Aircraft Propulsion
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Lecture - 21
Turbofan Engine: Configuration and Examples

Welcome to the class. We are going to see today about the examples for turbofan engine. First, we are going to see how is the composition of a given turbofan engine.

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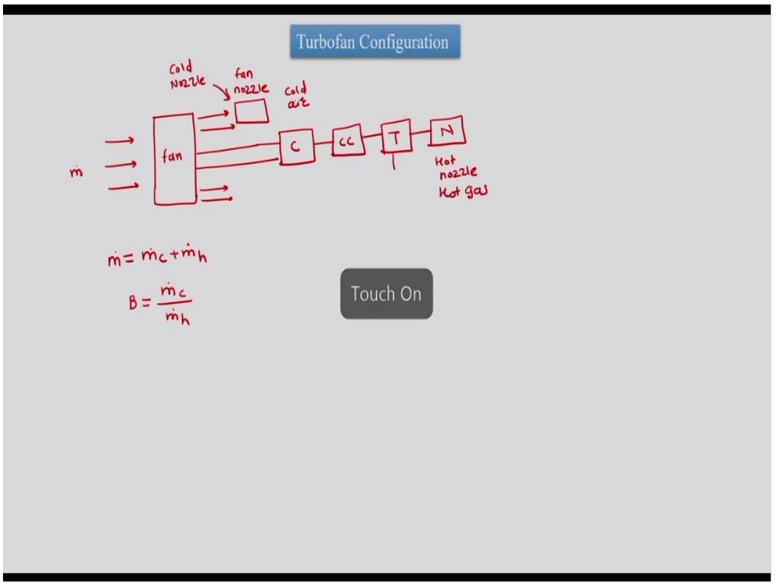

In a turbofan engine, if I plot the schematic, then first there is a fan, there is a fan which is receiving complete mass flow rate of complete mass flow rate and then some air is going to pass directly to a fan nozzle. However, some air is going to pass from fan to a compressor, further it will go to a combustion chamber and then from there to a turbine and then from there to the nozzle.

So, this will have 2 nozzles, one is called as cold nozzle where air which was not having any combustion that is passing and other is air which is passing through the combustion chamber and then that is hot nozzle. So, we have basically 2 airs, from this nozzle we are having cold air and this is hot air or hot gas engine. So, if ṁ is total mass flow rate, then within that ṁC is cold mass flow rate plus ṁh is hot mass flow rate.

And then as per the specification of a turbofan engine, we have to define a bypass ratio which is percentage of cold air in comparison with hot air going from the fan. So, how much air percentage of hot air is flowing over the fan? So, this is what the bypass ratio is and then we know that in case of turbojet engine, the jet velocity is hired outlet. So, turbojet engine hold thrust is obtained from the combusted gas and then that combustion would lead to the lower efficiencies.

And then that is why to improve the efficiency, we have to find out a way and one of the ways is to implement fan. So, having fan we are partially generating some thrust based upon the cold nozzle and some thrust generated from hot nozzles, so this will improve the efficiency. Further, it also helps to reduce the noise. So, these are the details of turbofan configuration.

In general, the civil aircrafts which are seen by us, those civil aircrafts are generally having the turbofan engine where we can see under the wings, there are engines and then the frontal phase is comprised of fan and then downstream of it we have compressors, turbines, combustion chambers and the nozzle. The turbofan engine can have both nozzle as single where the both cold and hot gases will mix and then they will pass through a nozzle.

Or then there can be otherwise there can be 2 separate nozzles, which will have separate thrust generated. So, then there are 2 types of turbofan; one is mixed, another is unmixed. So, let us see some examples for turbofan.

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The following data apply to a twin-spool turbofan engine, with the fan driven by the LP turbine and the compressor by the HP turbine. Separate cold and hot nozzles are used.

Overall Pressure ratio	:	25.0
Fan pressure ratio	:	1.65
Isentropic efficiency of each propelling nozzle	:	0.95
Bypass ratio m_c/m_h	:	5.0
Turbine inlet temperature	:	1550K
Fan, compressor and turbine polytropic efficiency	:	0.90
Mechanical efficiency of each spool	:	0.99
Total air mass flow	:	215 kg/s
Combustion pressure loss	:	1.50 bar

It is required to find the thrust and *SFC* under sea-level static conditions where the ambient pressure and temperature are 1.0 bar and 288 K. Assume C_{pa} = 1.005 kJ/kg K C_{pg} = 1.147 kJ/kg K, Specific heat ratio of air =1.4, Specific heat ratio of gas =1.33

In the example, it is given that the following data apply to a twin-spool turbofan engine in case of twin-spool, we should understand that there will be 2 turbines instead of 1 and one turbine which is high pressure turbine will have its connection with compressor and low pressure turbine will have connection with fan, such that both would be driven by separate turbines.

We have seen such arrangement, multi-spool arrangement in case of the aircraft arrangements. Following data apply to a twin-spool turbofan engine, with a fan driven by low-pressure turbine and compressor by high pressure. Separate cold and hot nozzles are used. Overall pressure ratio is 25, this pressure ratio overall means from the atmospheric condition to the condition at the outlet of the compressor.

Fan pressure ratio is 1.65, so within that basically we are having fan pressure ratio which is 1.65, isentropic efficiency of each propelling nozzle is 0.95, bypass ratio which is ṁc/ṁhot as 5, turbine inlet temperature as 1500 Kelvin. Fan, compressor and turbine they have propulsive efficiency as 0.9, mechanical efficiency of each spool is 0.99. Here, it is a twin-spool arrangement so low-pressure turbine is connected with the fan, so there is one transmission.

High-pressure turbine is connected with compressor, there is one another transmission. So, both have mechanical efficiency of 0.99, total air flow rate is 215 kg per second, combustion pressure loss is 1.5 bar, it is required to find out thrust and specific fuel consumption under sea-level where pressure and temperature are 1 bar and 288 Kelvin. Again, we are given with specific heat of air and gas separately and we are given with their gammas.

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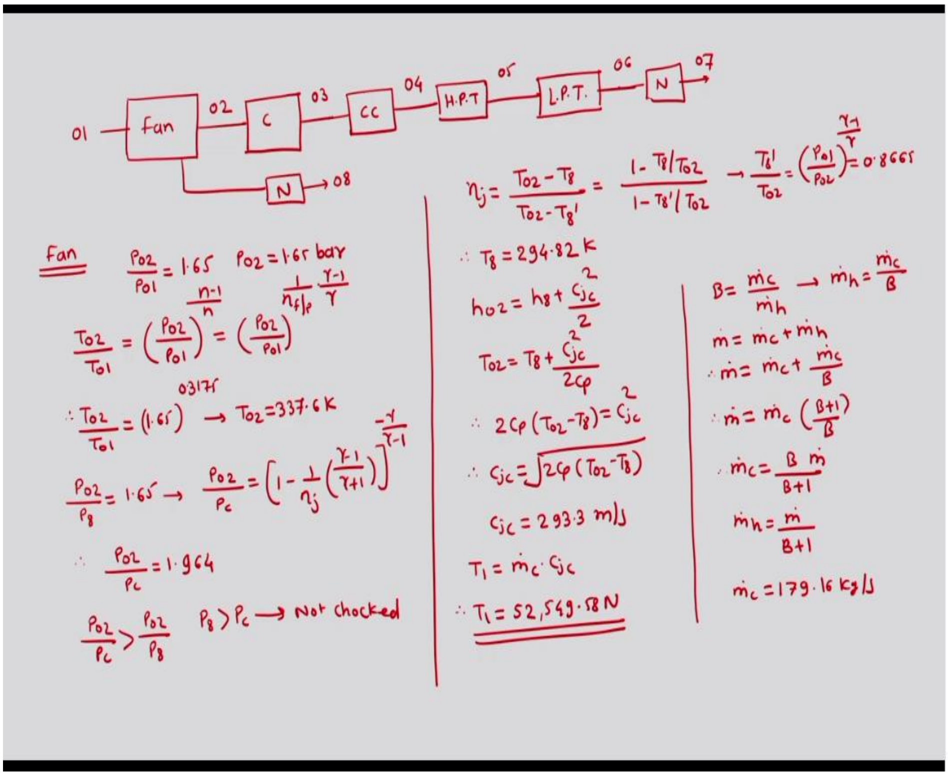

So, let us start solving this example where we need first we will number each corner here where we will have first a fan, then fan has 01 condition, at the exit we have 01, then compressor we have 02, then 03 at the end of the compressor, then we have combustion chamber, it has 04, then we have high-pressure turbine it has exit as 05, we have low-pressure turbine it has 06 and then we have 1 nozzle, it has 07.

But there is one more nozzle here, which is cold nozzle, its exit is 08. So, let us work out for fan to start with. We are told that fan pressure ratio is 1.65, so P02/P01 is 1.65 but we are told that P01 is 1 bar, so we have P02 as 1.65 bar. In this example, we are given with propulsive efficiencies, practically we need to know T02/T01 from P02/P01 and then that if it would have been isentropic flow, we would have written as gamma upon gamma – 1/gamma.

But since the flow is not isentropic, some polytropic efficiency is given, so we have to refrain it as n – 1/n with a polytropic index and we know this polytropic index has relevance with isentropic index gamma through polytropic efficiency of fan. So, this is 1/fan's polytropic efficiency into gamma – 1/gamma. So, we have T02/T01 is 1.65 bracket raise to 0.3175 and this gives us T02 as 337.6 Kelvin where T01 is given as 288 Kelvin.

Knowing T01 and T02, we can move ahead and then we can work out for the nozzle since we know P02/P8, which is atmospheric and that ratio is again 1.65, but what is known to us that this nozzle has efficiency and that nozzle efficiency is leading to the fact that we have to see whether this nozzle having certain efficiency choked or not. So, for that we have to find out choking condition and theoretical choking condition is

$$\frac{P02}{Pc} = \left(1 - \left(\frac{1}{\eta j}\right)\left(\frac{\gamma - 1}{\gamma + 1}\right)\right)^{\left(-\frac{\gamma}{\gamma - 1}\right)}$$

Here, this γ is for air, so it is 1.4 and efficiency is given as 95%. So, P02/Pc comes out to be 1.964. So, we know now P02/Pc is greater than P02/P8, so P8 is greater than Pc. This means that nozzle is not choked. This nozzle is not choked. So, we have to find out the conditions at the exit of the nozzle for this. So, we know exit pressure is P8, which is atmospheric but we do not know what is the velocity.

So, to find out velocity, we have to use the relations based upon the known quantities. So, before that let us find out temperature. So, using the nozzle efficiency, which is

$$\eta n = \frac{T02 - T8}{T02 - T8'}$$

So, we can take T02 common, so we will have T02 is taken common, so 1 - T8/T02/1 – T8'/T02. Here, we know that T8'/T02 is isentropic relation, which is P01/P02 bracket raise to (γ– 1)/γ and this ratio comes out to be 0.8665.

Knowing this ratio and efficiency, we can find out basically T8 and this T8 would come out to be 294.82 Kelvin. So, this is the temperature at the exit. Now, we know that for the nozzle

$$h02 = h8 + \frac{Cj1^2}{2}$$

We are telling this jet as 1 or we can say it as cold, no problem. So, this will, this gives us

$$T02 = T8 + \frac{Cjc^2}{2Cp}$$

So, this gives us twice Cp ×T02 – T8 = Cj cold square.

So, Cj cold = square root of twice Cp into T02 – T8 and this gives us Cj cold as 293.3 meter per second. So, this is the velocity of the air at the exit of the jet. Now, we need to find out the thrust from the nozzle 1. So, thrust 1 is equal to m dot cold into Cj cold but we should know what is ṁcold and ṁcold can be found out from bypass ratio since bypass ratio is ṁc/ ṁh and we know ṁis also equal to ṁc+ṁh.

So, let us represent ṁh in terms of ṁc, so ṁh = ṁc /B. So, ṁ = ṁc + ṁc /B and so we have ṁ = ṁc × B + 1/B. So, ṁc = B/B + 1 × ṁ and then parallelly we can also find out ṁh and ṁh = ṁc/B, so it is ṁ /B + 1 and now we have ṁc from the known bypass ratio, which is 5 and known mass flow rate we can know ṁc as 179.16 kg per second.

So, thrust from the cold nozzle is 179.16 into Cj since the speed which is entering air has that is zero value, so basically we are having m dot into Cj – C, but C is 0, so this thrust turns out to be 52549.58 Newton. So, this is the value of thrust, which is obtained from the nozzle fan.

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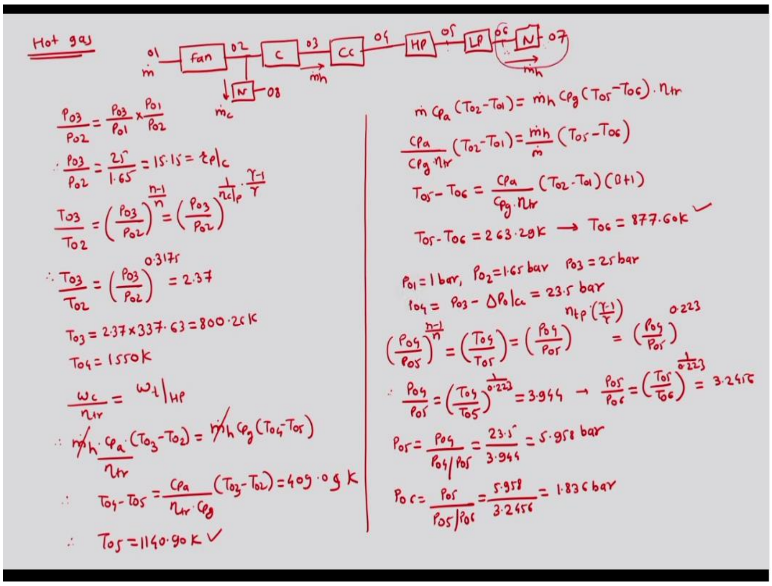

So, now let us see and work out for the hot gas or practically for the gas turbine. Now, for hot gas first we have to find out what is the compressor's pressure ratio since given things are total pressure ratio and fan pressure ratio. So, we are knowing that P03, we will just number everything again here as well for the reference. We have fan first, which has 01 and exit 02, compressor nozzle 08.

Then, we have combustion chamber, after the combustion chamber it is 04, then we have turbine 1 which is HP this has 05, we have LP this has 06 and then there is a nozzle, which has 07. Having said this what we are given is P03/P01, what we are interested is P03/P02, this can be written as P03/P01 into P01/P02 and this is total pressure ratio, which is given as number which is 25 and this is for fan which is 1.65. So, P03/P02 = 25/1.65, so we have 15.15 as the total pressure ratio for compressor. This is for r_{pc}.

Now, knowing this, we can find out T03/T02 and this has to be equal to P03/P02 since this is a real condition, so it will be n -1/n. This is a compressor, which has polytropic efficiency and due to which we are not having isentropic index, we have polytropic index, but we know that these two indices are having relevance using polytrophic efficiency. So, P03/P02 bracket raise to 1 upon compressor efficiency propulsive into gamma minus 1 upon gamma.

So, we have T03/T02 = P03/P02, polytropic efficiency is given, gamma is given. From those given numbers, it becomes 3175, which was same for fan as well and this ratio comes out to be 2.37. So, we can know now T03 is equal to 2.37 into 337.63 and this comes out to be 800.26 Kelvin. Now, we are given with T04 and T04 is given to us as 1550 Kelvin. Now, we are knowing that this compressor is connected with high pressure turbine.

So, compressor's work divided by transmission efficiency is equal to turbine's work high pressure. So, we have Cp of but here we have remember that we have to find out using mass flow rate and then this is mass flow rate hot into Cp of air into T02 - T01 sorry T03 – T02/transmission efficiency = m dot hot. So, here we are having m dot hot, here we are having m dot cold and here we are having m dot into Cp of gas into T04 – T05.

Knowing this, we can calculate T04 – T05, mass flow rate would cancel out and this would be Cp air/transmission efficiency Cp gas T03 – T02 and from known quantities, which is T03 is known, T02 is known, which is 337. So, from this Cp of air, Cp of gas and transmission efficiencies are known and from there this difference comes to be 1140.90 Kelvin. Having known this number, we know now what is the temperature at temperature difference between 04 and 05 sorry this number comes to be 409.09 and this gives us T05 as 1140.90 Kelvin.

Then, we can go ahead and we can work out for 06 and this is LP turbine and we know that it is connected with fan with the other spool, so we have m dot Cp of air into T02 – T01 is equal to this is work done for the fan, work input for the fan that is equal to m dot h hot into Cp of gas into T05 – T06 and then this into transmission efficiency okay. So, we can divide it over here and so we have Cp of air/CP of gas into transmission efficiency into T02 – T01 = m dot h/m dot into T05 – T06.

ṁh h/ ṁ we have calculated as this gives us ṁh /ṁ as 1/B + 1. So, this is going to give us T05 – T06 = Cp of air/CP of gas into transmission efficiency T02 – T01 into m dot/m dot h and then this is basically known to us as B + 1. So, we can replace it with B + 1 and bypass ratio is given, T02 is known 337, T01 is given. All these numbers are given, from here we calculate T05 – T06 and this number comes out to be 263.29 Kelvin and this gives us T06 to be 877.60 Kelvin.

Now, we are interested in finding out the turbine's pressure ratio, operating pressure ratio for the turbine. So, let us find out the operating pressure ratio for the turbine. We have basically, we are interested in finding out pressure P06, since P06 is known, then we can check whether this nozzle is choked or not. So, for that we should know P06. What we know is only P01 which is 1 bar, what we know latter P02 is 1.65 bar.

Then, we know P03 also and that was 25 bar as overall pressure ratio, then we could calculate P04 is P03 minus delta P0 combustion chamber and then this comes out to be 23.5 bar. Now, we do not know what is the value of P05 and what is the value of P06, so for that let us find out P04/P05 and this we know as relevance as n – 1/n = T04/T05 or rather P04/P05 is equal to this n is due to polytrophic efficiency of the turbine, otherwise it would have been isentropic index gamma.

So, this can be written as P04/P05 including the turbine's polytropic efficiency as gamma – 1/gamma. So, this number comes out to be P04/P05 comes out to be 0.223. So, we know P04/P05 = T04/T05 bracket raise to 1/0.223 and then this ratio comes out to be 3.944 and similarly P05/P06 = T05/T06 bracket raise to 0.223 and this gives us ratio which is T05 is known, we have calculated it here.

T06 is also known, we have calculated it here and this gives us the ratio and this ratio is 3.2456. So, knowing both ratios, we can calculate now P05, P05 is equal to this ratio which is P04/P04/P05. So, this is 23.5/3.944 and then this gives us P05 as 5.958 bar. Then, P06 = P05/P05/P06. So, it is 5.958/3.2456 and this gives us P06 as 1.836 bar. Now, we know P06 which is the total pressure and entry to the nozzle.

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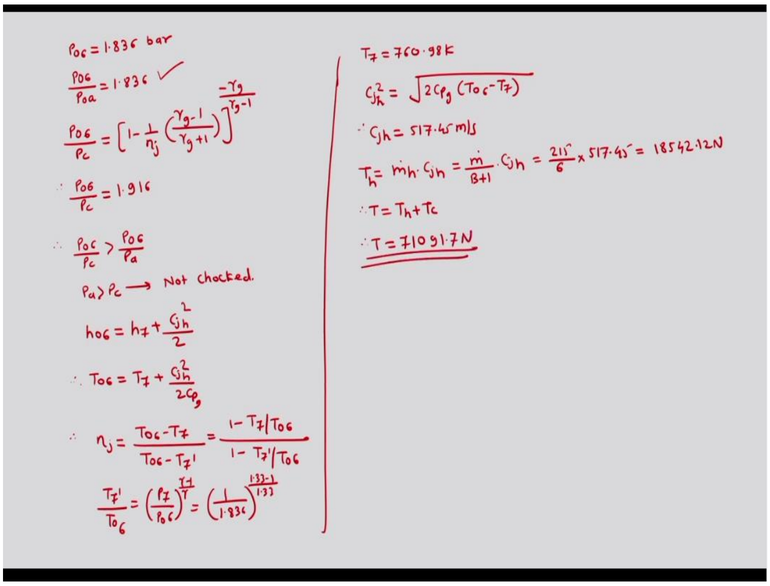

Now, this is how will we proceed to see whether the nozzle is choked or not. What we have calculated till time is P06 and that was 1.836 bar but P01 is 1 bar, so P06/P0a is 1.836. Now, let us see if this nozzle is choked. By seeing P06/Pc as 1 – nj γ gas – 1/ γ gas + 1 bracket raise to – γ gas/ γ gas – 1. γ gas is 1.33, nozzle efficiency is 95%, so we can get P06/Pc = 1.916.

So, we have P06/Pc is greater than P06/Pa, so we have Pa greater than Pc, so nozzle is not choked okay. So, we have to go ahead and find out what is the velocity of the second jet. So, for that again we will use h06 is equal to h7 plus Cj hot^2/2, so we have T06 = T7 + Cj^2 hot/2 Cp gas but here we need to know what is the T7. So, we can find out T7 from nozzle efficiency, which says that T06 – T7/T06 – T7'.

We can take T06 common, so 1 – T7/T06/1 – T7 dash/T06 but T7 dash/T06 is related with P7/P06 bracket raise to γ gas – 1/ γ and we have seen that this ratio P7 which is Pc which is P7/Pa is 1.836, so this can be evaluated from here and T7'/T06 can be found out from Pc/P06 which is 1.836 bracket raise to 1.33 – 1/1.33. So, we can get T7'/T06 which is required over here.

We know nozzle efficiency, we know T06, knowing all this, we can calculate T7 and T7 comes out to be 760.98 Kelvin. Knowing this, we can calculate Cj. Cj square hot = square root of twice Cp gas into T06 – T7. So, knowing this we get Cj hot as 517.45 meter per second. So, we can calculate second thrust or hot trust as m dot hot into Cj hot but ṁh is again ṁ /B + 1 into Cj hot.

So, this is 215/6 ×517.45, so this thrust comes out to be 18542.12 N. So, total thrust is

$$T = T_{hot} + T_{cold}$$

, so we have total thrust as 71091.7 N. So, the major care which we have to take in the example which we need to solve for the fan is this that we should take care for the mass flow rate. The nozzle has only cold mass flow rate and other gas turbine part like compressor, combustion chamber has hot mass flow rate.

So, this is coming into 2 ways; first thing it will come for calculation of thrust of the first nozzle where we have to use only $\dot{m}_c$, but while equating the networks that means the work of high-pressure turbine with compressor, we should use hot gas and while equating the work for fan and low-pressure turbine, we have to use both the mass flow rates, one is total mass flow rate for fan and the hot mass flow rate for low-pressure turbine.

And that is how this example becomes little complicated. Further, we have to always check whether the nozzle is choked or not in either cases by looking at the critical conditions and then if nozzle is not choked, then we have to use the corresponding formula or if nozzle is choked, then we have to use associated formula. This is how we can solve the example for turbofan engines. Thank you.