Introduction to Airbreathing Propulsion
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Lecture – 28
Performance / Cycle Analysis: Turbojet

Okay so once we have the discussion on this ramjet, scramjet and all these or rather pulse-jet. So those kind of engine they do not have any rotating part. Now we are moving to the discussion of kind of engine like jet engines turbojet or turbofan kind of engines where the important component is that it has the rotating parts that means the compressor turbine. So now onwards the discussion will be on this turbojet, turbofan or turbo ramjet or turbo popular kind of engines what you always get to see some kind of a rotating components.

And how the basic gas generator added to the turbine and compressor and how they behave together and we will be looking at the cycle analysis I mean specially the aero thermodynamic analysis and other advantage and disadvantage.

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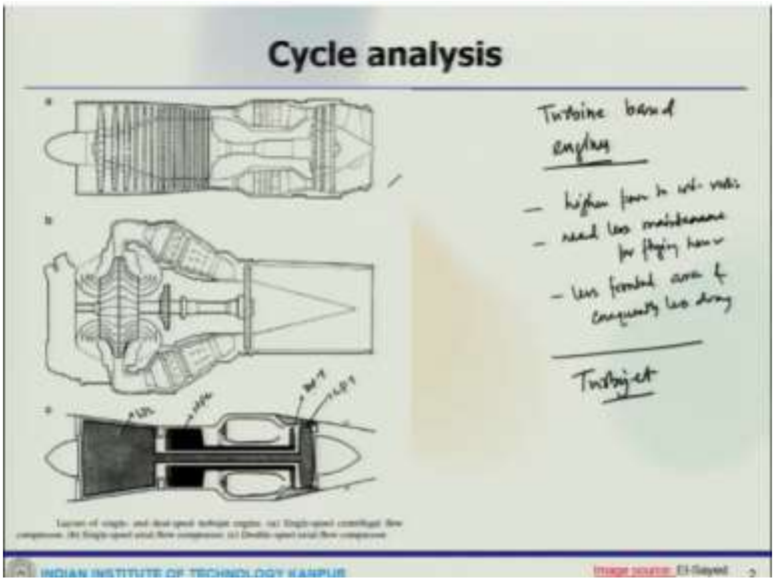

So, let us start with them talking about this turbine-based engine let us say we call it turbine-based engine. So, the advantage of this kind of turbine based engine over piston engine is that it has a higher power to weight ratio that is number one need less maintenance per flying hour and also less frontal area and consequently less drag okay. So these are basic these things now we will start with that one which is called turbojet.

And the first thing that we will look at let us look at a picture of this is a layout of a this is a single spool configuration and then this one is the twin spool configuration of turbo jet engine. So, this is I mean there are different example but this is how it looks like that kind of I mean when you talk about single spool and when you talk about twin spool I mean the basic difference.

You can see here I mean just to give you an idea here a compressor here is the turbine they are connected with the single shaft and obviously in between there is a combustor then there will be nozzle when you talk about the twin spool this is what is your so-called LPC this is HPC this would be HPT and this is LPT. So, HPT and HPC they are connected with one shaft LPT and LPC there can have been low pressure compressor low pressure turbine connected to a one shaft high pressure compressor and turbine connected to two shafts. So that is where it makes it to in spool configuration so that is the basic difference lies in between this configuration.

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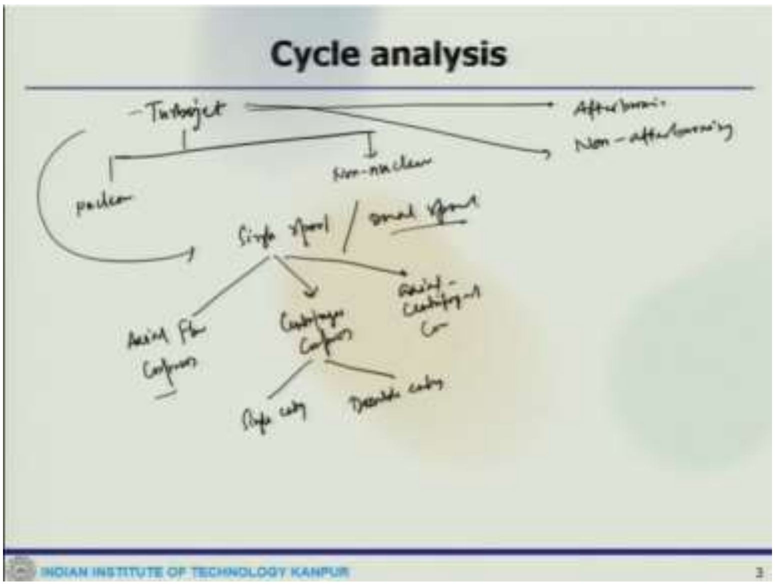

Now the other thing is that also you can see classification of this turbojet that means it could have two major category. One is the nuclear type another is non-nuclear type okay then or there could be another way to look at it so or one can have some other way they that afterburning or non-afterburning that means either we will have afterburner or you will not have or one can have single spool or dual spool okay.

Now in single spool you can have axial flow compressor you can have centrifugal compressor and you can have axial centrifugal compressor. Then again at centrifugal compressor it could have single entry or it could be double entry. So these are some of the classification that one can have even in turbojet engine but as soon as you see there is an strictly axial flow compressor or then you do not have I mean when you go to dual spool then you do not see this subdivision of a different kind of compressor because when you go to multi spool configuration pretty much you need axial compression. And now first we will start with in sort of an single spool engine and then look at this.

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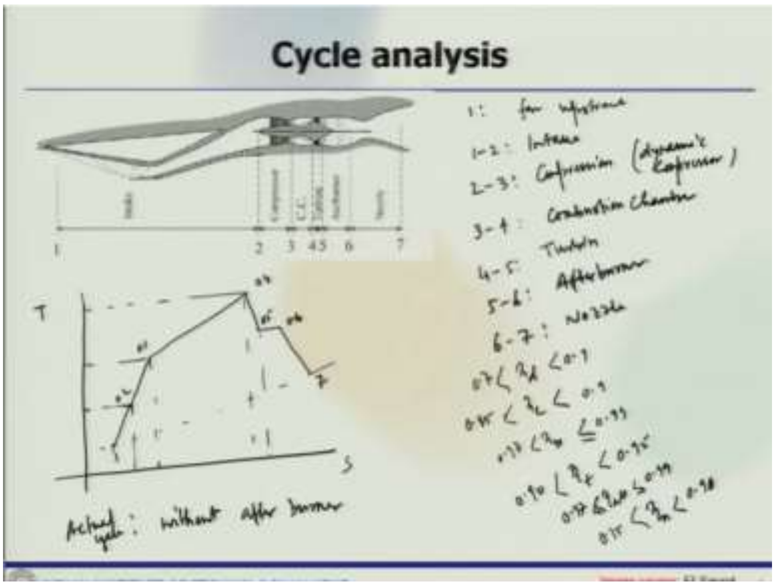

So, this is a configuration of a single spool engine and this at one you have air flows from the first stream. So, this is really far upstream and then 1 to 2 this is where it is an intake. So this intake what happens is that air flows through this inlet or ducting system to the compressor inlet since this always considered this to be a diffuser so the air velocity always decreases 2 to 3 this is an compression which is done through a dynamic compressor which does this compression then 3 to 4 so this is 3 to 4 is your combustion chamber where the fuel is burned fuel is injected there and heat is added to the incoming these things.

Then this is where the turbine or expansion takes place where the hot gases which are allowed to pass through the turbine then 5 to 6. So this is an afterburner it is not necessarily always be there if it is there then it would be further the mixture gas which comes out of the turbine that can be further heated up and added some more energy and 6 to 7 is the nozzle again which passed accelerate through the nozzle to get the desired.

Now here just to then we can do some of this now few comments which are there that all components are irreversible but they are adiabatic except burners. So, the isentropic efficiencies of intake compressor turbine nozzles this would be considered that is there then like in the diffusor portion or the intake there would be friction. So obviously we need to consider the diffusion efficiency to take into account then the compressor also and the compression of the here is the inside the compressor will increase pressure temperature and there would be also entropy increase due to irreversibility.

So also, compressor efficiency so typically the diffuser efficiency let us say vary between 0.9 to 0.7 compressor efficiency vary between 0.85 to 9 that means then you have the combustor efficiency is quite high. So, there it would be pretty much 0.97 then there is a turbine efficiency is also high and then finally there is an if there is an afterburner that also have efficiency high like 0.97 and then finally if you have nozzle efficiency also quite high so these are the things which are there.

Now we can draw the TS diagram and then so we draw those TS diagram let us say so we have 1 we want to go 2, 2 to go to 3, 3 to go to 4, 4 to 5 then 6 then 7 okay. So, this is 7 this is 06, 05, 04 so this is 03 this is 02 this is 1 okay. So, this is let us say without after burner and this is actual cycle TS diagram without afterburner or without afterburner without AB.

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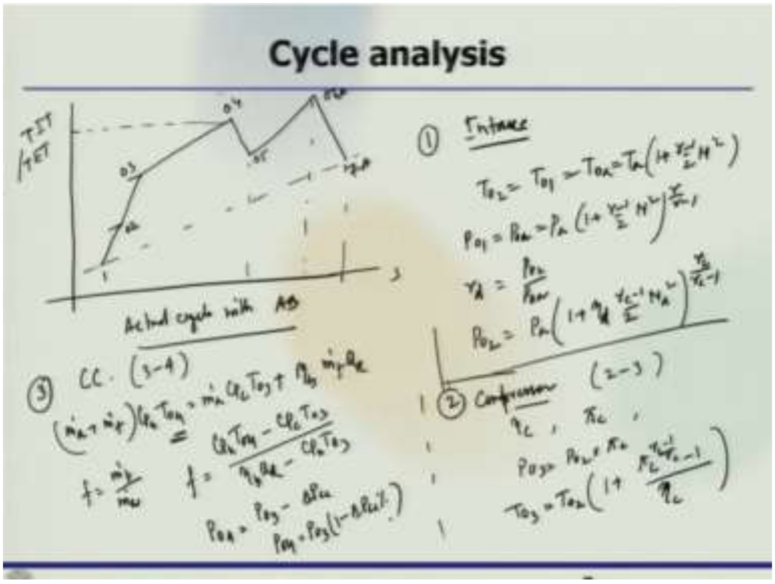

Or another TS diagram which could be looking like this where 1 to 2 2 to 3 3 to 4 4 to 5 5 to 6 and then 7. So, this case this is 1 this is 2 or 02 03 04 this is 05 06A 7A. So, this is an actual cycle with AB okay so when the afterburner is on or other operative conditions so we will start with let us say intake. So that is we will start with the intake now so here that here is decelerated and since the velocity at 2 is assumed to be 0 the deceleration is adiabatic.

So, the total and stagnation States at 0 and 1 are equal so we can correlate between station A1 and 2 that

$$T_{02} = T_{01} = T_{0a} = T_a\left(1 + \frac{\gamma - 1}{2}M^2\right)$$

Now outside the engine this would be

$$p_{01} = p_{0a} = p_a\left(1 + \frac{\gamma - 1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}}$$

So the total pressure which remains constant now there is a pressure recovery within the inlet may be given so the

$$r_d = \frac{p_{02}}{p_{0a}}$$

and also the efficiency η_d needs to be accounted for which will give us

$$p_{02} = p_a\left(1 + \eta_d\frac{\gamma_c - 1}{2}M_A^2\right)^{\frac{\gamma_c}{\gamma_c-1}}$$

so that is what we will get from there we will come to compressor.

So that is let us say first 2 is compressor where compressor it is 2 to 3. So this is also irreversible adiabatic compression process where takes place isentropic efficiency of the compressor is η_c there is a pressure ratio let us see π_c then what we can write

$$p_{03} = p_{02} * \pi_c$$

and

$$T_{03} = T_{02}\left(1 + \frac{\pi_c^{\frac{\gamma_c-1}{\gamma_c}} - 1}{\eta_c}\right)$$

So that is what you get in compressor.

Now the third component would be combustion chamber this is the process between 3 to 4 so here the fuel is injected these are atomized if it is liquid foil evaporated and then the ignition takes place so the from energy balance equation what we can write here

$$(\dot{m}_a + \dot{m}_f)C_{Ph}T_{04} = \dot{m}_a C_{Pc}T_{03} + \eta_b\dot{m}_f Q_R$$

So here the temperature at the exit of the combustor is T_{04} which is going to be the entry to the turbine this T_{04} is called the turbine Inlet temperature or turbine entry temperature.

So, this is important this temperature what is shown here this is TIT or TET turbine entry temperature or turbine inlet temperature this guy is essentially to some extent predetermined during the design process because the turbine material has a limit to withstand the temperature. So, once you know the material of the turbine blade then you have certain limit of the temperature that you cannot go beyond that is where it is going to come into the picture and restrict the rest of the operation inside the combustion chamber.

And so one of the important parameter is this turbine inlet temperature which you can see now this controls the whole design process towards the upstream and the downstream because turbine blade material has an limit of withstanding the temperature and that is going to come and that will limit the exit temperature of the combustor accordingly whatever happens in the combustor and upstream section.

So turbine Inlet temperature or TET or TIT that is an one of the design parameter for this gas turbine engine okay having said that now we can find out the fuel ratio and other properties like the pressure at the exit of the combustor which would be

$$p_{04} = p_{03} - \Delta p_{cc}$$

$$p_{04} = p_{03}(1 - \Delta p_{cc}\%)$$

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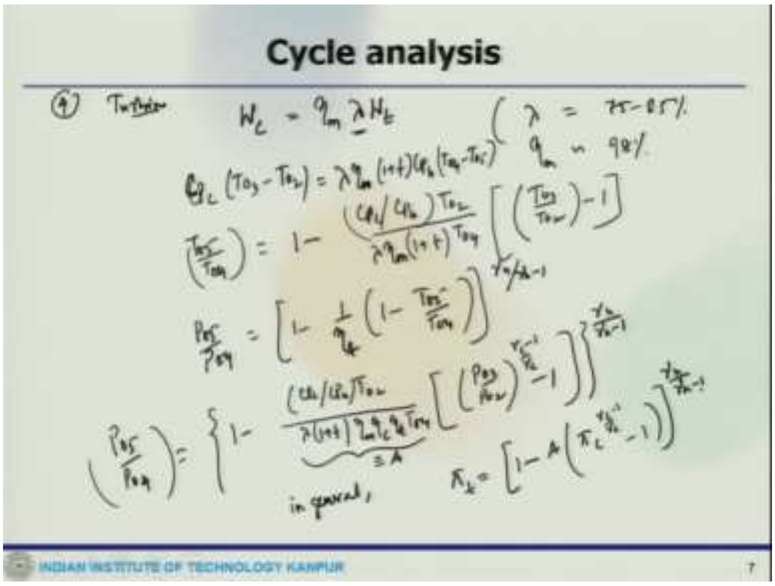

Now the fourth one is the turbine so this is where the power consumed by the compressor is generally produced by the turbine. So, if the ratio of the power needed to drive the compressor to the power available in the turbine is λ then compressor input would be

$$W_c = \eta_m \lambda W_t$$

So typical values of lambda which is in the range of 75 to 85%.

So you can see that 15 to 25% of the turbine power goes back to run the compressor and the mechanical efficiency is also important parameter that is the shaft which transmit so that is roughly 98 percent of the efficiency. Now once you put that when we do is then

$$C_{Pc}(T_{03} - T_{02}) = \lambda \eta_m (1+f) C_{Ph}(T_{04} - T_{05})$$

this would be

$$\frac{T_{05}}{T_{04}} = 1 - \frac{(C_{Pc}/C_{Ph})T_{02}}{\lambda(1+f)\eta_m \eta_c \eta_t T_{04}} \left[\frac{T_{03}}{T_{02}} - 1\right]$$

now the outlet pressure is calculated considering the adiabatic efficiency of the turbine let us say

$$\frac{p_{05}}{p_{04}} = 1 - \frac{1}{\eta_t}\left(1 - \frac{T_{05}}{T_{04}}\right)^{\frac{\gamma_h - 1}{\gamma_h}}$$

So, then the turbine and compressor pressure ratios are correlated like

$$\frac{p_{05}}{p_{04}} = \left\{1 - \frac{\left(\frac{C_{Pc}}{C_{Ph}}\right) T_{02}}{\lambda \eta_m (1+f) T_{04}} \left(\frac{p_{03}}{p_{02}}\right)^{\frac{\gamma_c - 1}{\gamma_c}} - 1\right\}^{\frac{\gamma_h}{\gamma_h - 1}}$$

Or in general one can write in general one can write

$$\pi_t = \left[1 - A(\pi_c{}^{\frac{\gamma_c - 1}{\gamma_c}} - 1)\right]^{\frac{\gamma_h}{\gamma_h - 1}}$$

okay.

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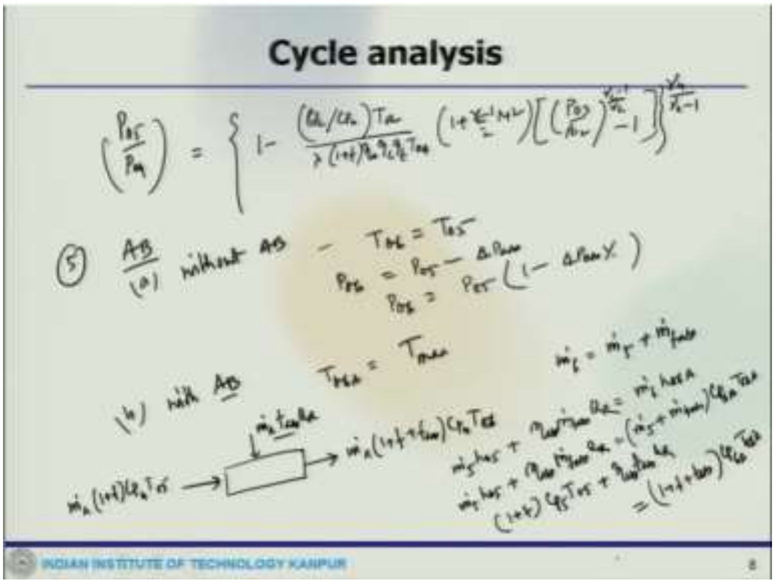

So what we get then we get

$$\frac{p_{05}}{p_{04}} = \left\{1 - \frac{\left(\frac{C_{Pc}}{C_{Ph}}\right)T_a}{\lambda(1+f)\eta_m\eta_c\eta_t T_{04}}\left(1+\frac{\gamma-1}{2}M^2\right)\left(\frac{p_{03}}{p_{02}}\right)^{\frac{\gamma_c-1}{\gamma_c}} - 1\right\}^{\frac{\gamma_h}{\gamma_h-1}}$$

So, this is what we get now the one is AB or afterburner now there could be two cases. So, if the jet engine is within an afterburner then there no work or heat transfer takes place between turbine and the nozzle so the stagnation enthalpy remains constant.

But if there is after burner and the things will be; so there could be case a without AB then what we can see that from the T_{06} would be T_{05} and then what we will get

$$p_{06} = p_{05} - \Delta p_{ab}$$
$$p_{06} = p_{05}(1 - \Delta p_{ab}\%)$$

or case b we have the afterburner then T_{06A} would be T_{max} so in this case the additional fuel is burned and here again the afterburner there would be some energy balance like

$$\dot{m}_a(1+f)C_{Ph}T_{05} + \dot{m}_f f_{ab} Q_R = \dot{m}_a(1+f+f_{ab})C_{Ph}T_{06}$$

So, this is the amount of extra fuel which is again injected in the; but what may possibly happen the temperature which is going to be afterburner which may be higher than the turbine Inlet temperature. The reason for such high temperature is possible because and the extra set of combustion or the takes place. So, but this should not create a lot of trouble as long as the internal body can handle the temperature because there is no rotating component or turbine attached in that.

So just to complete this portion of the analysis let us say

$$\dot{m}_6 = \dot{m}_f + \dot{m}_{fab}$$

and conservation of energy would give

$$\dot{m}_5 h_{05} + \eta_b \dot{m}_{fab} Q_R = \dot{m}_6 h_{06A}$$

So, what we can write this

$$\dot{m}_5 h_{05} + \eta_b \dot{m}_{fab} Q_R = \dot{m}_6 C_{P6} T_{06A}$$

So, this is

$$(1+f) C_{P5} T_{05} + \eta_b \dot{m}_{fab} Q_R = \dot{m}_6 C_{P6} T_{06A}$$

Now once we rearrange that what we will get.

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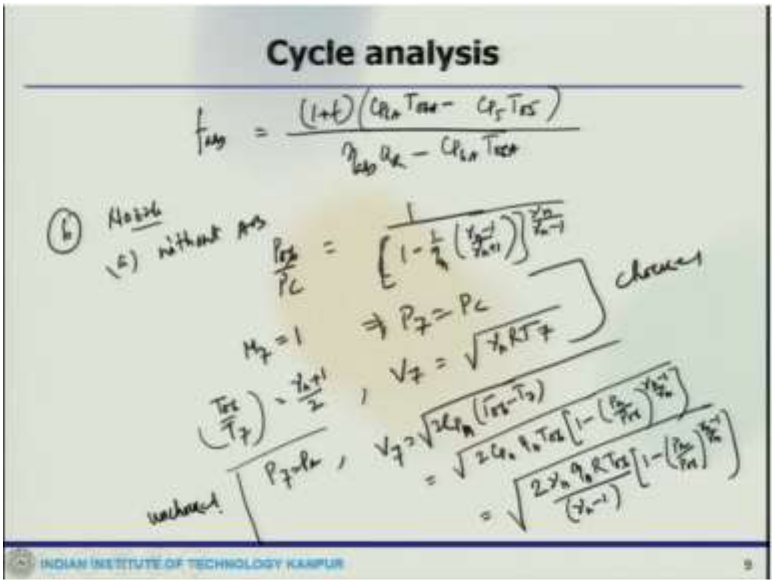

$$f_{ab} = \frac{(1+f)(C_{P6} T_{06A} - C_{P5} T_{05})}{\eta_b Q_R - C_{P6} T_{06A}}$$

Now similarly we will go to the nozzle, nozzle also we will have two different situation case a where without AB so if there is without AB and so first thing one has to check the nozzle for choking by critical pressure like

$$\frac{p_{06}}{p_c} = \frac{1}{\left[1 - \frac{1}{\eta_N}\left(\frac{\gamma_n - 1}{\gamma_h + 1}\right)\right]^{\frac{\gamma_n}{\gamma_n - 1}}}$$

So when the critical pressure is then compared with the ambient pressure so if it is greater than or equal to ambient pressure then the nozzle is choked. So, in that case M_7 would be 1 this means the p_7 would be p_c and so

$$\frac{T_{06}}{T_7} = \frac{\gamma_n + 1}{2}$$

and the exhaust velocity would be

$$V_7 = \sqrt{\gamma_n R T_7}$$

Now on the other hand if the ambient pressure is greater than the critical pressure then the nozzle is unchoked.

So this is a situation where this is choked if it is unchoked then the p_7 would be $p_{atmospheric}$ then the

$$V_7 = \sqrt{2C_{Ph}(T_{06} - T_7)}$$

$$V_7 = \sqrt{2C_{Ph}\eta_m T_{06}\left(1 - \left(\frac{p_a}{p_{06}}\right)^{\frac{\gamma_n - 1}{\gamma_n}}\right)}$$

$$V_7 = \sqrt{\frac{2\gamma_n \eta_m R T_{06}}{\gamma_n - 1}\left(1 - \left(\frac{p_a}{p_{06}}\right)^{\frac{\gamma_n - 1}{\gamma_n}}\right)}$$

So, this is a situation where this is unchoked so every time one has to check whether it is choked or it is unchoked. Similarly, with that case with afterburner also we will look at it but every time when you will deal with the nozzle you need to check the critical pressure at the nozzle exit and you have to make sure or rather find out the condition of the nozzle is choked or unchoke and accordingly you get the pressure conditions and the temperature which would be used to calculate the exit velocity. So, we will stop the discussion here and continue in the next class.