Aircraft Propulsion

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Lecture - 23
Examples of Ramjet Engine

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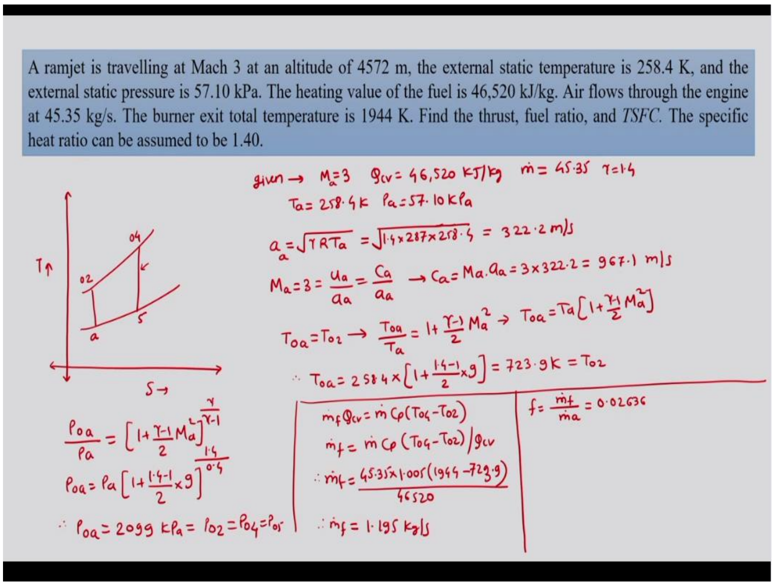

Welcome to the class. We are going to see today the examples on ramjet engine. Let us see. The first example reads that a ramjet engine is traveling at Mach number 3 at an altitude of 4572, the external static temperature is 258.4 Kelvin and static pressure is 57.10 kilopascal. The heating value of fuel is 46,520 kilojoule per kg air flows through the engine at the 45.35 kg per second. Burner exit temperature, exit total temperature is 1944 Kelvin. Find the thrust, air, fuel ratio and thrust specific fuel consumption.

So, specific heat ratio can be assumed to be 1.4. Let us try solving this example. In this example, no losses are supposed to be taken, so we have it as an ideal ramjet and hence it is very simple to solve this example where we have 01 and then we have 04, 05. So, this is 02. So, we will solve this example where we are given that Mach number = 3, we are told that Qcv = 46,520 kilojoule per kg, $\dot{m}$ = 45.35 and then γ = 1.4, Ta or so this is atmospheric condition.

This is 5 and this is a, so Ta is 258.4 Kelvin and Pa = 57.10 kilopascal. Now, we can first find out the velocity with which the fluid is approaching the engine. So, for that we have to find out acoustic speed for atmospheric condition, which is gamma RTa. So, we know gamma is 1.4, R is 287 for air and Ta is 258.4. So, this gives us acoustic speed as 322.2 meter per second. Having known this we can know that Mach number a, which is given as 3 is equal to Ua or what we call it as Ca/aa.

So, Ca/aa so this gives us Ca = Ma into aa, so this is 3 into 322.2, so it is 967.1 meter per second. So, this was one of the requirements for finding out thrust. We should know what is the field with which it is approaching. So, now we should also know the temperatures, so what is the temperature at 02 we will first find out. Before that we should notice the total temperature at a, which is rather needs to be calculated.

So, T0a is equal to basically T02 since it is isentropic compression that can be found out from

$$\frac{\mathrm{T0a}}{\mathrm{Ta}} = 1 + \frac{(\gamma - 1)}{2} Ma^2$$

So,

$$\mathrm{T0a} = (1 + \frac{(\gamma - 1)}{2} Ma^2)\mathrm{Ta}$$

So, T0a is Ta is 258.4 into 1 + 1.4 – 1/2 into 9. So, this gives us total temperature at the intake as 723.9 Kelvin. So, having known this, we know this is equal to T02, which is the temperature at the entry to the combustion chamber.

So, further we need to calculate the pressures. We can calculate that

$$\frac{\mathrm{P0a}}{\mathrm{Pa}} = \left(1 + \frac{(\gamma - 1)}{2} Ma^2\right)^{\frac{\gamma}{\gamma - 1}}$$

So, P0a = Pa into 1 + 1.4 – 1/2 into 9 bracket raise to 1.4/0.4. This gives us total pressure at the inlet is 2099 kilopascal and this is equal to P02 and this is also equal to P04 and this is also equal to P05. So, since all the processes are isentropic in case of this ramjet engine.

Now, we can find out the heat supplied by the relation which we know that

$$\dot{m}f \times \mathrm{Qcv} = \dot{m}\mathrm{Cp}(\mathrm{T04} - \mathrm{T02})$$

Here, now we know that the temperatures are given to us where we need to find out ṁf, we will neglect the presence of m dot f in this total mass flow rate, so it is ṁCp×(T04 – T02)/Qcv, so ṁf is equal to mass flow rate is given that is 45.35 into Cp is 1.005 into T04 is given as 1944.

So, total temperature although it is said at the exit of the burner, so total temperature is going to remain constant since this is nozzle. So, T04 is equal to T05, so this is 1944 minus T02 which we have calculated 723.9 divided by Qcv is given as 46520. Here, it is given in kilojoule per kg that is why we are using Cp also in kilojoule per kg. So, this gives us m dot f as 1.195 kg per second.

So, this is helpful for us to get ṁf/ṁa and then that would come out to be 0.02636. This is the air-fuel ratio. Now, we need to find out thrust.

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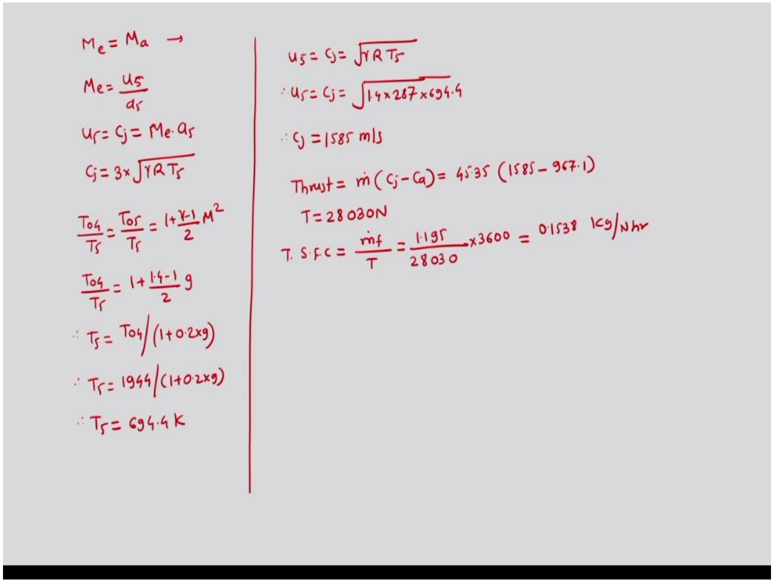

So, for that we can find out the exit velocity and exit velocity can be found out from exit Mach number but for ideal ramjet we know that exit Mach number is equal to inlet Mach number. So, which says that exit Mach number is equal to U5/a5, so U5 = Cj = Me into a5. So, Cj = 3 into square root of gamma RT5 and we should know what is T5. For that we can calculate T04/T5, which is T05/T5 is equal to 1 + gamma – 1/2 M square where M is 3.

So, T04/T5 = 1 + 1.4 – 1/2 into 9, so this gives us T5 = T04/1 + 0.2 into 9 and we know T04 is equal to. So, this is known to us T04 = 1944/1 + 0.2 into 9. This gives us T5 = 694.4 Kelvin. Hence, it is helpful for us to find out U5 now is equal to Cj is equal to under root gamma RT5 or Tj and then this U5 = Cj = 1.4 into 287 into 694.4. This gives us Cj = 1585 meter per second.

Thus, we can calculate the thrust as thrust is equal to m dot into Cj – Ca. We have neglected presence of fuel where m dot is given as 45.35, Cj is 1585, Ca we have already calculated Ca as 967.1 and this gives us thrust T = 28030 Newton. So, specific fuel consumption or thrust specific fuel consumption is $\dot{m}f/T$, so it is m dot f we have calculated m dot f as 1.195/28030 into 3600. This is coming to be 0.1538 kg per Newton hour.

Here, we are taking m dot f in kg per hour. Now, this is how we would solve one example for ramjet. Let us move to the next example.

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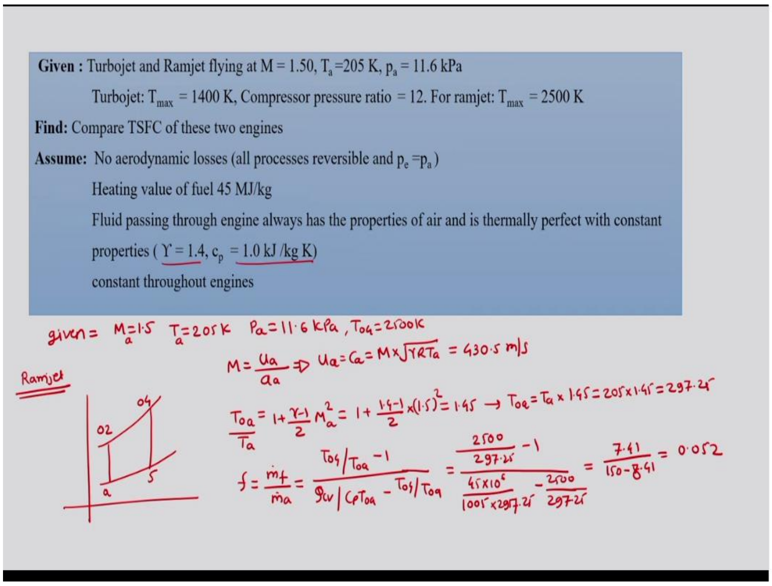

This is a typical example which says that we need to compare between 2 engines, one is turbojet, another is ramjet, both are flying at Mach number 1.5 in the altitude where temperature is 205 Kelvin and pressure is 11.6 kPa. Turbojet has total temperature of 1400 Kelvin and pressure ratio as 12 where ramjet has total temperature as 2500 Kelvin. We have to consider both as ideal engines and we have to consider no losses.

Further gamma is given as 1.4 Cp is given as 1. So, we are supposed to find out specific fuel consumption for both the engines. So, let us start. We are given that Mach number is equal to 1.5, temperature atmospheric is 205 Kelvin, pressure atmospheric is 11.6 kPa. Let us start for ramjet and then for ramjet T0 will plot it, then we can know the numbers. So, for ramjet we say this as atmospheric, this as 2, this as 4 and this as 5.

So, let us start. We know Mach number, so Mach number is equal to Ua upon acoustic speed of atmosphere. So, this is helpful to find Ua is equal to Ca is equal to Mach number into under root γRTa. So, γRTa into m which is 1.5 gives us Ua as 430.5 meter per second and this is valid for both the engines, which is ramjet and turbojet.

So, let us start. We know that we are interested initially to find out T0a and

$$\frac{\text{T0a}}{\text{Ta}} = 1 + \frac{(\gamma - 1)}{2} Ma^2$$

where Ma is given and this is helpful for us to find out total temperature at the inlet. So, 1.4 – 1/2 into 1.5 square and this ratio is 1.45, so T0a = Ta into 1.45, Ta is given to us as 205 into 1.45 and this gives us as 297.25. So, this total temperature is known to us.

Now, we know the formula for ṁf/ṁa for ramjet as T04/T0a – 1/Qcv/Cp T0a – T04/T0a. We have derived this formula. So, this gives us 2500/297.25 – 1/45 into 10 to the power 6/1005 into 297.25 – 2500/297.25. So, this gives us 7.41/150 – 8.41 and hence f comes to be 0.052. So, now we have calculated f which is air-fuel ratio.

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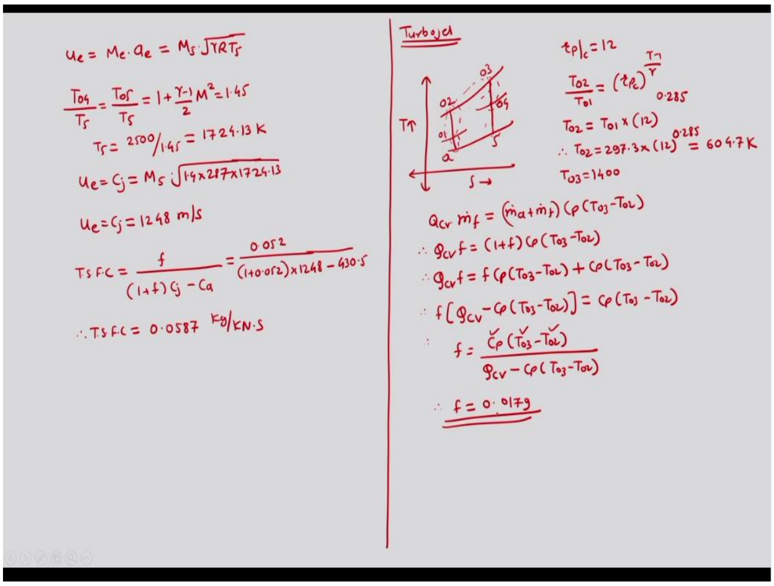

So, now we can calculate Ue, which is required for exit velocity is required for calculation of thrust. We know exit velocity is equal to exit Mach number into exit acoustic speed where it is M5 into under root of γRT5, we know that Mach number is same at the inlet and outlet, so it is Ma but we should know T5, so we can find out T5 with the formula T04/T5 is basically is equal to

$$\frac{\text{T05}}{\text{T5}} = 1 + \frac{(\gamma - 1)}{2} M^2$$

and this ratio is 1.45.

We are told that total temperature for ramjet is 2500 Kelvin; it is given in the example. For ramjet, total temperature is 2500 Kelvin. So, 2500/1.45 and we get exit temperature or T5 as 1724.13 Kelvin. So, this we can use over here and find out Ue = Cj = Mach number 5 into under root 1.4 into 287 into 1724.13. So, this gives us exit velocity or jet velocity as 1248 meter per second.

Now, we can calculate thrust specific fuel consumption as

$$sfc \ = \frac{\mathrm{f}}{(1 \ + \ \mathrm{f}\,)Cj - Ca}$$

So, it is f is known 0.052, 1 + 0.052 into 1248 – 430.5. So, we get thrust specific fuel consumption here as 0.0587 kg per kilo Newton second. So, we have divided it by multiplied it by 1000 to get the number in kilo Newton. So, this is the solution for ramjet okay. Having said this we can proceed for turbojet.

In case of turbojet, we have to first find out, this is atmospheric, then this is 01, this is 02, this is 03, 04, 5. This is TS diagram for turbojet, this is for intake, this is for compressor, this is for the combustion chamber, this is for turbine and this is for nozzle. Having known this, we can proceed and then we are told that rp for compressor is 12. In the example, it is told that compressor pressure ratio is 12.

So, knowing this we can go ahead and say

$$\frac{T02}{T01} = (\mathrm{rpc})^{\frac{\gamma-1}{\gamma}}$$

we can calculate total temperature at station two as T02 = T01 into 12 raise to 0.285. So, for this T01 is already calculated by us, which was 297.25, it is consistent. Here, we can use that 297.3 into 12 raise to 0.285. This gives us T02 as 604.7 Kelvin. So, now we know what is the value of T02.

For turbojet, it is already told that maximum temperature is 1400. So, we know applying energy equation for the burner, we get (ṁa+ṁf)× Cp h03 is equal to applying energy equation, we can get

$$\mathrm{Qcv} \ \times \ \dot{m}\mathrm{f} = (\dot{m}\mathrm{a} \ + \ \dot{m}\mathrm{f}) \ \times \ \mathrm{Cp}\ (\ \mathrm{T03} - \mathrm{T02})$$

So, it is basically Qcv × f = 1 + f×Cp×(T03 – T02). So, we can write it down as the terms in f - Cp×(T03 – T02).

So, this would give us, so Qcv × f = f × Cp ×(T03 – T02) + Cp×(T03 – T02). So, we can take both the terms of f common, so Qcv - Cp ×(T03 – T02)= Cp ×(T03 – T02). So, this is basically f formula which is air-fuel ratio or fuel air ratio as Cp into T03 – T02/Qcv – Cp into T03 – T02. Now, total temperature is given, Cp is known, T02 is found out, similar terms are there at the bottom.

Putting all them together, we can get f as 0.0179 for the turbojet engine. Having said this, now we know what is f, we have to proceed and find out conditions at exit which are related to 5 so as to get the thrust.

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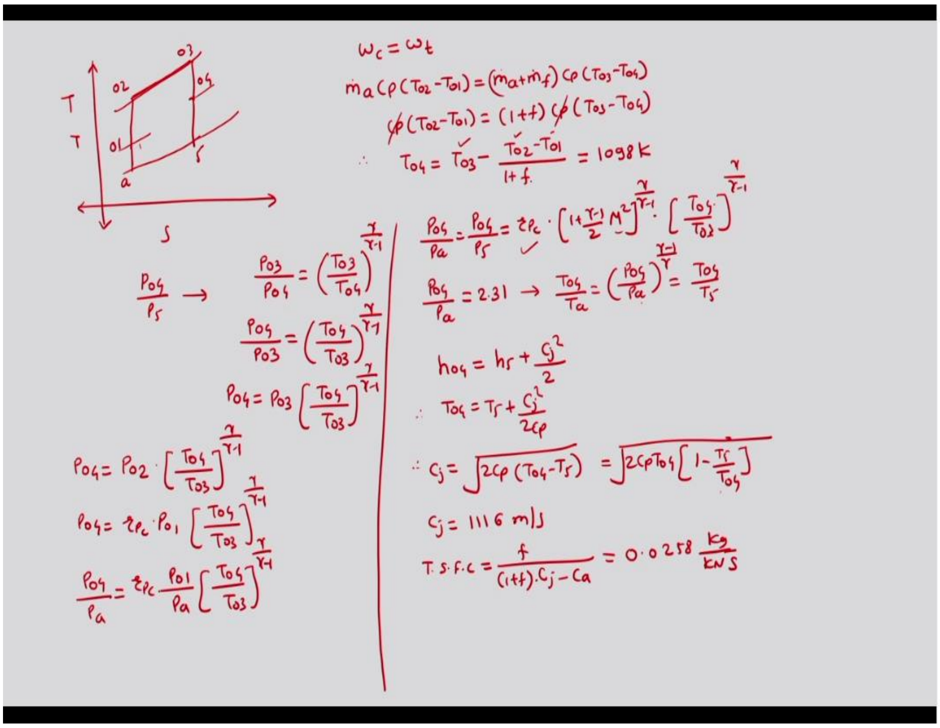

So, we will plot the same TS diagram for the reference where we have this a to 01 to 02 to 03, 04 and then 5. Here, again we can equate compressor work equal to turbine work so that it will be helpful for us to get the outlet conditions. So, compressor has ṁa× Cp ×(T02 – T01) but here we have ṁa into m dot f into Cp into T03 – T04. So, we can say that here m dot a into Cp T02, ṁa be divided. So,

T02 – T01 = 1 + f Cp ×(T03 – T04).

So, Cp Cp would get cancelled here since we are considering both to be almost equal and then we have T04 = T03 – T02 – T01/1 + f.

So, having said this we can get we know T03, we know T02, T01, f is also evaluated, so this gives us T04 as 1098 Kelvin. So, we know T04 as 1098 Kelvin. We can calculate the pressures at the exit, which is required for the finding out the pressure ratio between the, we need P04/P5 to find out the exit velocity. So, this we can find out from the fact that P03/P04 is isentropic and it is

$$\frac{\mathrm{P03}}{\mathrm{P04}} = \left(\frac{T03}{T04}\right)^{\frac{\gamma}{\gamma-1}}$$

So, we have

$$\frac{\mathrm{P04}}{\mathrm{P03}} = \left(\frac{\mathrm{T04}}{\mathrm{T03}}\right)^{\frac{\gamma}{\gamma-1}}$$

So, this gives us

$$\mathrm{P04} = \mathrm{P03}\left(\frac{\mathrm{T04}}{\mathrm{T03}}\right)^{\frac{\gamma}{\gamma-1}}$$

but this P03 = P02 and P02 is basically 12 times P0a. So, this we can write down differently saying that P04 = P03 = P02, so it is P02 here into T04/T03 bracket raise $\frac{\gamma}{\gamma-1}$. So, this P02 is basically 12 which is rp compressor into P01 into T04/T03 bracket raise to gamma/gamma – 1.

Now, let us divide both sides by Pa, so we have rpc into P01/Pa into T04/T03 bracket raise to $\frac{\gamma}{\gamma-1}$. So, this P04/Pa is necessarily P04/P5 and this is rp compressor and we know

$$\frac{\mathrm{P04}}{\mathrm{Pa}} = \mathrm{rpc}\left(1 + \frac{(\gamma-1)}{2}M^2\right)\left(\frac{T04}{T03}\right)^{\frac{\gamma}{\gamma-1}}$$

So, this we can, we know now compressor pressure ratio is 12, Mach number is known for the free stream, T04 is evaluated, T03 is given.

And this gives us P04/Pa as 2.31. Now, we can get it used to find out

$$\frac{T04}{Ta} = (\mathrm{P04/Pa})^{\frac{\gamma-1}{\gamma}}$$

So, this we can use and then get temperature at the exit which is T5. This can be used to find out T5, so this we can write down as in our requirement, which is for the energy equation for the nozzle is

$$h04 = h5 + Cj^2/2.$$

So,this is $T04 = T5 + Cj^2/2Cp$.

So, here we have so Cj = square root of twice Cp into T04 - T5. So, this is how we can write down the expression for the jet thrust. So, this we can write down in terms of we can take T04 common, square root of twice Cp T04 into 1 - T5/T04. This can be expressed in terms of pressures and then we can find out finally Cj which turns out to be 1116 meter per second. So, then we can find out thrust specific fuel consumption.

And then that is

$$\frac{\mathrm{f}}{(1 + \mathrm{f})Cj - Ca}$$

and if we put all the known numbers, which we have obtained, we can get it as 0.0258 kg per kilo Newton second. So, this if we compare with what we obtained for the turbojet for this ramjet, then it is evident that ramjet produces more thrust and it has requirement of. If we compare, then we can see that for ramjet, thrust specific fuel consumption is more than that of the turbojet.

This is what it was expected from the comparison. This is how we can solve the examples for turbojet or we can do the comparison between turbojet and ramjet. Thank you.