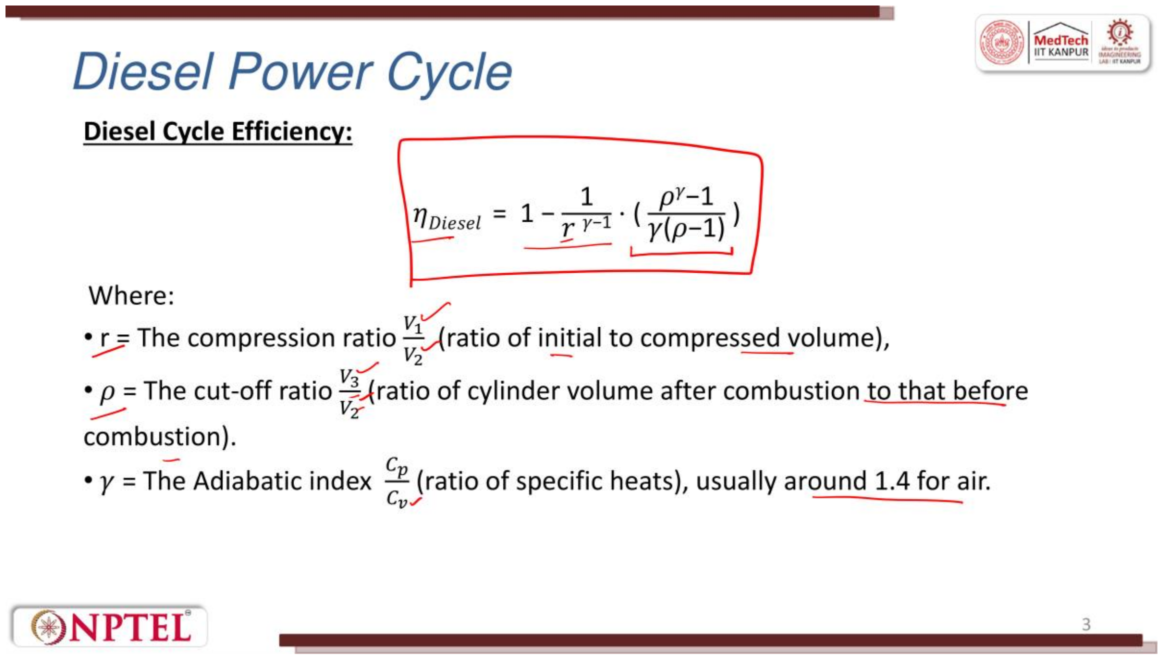
That is, 1 to 2 is isentropic compression. From 1 to 2, when it goes, it is isentropic compression. Isentropic means entropy does not vary. In the TS diagram, you see the entropy is constant here from 1 to 2. Then the process 2 to 3 is constant pressure heating.

At constant pressure, when we say heating, the temperature rises. And the temperature rises from 2 to 3 here. You can see the temperature difference between stages two and three in the TS diagram. But the pressure is constant at stage two and stage three. The pressure is constant.

Then comes process three to four, which is isentropic expansion. Now the expansion occurs here because it happens from three to four. We have the volume increases. It is from 3 to 4. There is an increase in volume.

And this is isentropic. The entropy does not change. Then comes process 4 to 1. That is constant volume cooling. Like heating was there.

This was exactly opposite to it. Constant volume cooling from 4 to 1. That is the entropy decreases. And when it is cooling, there is heat rejection. You can see Q421 is heat rejection. And there was heat addition Q223 when constant heating was there.

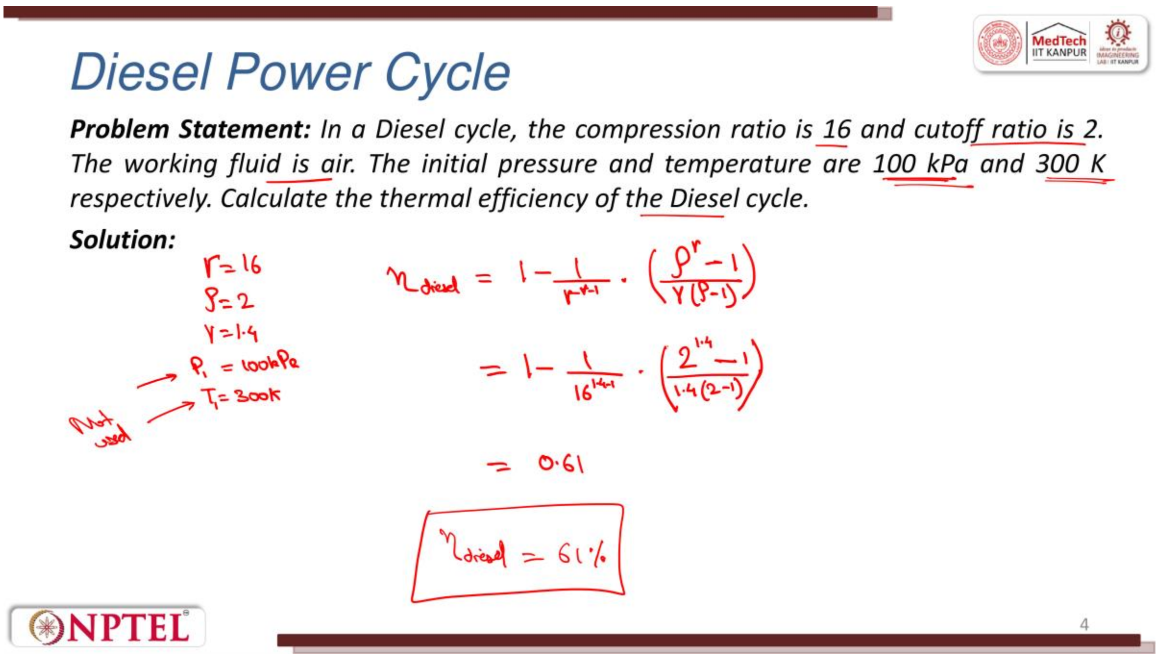


Let me try to see some relations in the diesel cycle. For instance, the efficiency of a diesel cycle is given by the relation

$$\eta_{Diesel} = 1 - \frac{1}{r^{\gamma-1}} \cdot \left(\frac{\rho^{\gamma}-1}{\gamma(\rho-1)} \right)$$

Where:

- r = The compression ratio $\frac{V_1}{V_2}$ (ratio of initial to compressed volume),
- ρ = The cut-off ratio $\frac{V_3}{V_2}$ (ratio of cylinder volume after combustion to that before combustion).
- γ = The Adiabatic index $\frac{C_p}{C_v}$ (ratio of specific heats), usually around 1.4 for air.



Let me directly come to a problem statement. In a Diesel cycle, the compression ratio is 16 and cutoff ratio is 2. The working fluid is air. The initial pressure and temperature are 100 kPa and 300 K respectively. Calculate the thermal efficiency of the Diesel cycle.

r = 16

ρ = 2

γ = 1.4

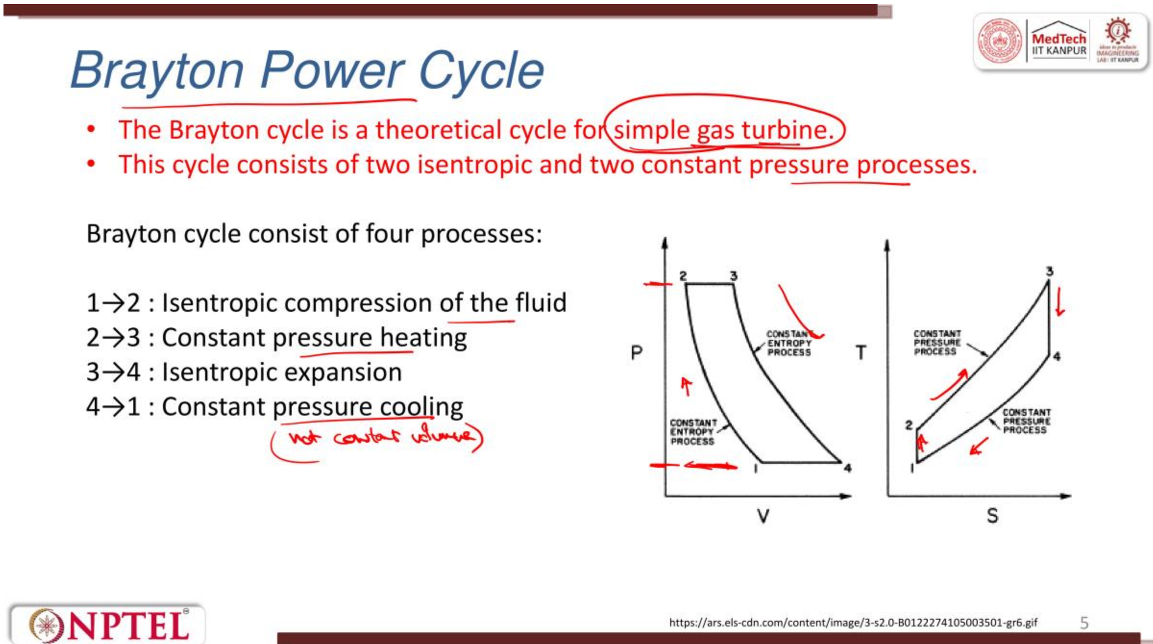
P1 = 100kPa

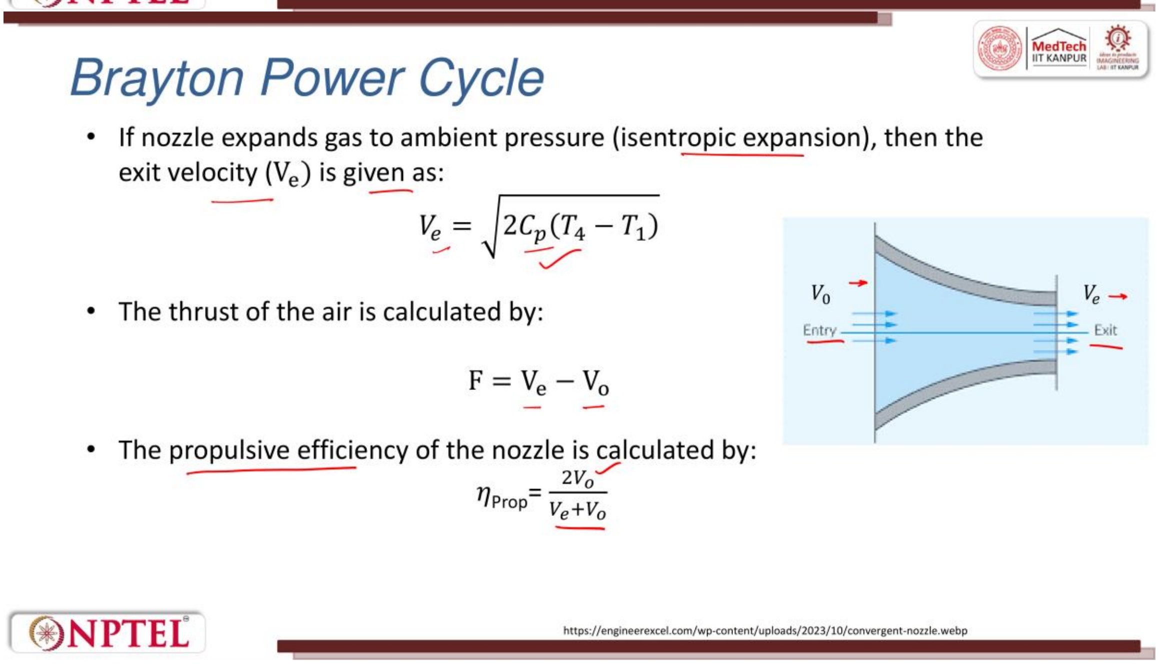
T1 = 300K

Solution:

$$\eta_{Diesel} = 1 - \frac{1}{16^{1.4-1}} \cdot \left(\frac{2^{1.4}-1}{1.4(2-1)} \right) = 0.61$$

$$\eta_{Diesel} = 61\%$$





There is another cycle known as the Brayton cycle, in which heating is constant pressure and cooling is also constant pressure. That is, it is not constant volume cooling. If it is constant volume cooling, then it becomes the diesel cycle. So this is the Brayton power cycle. The Brayton power cycle is a vital cycle for simple gas turbines.

This cycle consists of two isentropic and two constant pressure processes. The Brayton cycle consists of four processes. That is, isentropic compression of the fluid. That is, from

1 to 2, isentropic compression of the fluid. That is, compression of the fluid, where the pressure increases.

That is isentropic, meaning the entropy does not change here. And 2 to 3 is constant pressure heating process. 2 to 3 is pressure constant here, but it is heating process. 2 to 3, the temperature is rising. Then comes isentropic expansion.

The process 3 to 4. 3 to 4 is centropic. Centropy does not change. But it is expansion. That is the volume is increasing from state 3 to state 4.

Then comes constant pressure cooling here. This pressure is constant. You see here. The pressure is constant from 4 to 1. And it is cooling here.

That is temperature is also decreasing from 4 to 1. This is the Brayton power cycle. I did not do any longer numerical statements in the diesel power cycle because I have discussed that in the previous part of this tutorial. Similar problems could also be discussed in the diesel power cycle or Brayton power cycle. But to just calculate the simple values here, I will try to use these relations.

If the nozzle expands gas to ambient pressure, that is, isentropic expansion, then the exit velocity is given as Ve, which is given as

$$V_e = \sqrt{2C_p(T_4 - T_1)}$$

The thrust of air is calculated by

$$\mathrm{F} = \mathrm{V_e} - \mathrm{V_o}$$

The exit velocity is given by this relation. The propulsive efficiency, because we are talking about the gas turbine cycle, though it is a vertical cycle, but for gas turbine, it is entry, it is exit, it is propulsion efficiency or propulsive efficiency of the nozzle, which is calculated by

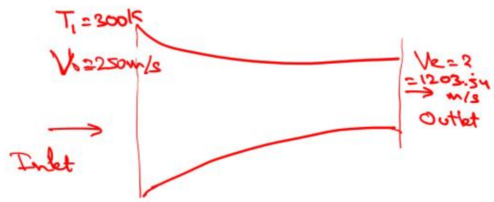
$$\eta_{\text{Prop}} = \frac{2V_o}{V_e + V_o}$$

Brayton Power Cycle

Problem Statement: *A turbojet engine flying at an altitude where air enters the diffuser at 250 m/s. The pressure ratio across the compressor is 10, and the maximum cycle temperature is 1300 K. Assume ideal Brayton cycle behavior with perfect gases, γ = 1.4, C_p = 1.005 kJ/kgK, and inlet temperature is 300 K. The nozzle expands the gas to ambient pressure.*

Determine:

1. *The exhaust velocity.*
2. *The thrust per kg of air.*
3. *The propulsive efficiency.*



Solution:

$V_0 = 250$ m/s $\quad r_p = 10$

$T_1 = 300$ K

$T_{max} = 1300$ K $= T_3$

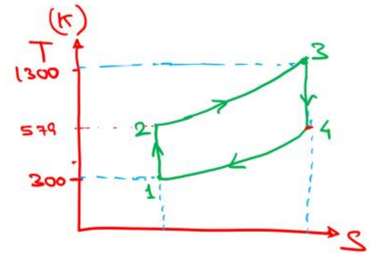
$\gamma = 1.4 \quad C_p = 1.005$ kJ/kgK

Brayton Power Cycle

Solution:

$$\frac{T_2}{T_1} = r_p^{\left(\frac{\gamma-1}{\gamma}\right)}$$

$$T_2 = 300 \cdot 10^{\left(\frac{1.4-1}{1.4}\right)} = 579.2\text{ K}$$



Assuming Turbine work = Compressor work

$$C_p(T_3 - T_4) = C_p(T_2 - T_1)$$

$$T_4 = T_3 - (T_2 - T_1) = 1300 - (579.2 - 300)$$

$$T_4 = 1020.79\text{ K}$$

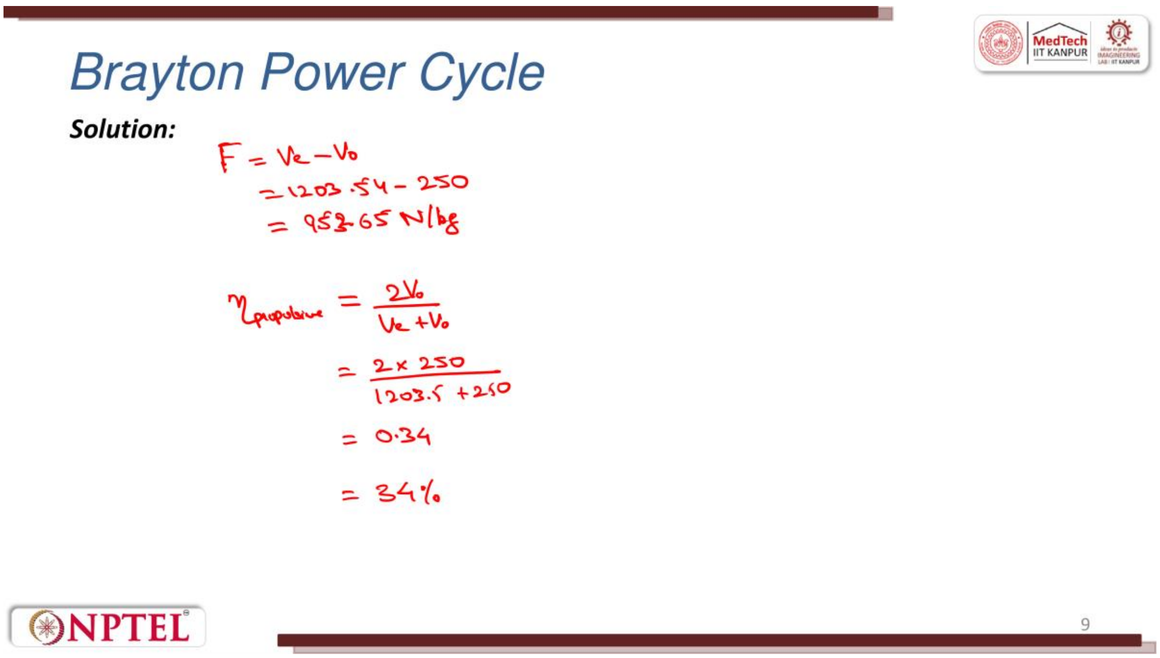
Exhaust velocity

$$V_e = \sqrt{2 C_p (T_4 - T_1)}$$

(converting C_p from kJ/kgK to J/kgK)

$$= \sqrt{2 \times 1.005 \times 10^3 \times (1020.79 - 300)}$$

$$= 1203.65\text{ m/s}$$



So, let me just try to see two simple numerical statements here. A turbojet engine flying at an altitude where air enters the diffuser at 250 m/s. The pressure ratio across the compressor is 10, and the maximum cycle temperature is 1300 K. Assume ideal Brayton cycle behavior with perfect gases, γ = 1.4, Cp = 1.005 kJ/kgK, and inlet temperature is 300 K. The nozzle expands the gas to ambient pressure.

Determine:

1. The exhaust velocity.
2. The thrust per kg of air.
3. The propulsive efficiency.

V0 = 250m/s

T1 = 300K

T_{max} = 1300K = T3

Cp = 1.005 kJ/kgK

γ = 1.4

r_p = 10

Solution:

$\frac{T2}{T1} = r_p^{\frac{\gamma-1}{\gamma}}$

T2 = 300.10 ^ $\frac{1.4-1}{1.4}$

= 579.2K

Assuming turbine works = Compressor works

Cp (T3 - T4) = Cp (T2 – T1)

T4 = T3 – (T2 – T1)

= 1300 – (579.2 – 300)

T4 = 1020.79K

Exhaust velocity,

$$V_e = \sqrt{2C_p(T_4 - T_1)}$$

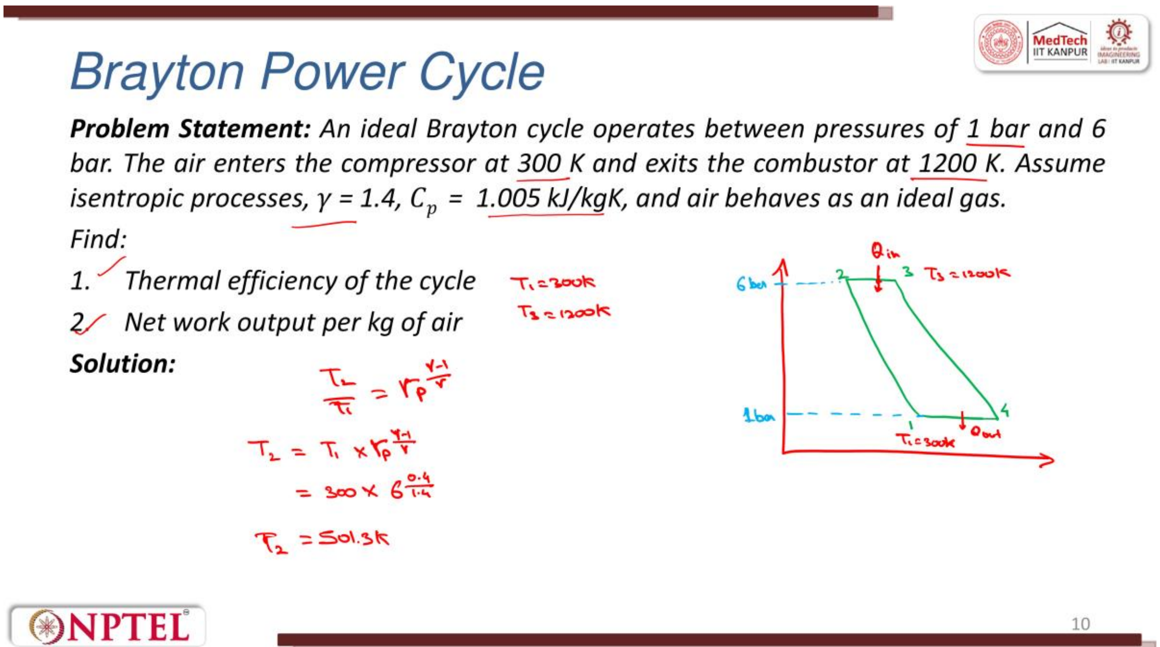
$= \sqrt{2 \times 1.005 \ \times 10^3 \ (1020.79 - 300)}$ = 1203.65 m/s

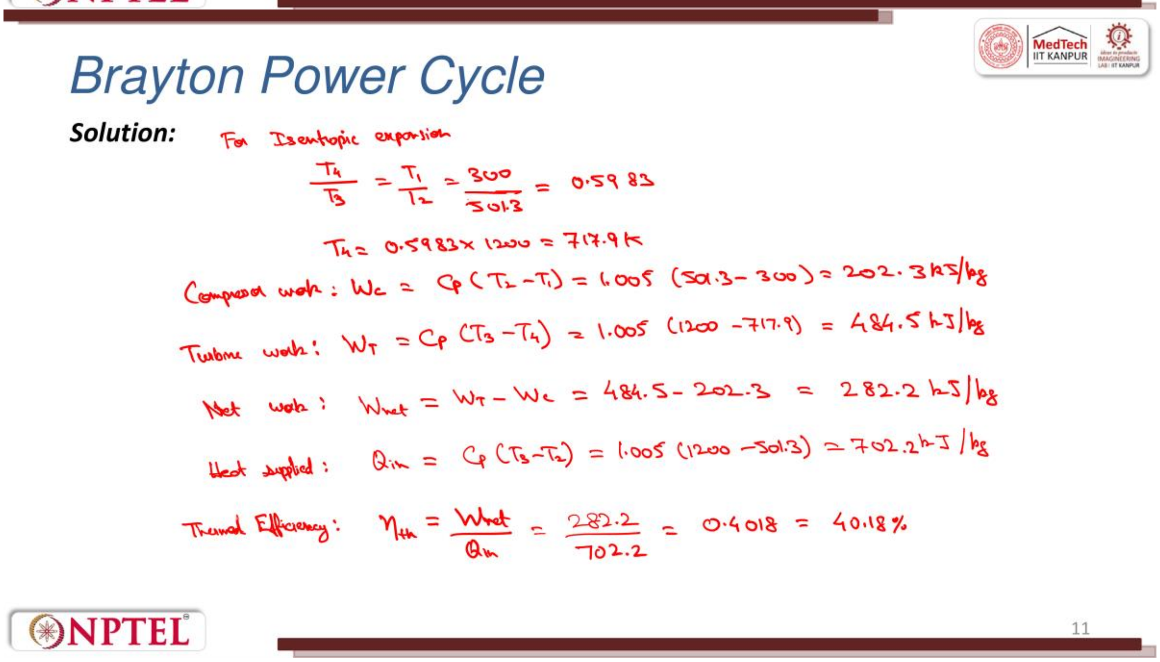
F = Ve – Vo

= 1203.65 – 250 = 953.65 N/kg

$n_{propulsive} = \frac{2V_o}{V_e+V_o}$

$= \frac{2\times250}{1203.5+250}$ = 0.34 = 34%





An ideal Brayton cycle operates between pressures of 1 bar and 6 bar. The air enters the compressor at 300 K and exits the combustor at 1200 K. Assume isentropic processes, γ = 1.4, Cp = 1.005 kJ/kgK, and air behaves as an ideal gas.

Find:

1. Thermal efficiency of the cycle

2. Net work output per kg of air

$\frac{T2}{T1} = r_p^{\frac{\gamma-1}{\gamma}}$

T2 = T1 x $r_p^{\frac{\gamma-1}{\gamma}}$

= 300 x $6^{\frac{0.4}{1.4}}$

T2 = 501.3K

For isentropic expansion

T4/T3 = T1/T2 = 300/501.3 = 0.5983

T4 = 0.5983 x 1200 = 717.9K

Compressed work: Wc = Cp (T2 – T1) = 1.005 (501.3 – 300) = 202.3 kJ/kg

Turbine work: W_T = Cp (T3 – T4) = 1.005 (1200 – 717.9) = 484.5 kJ/kg

Net work: $W_{net} = W_T - W_C$ = 484.5 – 202.3 = 282.2 kJ/kg

Heat supplied: Q_{in} = Cp (T3 – T2) = 1.005 (1200 – 501.3) = 702.2 kJ/kg

Thermal Efficiency = $n_{th} = W_{net}/Q_{in}$ = 282.2/702.2 = 0.4018 = 40.18%

Using all these relations, you can try to find the thermal efficiency and net work output per kg of the air this is a problem for you to solve. You will get the solution in the notes file. I will solve it here and give it to you so that you can check your results with what I have calculated. With this, I am closing my Tutorial 3, which was on power cycles. It is delivered in two parts. I will come with another tutorial, Tutorial 4, as the next lecture, which will be covering psychometrics.

Thank you.