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# Aerospace Propulsion
## Air breathing Engine-Turbojet II

**Lecture – 3**

**Prof. Ramakrishna P A**
**Department of Aerospace Engineering**
**Indian Institute of Technology Madras**

We were discussing in the last class about the thrust developed by the turbojet engine and we had derived an equation for the thrust of the turbojet engine as shown here oh thank you very much I am sorry.

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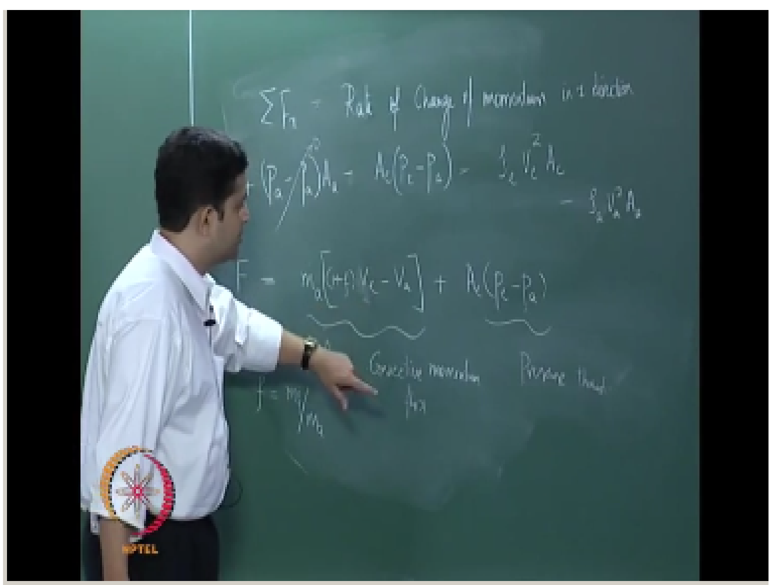


This mass flow rate has to be multiplied by the cross-sectional area a so this is the mass flow rate m dot a and this portion rho eve into AE is nothing but m dot a into 1 + m and this is the exit velocity this is the entry velocity now this part of the thrust is known as convective momentum flux trust due to convective momentum and this is known as the Ash thrust typically in aircraft engines this portion will be very small compared to this portion.

This is the larger portion this will be very small compared to this portion so later on sometimes we might assume that this portion is very small okay now in this equation if you look at this equation the thrust will be maximum.

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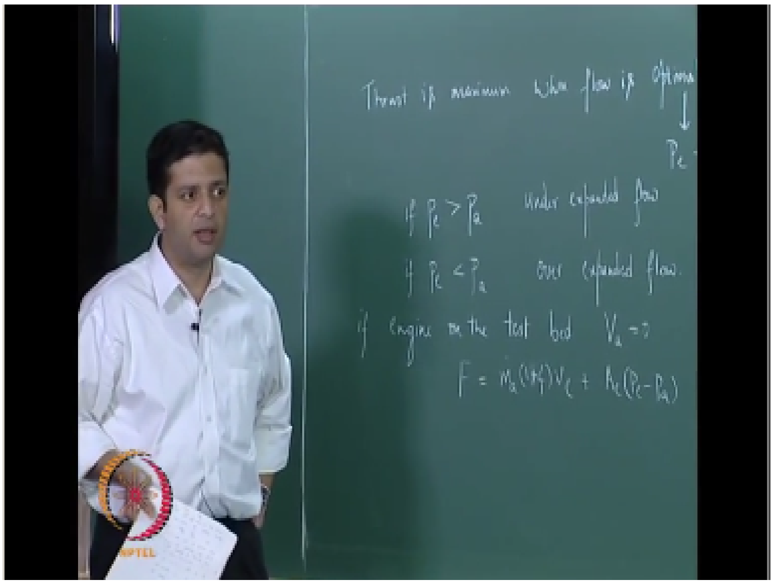


When PE = PA that is the stress maximum when flow is optimally expanding what do we mean by optimally expanded when the e is equal to ei and the exit pressure is equal to the ambient pressure we call it I am optimally expanded and that is the condition under which it gives the maximum thrust okay we will see little later why this happens this way and if PE > Pa it is called as under expanded flow.

And if he is less than a it is known as over expanded flow okay now let us say if the turbojet engine is on a test bet then there will be no velocity that is coming in ba so if engine is on the test bed V =0 and therefore you get F is equal to okay is also known as static thrust was it thrust that the engine can provide when he aircraft is not yet started move.

Now we will learned what is how to get the equation for the thrust of the gas turbine engine now let us look at how to determine what is the how efficient is this the parameter that defines the efficiency or how much of thrust is delivered per unit fuel burnt is known as specific fuel consumption.

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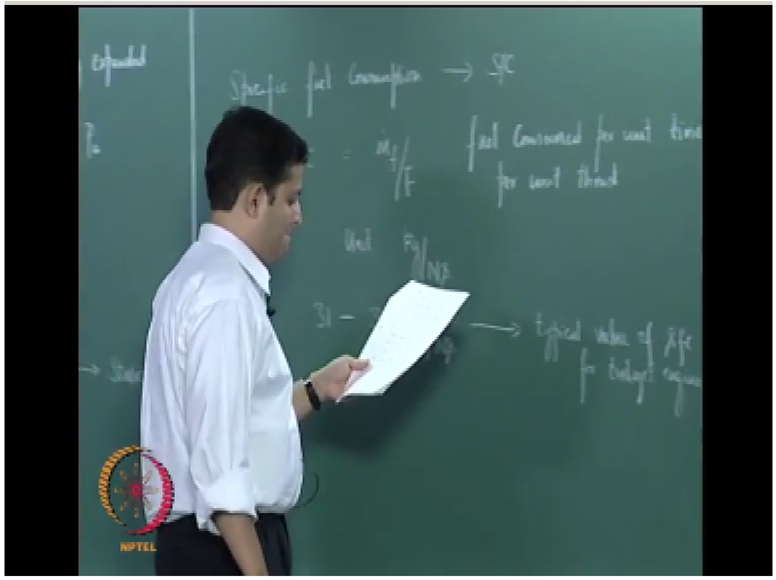

It is also indicated as SFC now SFC is nothing but that is mass flow rate of fuel per unit thrust okay or fuel consumed per unit time per unit thrust this is SFC and the unit is kg per Newton second the typical value of SFC for a gas turbine engine ranges between 31 to 36 milligrams per Newton second this is the typical value of s FC for turbojet engines yeah now let us say we have two special edition yes we will be maximum.

When I said we will get to that a little later in the course when we discuss about rocket engines I will be able to show you why it happens that okay so just hold your question till probably about few more classes now let us say we were to decide about you know buying a particular kind of engine okay you must be knowing this that our LCA program okay we are looking for an aircraft engine what are the parameters that we have to keep in mind if somebody.

Something if we have to buy an new engine for a particular aircraft what are the parameters that you think that one must take care of if we have to buy an engine or if you have to decide on an engine for a particular air craft a doctor that is take off okay any other okay.

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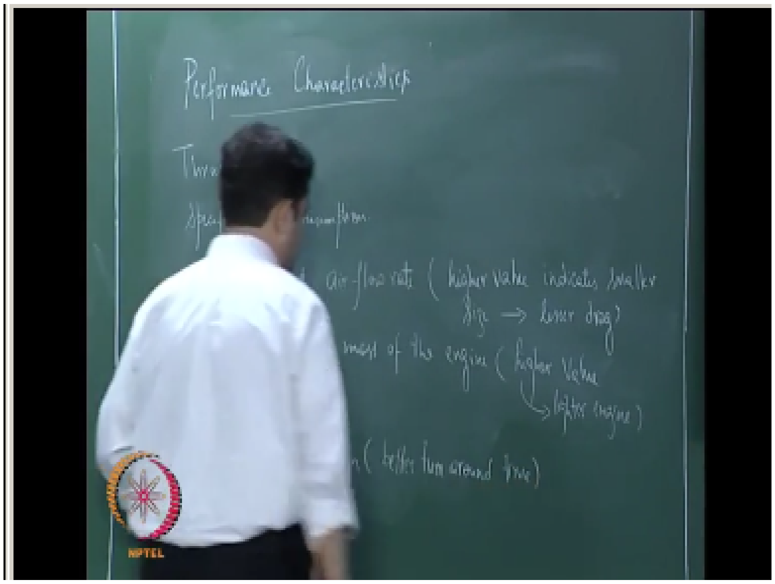


Let us look at it so the performance characteristics of a turbo jet engine are firstly it is the thrust that is the engine should be able to meet the thrust that is desired of it okay it also includes the static thrust or the takeoff thrust that you talked about then the next one is the specific fuel consumption this is a very important parameter because if your SFC is low you will have to spend more to keep the fleet aligned yep more.

So if you are operating a commercial flight then if you are operating a military one okay because if your specific fuel consumption is more than your costs are going to be much higher so you need to have a slow a specific fuel consumption as possible then the other thing that you talked about is I will call it as rust per you need air flow rate what does this indicate this will indicate what is the size of the aircraft or the size of the engine.

So higher value indicates smaller size which means lesser drag so you want a large value of thrust per unit air flow rate so that the drag on the aircraft overall drag of the aircraft is smaller then you have that is per unit mass of the engine here again you need a higher value that means a lighter engine this all and you think they remote with life of components yes any engine or anything that you buy things periodically go back.

So what is the life of each of the components that the engine is made up of is an important parameter because that will be that will determine the actual running costs of the and a fleet okay typically what aircraft engine manufacturers will do is they will sell you an engine at a lower price because they know that for spares you need to go back to them.

And that is where they will escalate the prices okay so life of components is a very important parameter and it should have a longer life than any other that is soon as modularity of design which ensures better turnaround time what do we mean by that let us say you must have all seen this if you have a kinetic Honda or something similar to that Mahindra duo or any other scooter like that.

What you will see is that if there is a problem in the spark plug you will have to take out a lot many things covering that engine to just get to the problem and then fix it so if there is a small repair it will take a very longtime to do that whereas if you look at a bike engine you can access it very easily okay what you would want is that access to be much more easier and you are able to do there pair as quickly as you can which means that.

The engine will be back in operation as quickly as it can be engine not in operation is a bad thing because if engine is not in operation then you are unnecessarily paying the cost without operating it so it is better to have the engine in operation so therefore you can recover the cost so that is one of the crucial parameters then lastly.

These days you have exhaust pollution levels there are stringent restrictions on how much of knocks that your engine produces and how much of carbon monoxide emissions that it produces and there is a limit to it and you cannot exceed that limit otherwise you will not get a certification for your engine.

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**Turbojet engines**

| Name | Dia, m | Length (L), m | Mass (M), Kg | Thrust (F), kN | sfc, mg/Ns | $\pi_c$ | TIT, K | $\dot{m}_a$, kg/s | F/M, N/kg | Nozzle |
|---|---|---|---|---|---|---|---|---|---|---|
| Mamba | 0.15 | 0.42 | 6.4 | 0.25<br>0.20 | | 2.8 | 1043 | 0.5 | 38.3 | C |
| Lucas CT-3201 | 0.3 | 0.58 | 18.6 | 0.51<br>0.32 | 37.1 | 3.5 | 1190 | 0.93 | 27.4 | C |
| Atar 9K-50 (AB) | 1.02 | 5.94 | 1582 | 49.2<br>70.6 | 27.5 | 6.1 | | 70.7 | 44.6 | C |
| Orpheus 703 | 0.82 | 1.80 | 400 | 22.0 | 29.7 | | | | | C |
| Olympus 593 | 1.20 | 4.02 | 3175 | 139.4<br>169.2 | 28.3<br>39.6 | 15.5 | 1560 | 186 | 53.2 | CD |

sfc: Specific fuel consumption
$\pi_c$ : Compressor pressure ratio
TIT: Turbine inlet temperature

$\dot{m}_a$ : Mass flow rate of air
C : Convergent
CD : Convergent Divergent

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Now some of these things are put together here in this table here okay the first column here indicates different kind of engines then you have the diameter and the length which will give you the overall volume of the engine then you have the mass of the engine that is indicated here then the thrust that is produced the specific fuel consumption.

Then mass flow rate through the engine depending on this you can derive your thrust per unit mass flow rate and thrust per unit weight of the engine okay now if you see the first few engines are all micro gas turbines and the last ones are the large engines notice here that the nozzle kind in most of these is only a convergent nozzle which is indicated by C.
And only the last one that is the Olympus engine has a convergent divergent nozzle where is this Olympus engine used any idea it is used on Concorde aircraft okay that is the only one that uses their converging diverging nozzle concurred while it was operational was the only beyond Mach one aircraft okay could fly at Mach two now what they used to say is that it could be time that is between Europe and America if you have breakfast in Europe.

And start off you can have your second breakfast when you reach America the time would not have been the breakfast time yet in America when you reach it so it can be time as what it was said to be and it that's the only engine that uses a converging diverging nozzle the other thing about that Olympus engine is that it uses something known as afterburner that we are going to discuss next for most of its operational time.

Which means that the cost of all the fuel consumption would be higher and therefore the cost would be very much higher typically people would spend their lifetime savings to go once from Europe to America to enjoy that one break first year and the second breakfast yeah okay so the units is kg per kg ax kg force R that is different from milligrams per Newton second this is in this is in SI units.

And that is in case units that have so okay, okay now I talked about afterburner and things like that why are afterburners used okay so let us look at what is known as thrust augmentation next why do you think we need this kind of thrust augmentation why cannot what is it that is designed for help us out.

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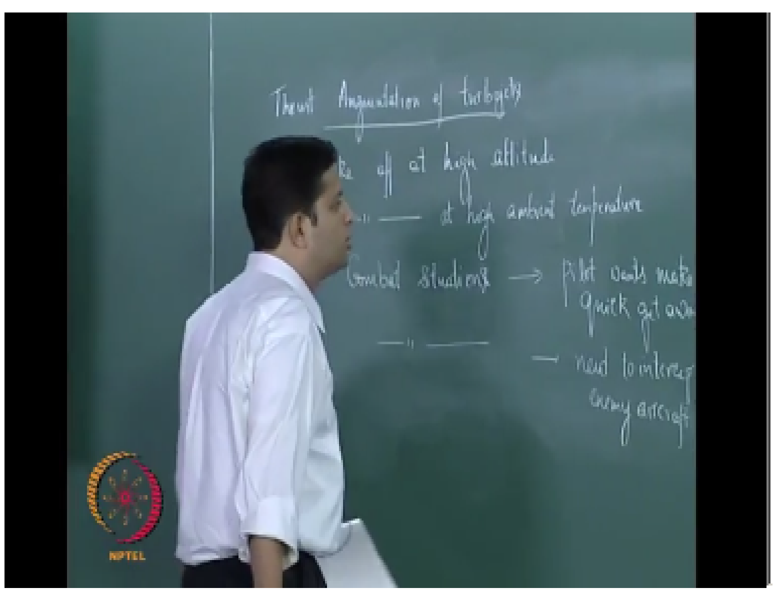

Why do you need this extra thrust augmentation that is okay that you are telling me there is a scope for improving the trust I am asking why should we look at increasing the thrust can we not provide it with just the main combustor alone okay sometimes if you have to take off in an airport that is at a very high temperature okay the density of air depends on temperature and if the density is lower than the thrust delivered will also be lower.

So that is the case and again if you are taking off from a high altitude again you need a larger thrust just for takeoff in addition if it is a military aircraft on which the turbojet is mounted there are situations in the battle where the pilot would want to drop a bomb and get away from that place very quickly so then he might want to use the turbo jet with an afterburner on for a short time.

Okay or if you have to intercept the enemy aircraft that has already come into your territory then you need to take off very quickly and intercept the enemy aircraft quickly so that again will require the afterburner so there are four situations which for which the afterburner is required take off at high altitude take off I ambient temperature you might ask me why cannot we have a longer runway well typically the runway length is fixed.
So if you have a larger aircraft and a larger takeoff weight suddenly you will want this extra thrust so that you can take off within the limited run combat situations violet wants to make a quick getaway or again in combat situation need to intercept all this for call for a larger thrust for a very small duration of time okay.

So we need to have a possibility where in we can get this without having to do it all the time but do it only for this short time and the requirement is there and typically this is done through two means there are two ways of doing.

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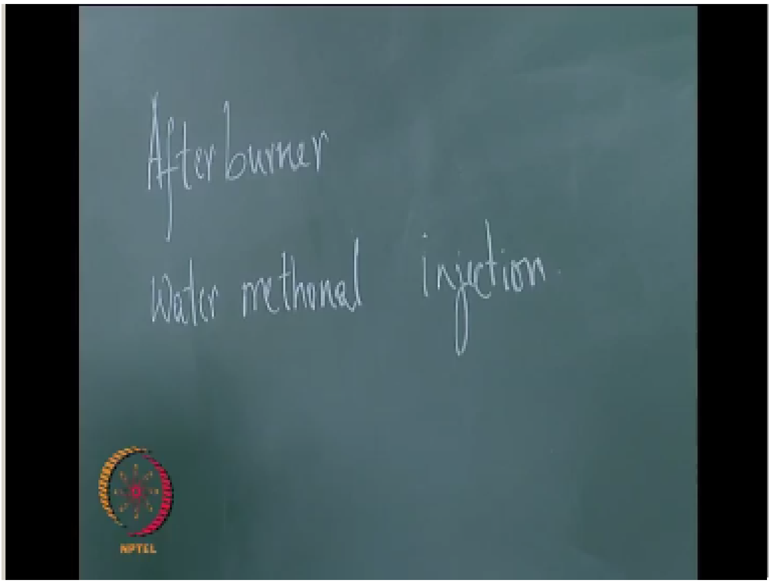


This the first is use afterburner okay and the second one is something known as what a methanol injection okay now what is this afterburner you are saying that because in the combustor main combustor we do not burn the fuel at its to isometric condition right we do not want the temperatures to go.

To something like two thousand three hundred Kelvin we would want to restrict it to something like thousand six hundred two thousand eight hundred or even lesser the way it has done is you use excess air to do that okay you use excess air to bring down the temperatures in the main combustor.

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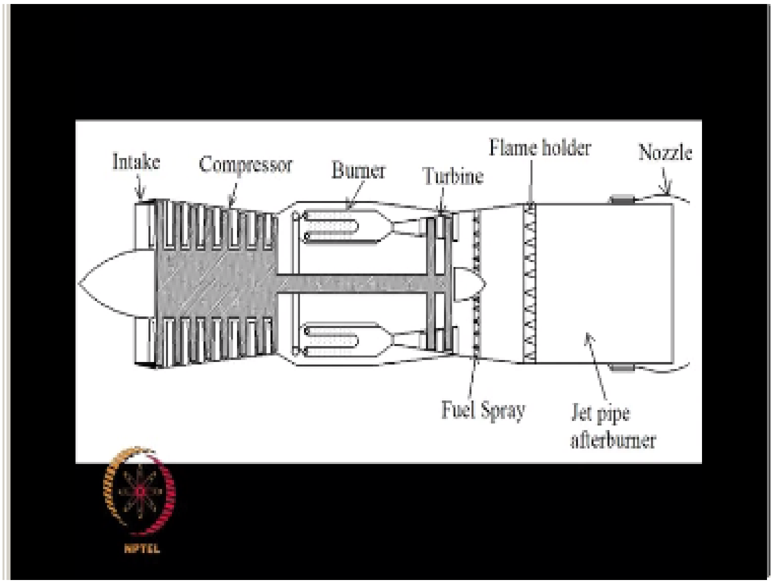


Now if you look at this turbojet engine here because there is a turbine you need to bring down the temperatures in the in front of it because turbine blades are only capable of withstanding a certain amount of temperature but there is also air that is in excess that is used here to bring down the temperature that is available for further fuel addition downstream.

And that is what is an afterburner that is you add fuel downstream of the turbine now you do not have the restriction of turbine in let temperature and therefore you can burn things in stoichiometric condition and that is what is done in their after burner you have this flame holder or the V greater here and this is the afterburner.

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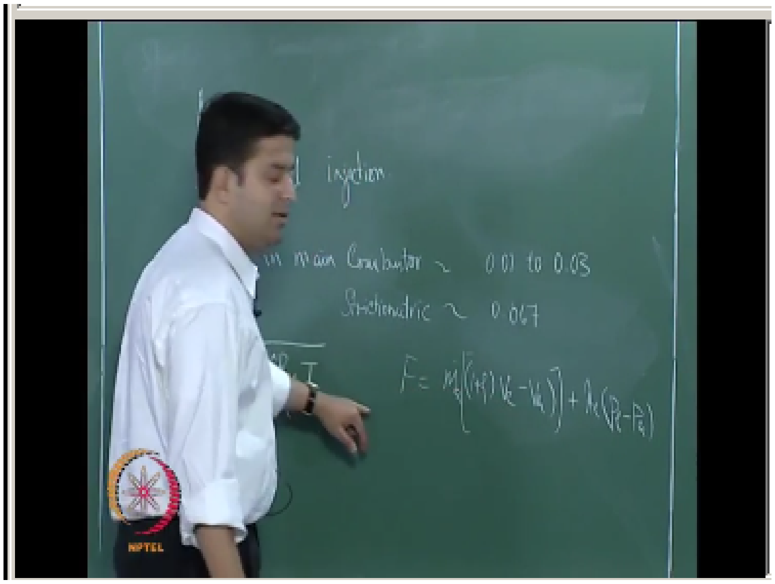


Okay let us look at how this afterburner produces the excess thrust as I said F in main combust or ranges from 0.01 to 0.02 and 2000 metric value is around 0.67 0 6 7 So a large amount of excess air is there which you can use to add more fuel and burn now what happens if you burn this excess fuel remember when we talked about the nozzle we said ve is equal to right so the exit velocity depends on the temperature right.

Now if this temperature is larger than the exit velocity will be correspondingly larger if you have the afterburner the temperatures without the afterburner if you look at the temperatures, temperatures will not be very large because it has expanded in the turbine first and then it goes through the nozzle or if you had add heat in the afterburner then the temperatures are much higher.

And consequently this temperature will also be higher and therefore you will get a larger V and from our thrust equation which is F is equal to we see that if we E is larger than we get a higher thrust so that is how the afterburner delivers higher thrust let us look at how the TS diagram for this looks like.

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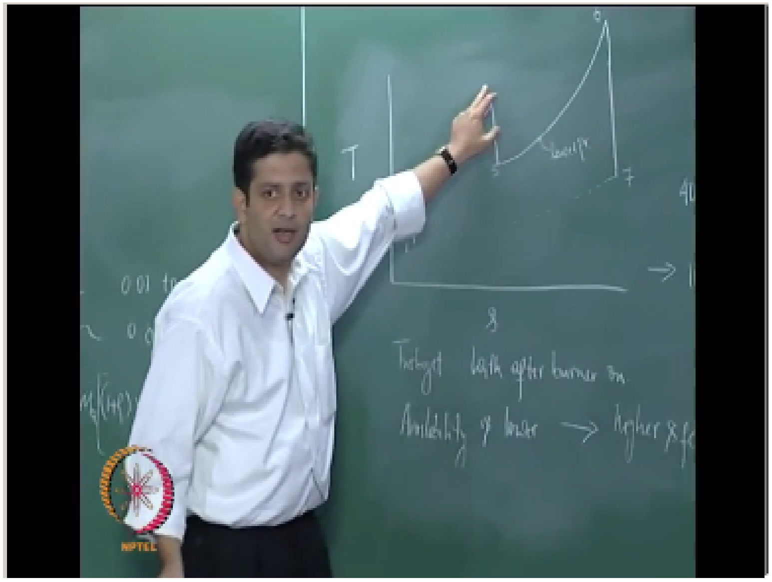

This is the TS diagram for turbojet with after burner on okay notice that earlier this was the maximum temperature that you were able to go up to because of the limitation so the turbine now if you are adding heat in the afterburner you can go to a much higher temperature but we need to remember one thing that we are adding heat at a lower pressure here this is lower than the main combustion chamber pressure.

Because the fluid has already expanded through the turbine so as to produce work that is sufficient to run the compressor okay so you have already taken out this work and the pressures are lower here now you are adding heat at lower pressure in the afterburner you must be aware of this from your thermodynamics that if you add heat at a lower pressure then the availability will be lower.

Okay so and consequently you will get a higher specific fuel consumption okay the fuel consumption if you have the after burner on without the after burner on changes by around 100 percent if 40to 60% is first augmentation then you correspond to 100 % increase in SSE so you will get the additional thrust at a much higher cost than you would have got it if the combustion was only in the main combustion chamber.

So there is always this scope that you would want to go in for a larger and larger turbine Inlet temperature so that you can make the engine give you higher thrust as demanded okay there is another thing that pilots are instructed to do when they switch on this afterburner what is that as soon as they switch on the afterburner the pilots are instructed or the engine itself has it in it that it does something what does it do?

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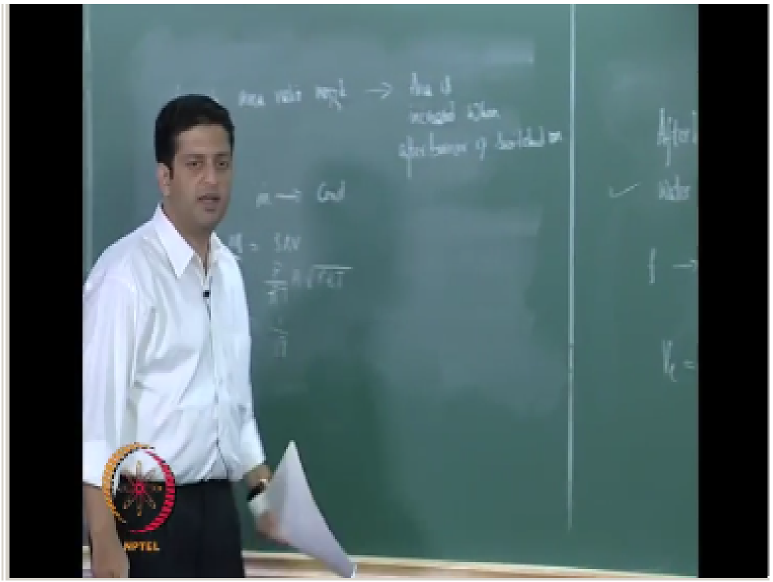

The idea most of these engines will have variable area NATO nozzle and the nozzle will open up okay so variable area ratio also is used and area is increased when afterburner switched on why do you think we need to do this why should we increase the area if you switch on the afterburners Roscoe the gold is you correct what happens here is if you look at the mass flow rate through the engine that has nearly the same with.

And without the afterburner switched on there is a small increase in fuel but if you look at the numbers this is a very small number right so the increase from this to this is even smaller so the fuel increase is much smaller so the mass flow rate essentially is constant MDOT is constant what happens is because of the increase in temperature the density drops okay density drops but velocity increases right.

So you need to look at MDOT is nothing but $\rho$ AV right $\rho$ depends on temperature as P / RT and velocity because the nozzle is choked depends on temperature like this so you notice that it goes M0 goes as 1by roof temperature so as temperature is increased MDOT will decrease right so if you have to bring back the same mass flow rate then you need to increase the area.

And that is why the nozzle area is increased when the afterburner is switched on if you do not do this what happens is there will be a pressure buildup and it could lead to stall in the compressor this pressure build up could travel backwards and could lead to an increase in pressure ratio across the compressor and lead to stop.

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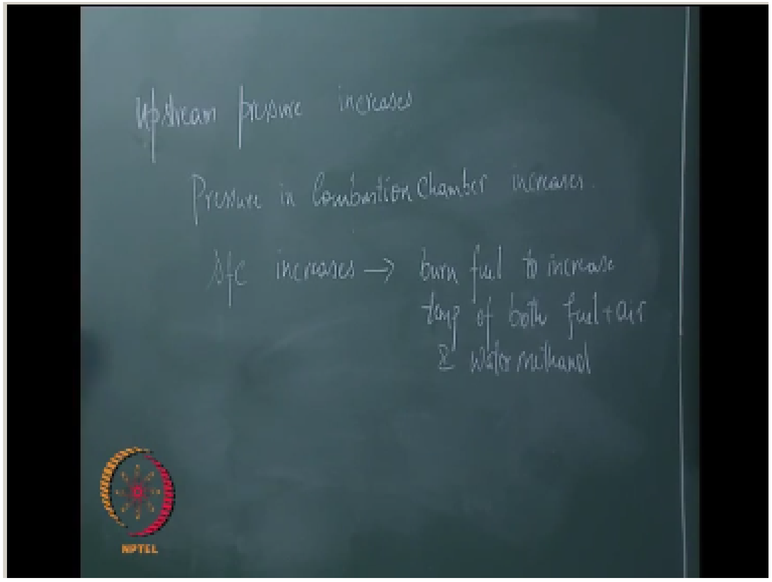


Now let us discuss the next method to increase the thrust of the turbojet that is water methanol injection now typically one would have added only water but methanol is also added because water at low temperatures that are encountered and the aircraft flies at high altitudes can freeze and that is an undesirable situation to be in.

So you add methanol to prevent this freezing okay and the methanol also acts as a fuel there so it reduces the amount of fuel main kerosene that you use in order to get this thrust enhancement some ethanol has two purposes there one is to prevent freezing and secondly acts as a fuel now how does this work if you look at this double jet engine there are two places where you can do this water methanol injection one is in the compressor and the other one is in the burner.

Let US look at both cases if we look at all TS diagram and just for the compressor and if we look at an actual process it will go something like this right the actual process is a non is entropic process and it go like this now when you add water methanol what happens is water is in liquid phase water in methanol are in liquid phase and they evaporate as they go through this and while they evaporate.

They cool the entire mixture and therefore the temperature decreases and the process tends to become more is entropic than the non isentropic part so you might get an actual process something like this with the water methanol injection and as a consequence remember the turbine work and the compressor work should match you are using.

This batch of from 2 - 2 3 – this is the amount of work that you are inputting to the compressor for a non is entropic process if the non is entropic City decreases then for the same amount of work input you might actually end up getting a higher pressure here okay so that is what is happening if you add water and methanol in the compressor itself you get one it is a more is entropic coil and at the end of it you get a higher pressure.

Now if you get the higher pressure then the first is getting a higher pressure but the temperature at this point is much less than 3 - so you need to burn additional fuel to take it from here to 4 right so the SFC will have to increase okay this is our water methanol injection works if you add it in the compressor then.

Let us look at next what happens when we add water and methanol in the main combustion chamber that is if you look at this figure you can add water and methanol in the main combustion chamber itself and let us see what happens if we add water and methanol in the main combustion chamber if we add water and methanol in the main combustion chamber remember.

That the flow at the exit of the combustion chamber is choked okay you will, will derive this a little later in the course you can take it that if the flow is choked if you add more mass then the upstream pressure will increase that is pressuring combustion chamber increases now this increase in pressure in the combustion chamber is not accompanied by an increase in pressure across.

The compressor the compressor did not do any work to get this increase in pressure and this was because of the evaporation of water vapor to evaporate the water vapor what you need to do is burn more fuel okay so therefore the SFC increases because you need to burn more fuel to increase temperature of both fuel air mixture and water methanol ethanol reduces this but cannot completely take over you still need to add some more fuel to be burned.

So that the temperature turbine In let temperature is achieved now SFC increases and the pressure ratio across the turbine is increased not only that the mass flow rate through the turbine is higher now because you have water methanol as well as fuel air mixture going through the turbine so if you look at - water is the amount of mass flow-rate going through the compressor that is much smaller than this.

So therefore the mass flow rate through the turbine is increased pressure ratio across the turbine is increased so you get what typically happens is if this is the TS diagram for the turbine portion we are only looking at the turbine portion let say if okay four and five now what happens is firstly pressure ratio is increased right so it goes to sorry pressure ratio is increased well turbine in let temperature is the same.

So this is the new point for - okay now because the mass flow rate through the turbine is more the endpoint will be much higher than what you get here so this will be the new five - and this is five so five - has a higher temperature and pressure compared to five so you can expand more in the nozzle there is an availability of expansion greater availability of expansion in the nozzle therefore you get the higher thrust okay we will stop here and continue in the next class.


**Online Video Editing /Post Production**

Mahendra babu. K.R
Soju Francis
Subash. S
Pradeepa. S

**Camera**

Selvam
Robert Joseph
Karthikeyan
Ram Kumar
Ramganesh
Sathiaraj

**Studio Assistance**

Krishnakumar
Linuselvan
Saranraj

**Animations**

Anushree Santhosh
Pradeep Valan .S.L

**NPTEL Web Facilities, Faculty Assistance &**

Allen Jacob Dinesh
Bharathi Balaji
Deepa Venkatraman

Dianis Bertin
Gayathri
Gurumoorthi
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Sridharan
Suriyakumari

**Administrative Assistant**
Janakiraman. K.S

**Video Producers**
K.R. Ravindranath
Kannan Krishnamurty

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