Indian Institute of Technology Madras
Presents

NPTEL
National Programme on Technology Enhanced Learning

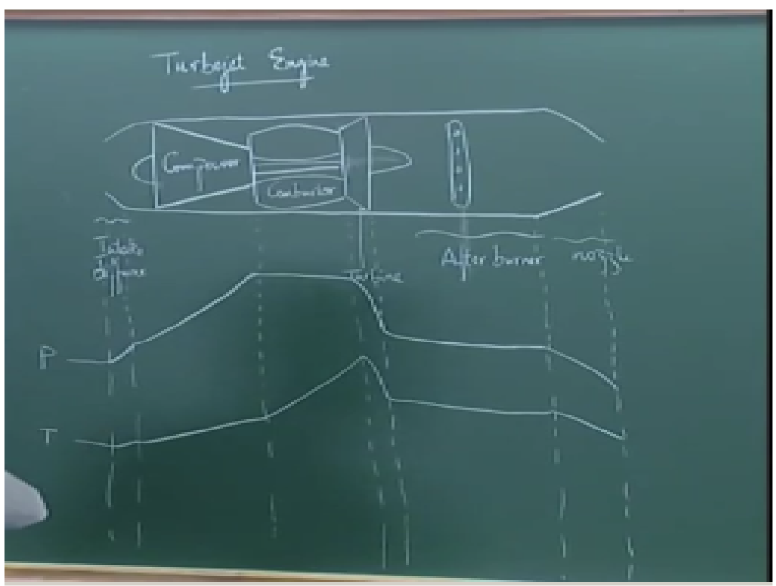
Aerospace Propulsion
Air breathing Engines – Turbojet I

Lecture - 2

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

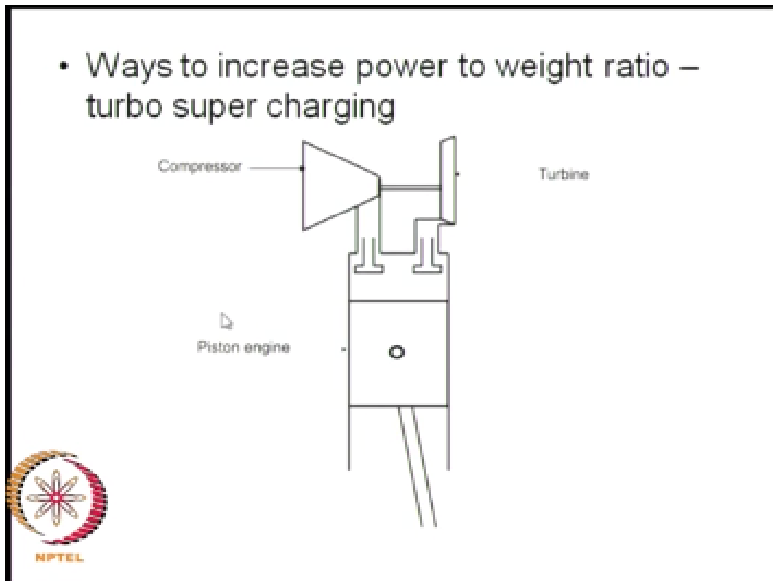
Good morning in the last class we had stopped at the point where and we were introducing ourselves to turbo jet engines right, we said it was developed during the initial phase of the Second World War let us look at our turbojet engines.

(Refer Slide Time: 00:35)



Now this is the sketch of a turbo jet engines, now this is the compressor this is the combustor this is the turbine this is the afterburner portion this is the nozzle and here you have the intake or diffuser section okay.

(Refer Slide Time: 03:38)



Now if you remember in the last class I had said that while discussing about piston engine propeller combination as we go higher in altitude we needed to do something known as turbo super charging and therefore we had a compressor connected to a turbine and the exit of the compressor was connected to the piston engine I said the gas turbine engine or the turbojet engine is a evolution from the from this concept to what is seen here we see a compressor and in between a combustor instead of going into a piston engine and then there is a turbine.

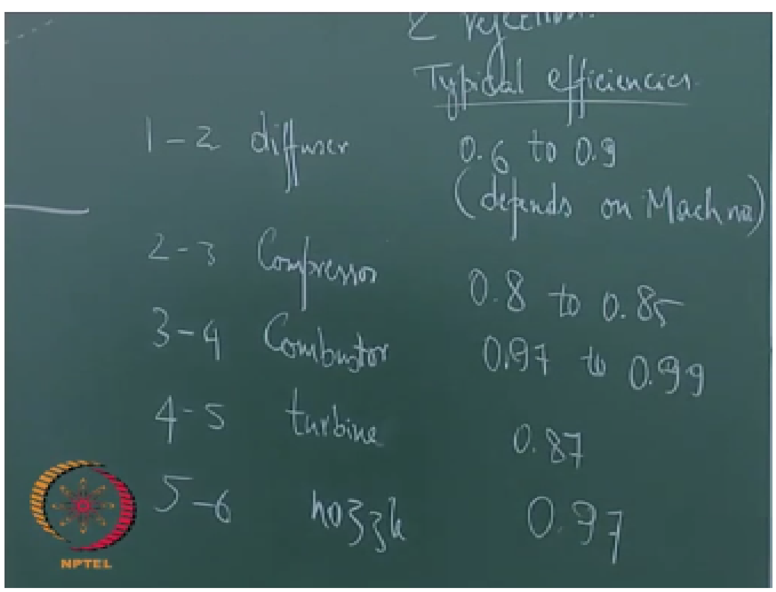
Now the turbine develops enough power to run the compressor and this is the after burner portion and this is the nozzle, now let us look at how pressure and temperature vary across the length of the turbo jet engine okay, now let us first look at pressure this is the diffuser section in the diffuser what happens is the incoming flow is it has a high velocity its velocities are reduced and therefore you gain in terms of pressure the kinetic energy is converted here and you get higher pressure at this point.

Now this is then further compressed in the compressor and you get much higher pressure here in the combustor it is a constant pressure process again you have the turbine where the pressure drops and then in the afterburner which is nothing but a second combustor pressure is again constant and in the nozzle the pressure drops let us look at how the line goes this is how the pressure varies as a function of the length of the turbo jet engine.

Now if we look at what happens to temperature initially in the diffuser portion temperature again slowly increases because it is undergoing compression and in the compressor again the temperature increases, but the temperature increase is not similar to the pressurized is much more and in the combustor you are adding heat you are burning fuel and the fuel plus air is combusted here and therefore the energy is being supplied chemical energy is being converted into heat, so the temperature increases tremendously here.

And then in the turbine again temperatures fall because there is an expansion process and in the after burner the temperatures, let us now look at a case wherein we have not switched on the afterburner so the temperature remains constant and again it expands in the nozzle okay, now we will discuss afterburner a little later in the class this is how pressure varies this is how temperature varies notice that pressure almost comes back to the ambient pressure at the end of it whereas temperatures are still very high at the nozzle exhaust okay now if we were to convert this information into what is known as a TS diagram.

(Refer Slide Time: 08:37)



It looks something similar to what you might already be aware of a Brighton cycle gas turbine engines or turbo jet engines follow Brighton cycle, if on a TS diagram firstly let us look at ideal processes, now I have numbered them 1 to 6 I will do the same here too this is one end of intake or diffuser section S2 2 to b 3 is compressor 3 to 4 is combustor 4 to 5 is turbine 5 alcohol this point also 5 because we are not switched on the afterburner, so it is a constant pressure constant of a temperature process right now and lastly this point as 6 that is the nozzle exit as 6.

So if you look at this diagram here1 to 2 is compression in the diffuser and 2 to 3 is compression in the compressor 3 to 4 is temperature rise in the combustor and 4 to 5 is process through the turbine and 5 to 6 through the nozzle this is an ideal cycle for a turbojet engine, now what happens if we look at an actual cycle what we have assumed here is isentropic compression and expansion and constant pressure heat addition and rejection this is what constitutes a Brighton cycle.

Now if you see here the x-axis is entropy and you see that entropy is constant during the combustion compression process and entropy is also constant during the expansion process this is a constant pressure process and this is also a constant pressure process and notice have wantly done this that the slope of this line is much more than the slope of this line this is because if you look at a TS diagram pressure increases much more stiff P at higher values than at lower values and therefore the slope of this is much smaller and this is a dotted line because it does not come back to this position okay.

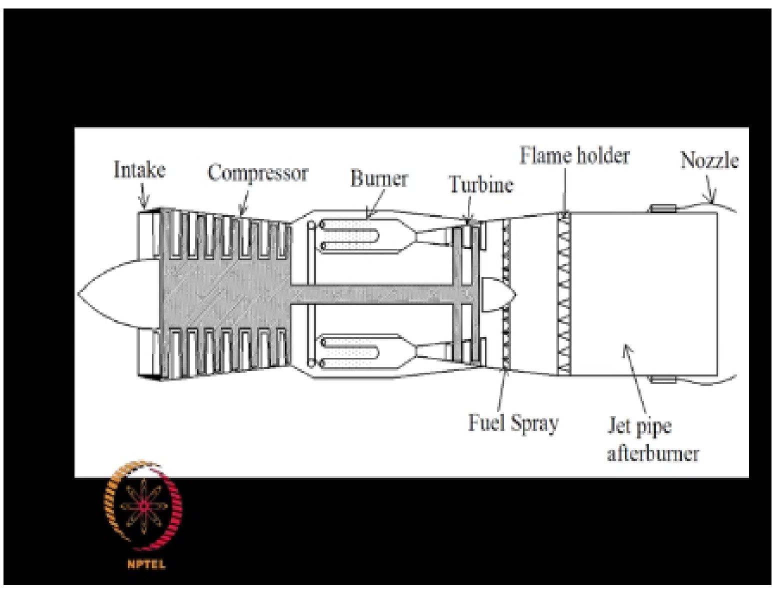
Now as I said you assume constant pressure heat addition and heat rejection and isentropic processes actual processes what kind of processes will be they be will they be compression adiabatic or there is a difference between an isentropic and an adiabatic process isentropic process is reversible adiabatic and adiabatic process is where there is no heat transfer so actual processes are without any heat transfer, so it is typically will be a actual cycle will be will have non- isentropic processes okay so you will have entropy increasing always so you will have one to two and then two to three let me call this new point as two - this new point as 3 -what happens in the combustor is the process a constant pressure process.

If you are adding heat in the combustor there is something known as a rally process wherein the pressure drops okay, so you will get something like this for- and then expansion is again non-isentropic 6 - this is the typical TS diagram for an actual cycle also, now let us look at what are the typical efficiencies that we get so one to two diffuser the typical efficiencies are this is around 0.62 0.9 this depends on the Mach number at which the vehicle is flying, now if the vehicle Mach number is lower you are going to get somewhere higher efficiencies.

But as you go to higher Mach numbers you will get lower efficiencies and in the compressor the efficiencies range from 0.82 0.85 and combustor it is very high around 0.972.99 okay and 4 to 5 you have turbine this is somewhere around 0.87 and lastly 5 to 6 through the nozzle the efficiency is around 0.97 you will notice that the efficiencies for these two processes are much lower than efficiencies for these two processes why do you think that is yes, if you take a look at the diffuser of the compressor.

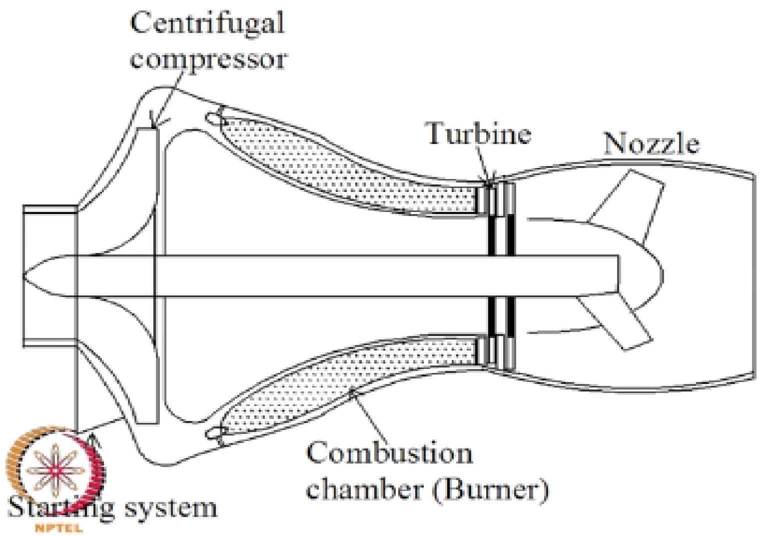
In the diffuser and the compressor the pressure is increasing so you have what is known as an adverse pressure gradient whereas, if you look at the turbine and the nozzle there is a favorable pressure gradient okay, so therefore the efficiencies with turbine and nozzle are bound to be higher than efficiencies with diffuser and compressor now let us look at some typical engines.

(Refer Slide Time: 19:08)



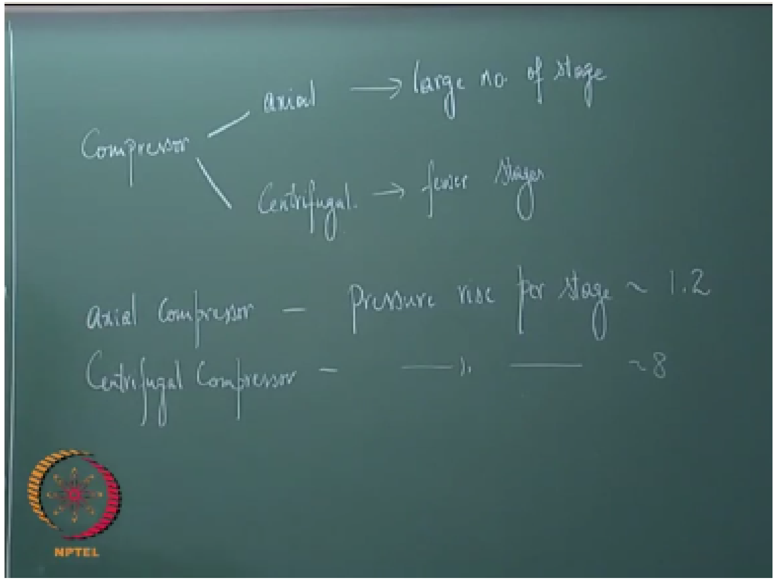
This is a typical gas turbine engine with axial compressor here you have the intake and this is the axial compressor what we mean by axial compressor is the flow is along the axis and you have the burner or the compressor then you have the turbine and jet pipe of the afterburner and then the nozzle okay, now this is with a axial compressor as opposed to this.

(Refer Slide Time: 19:45)



You can also have something known as a centrifugal compressor okay wherein the flow comes in axially and goes out radially and again if you want to have another stage, it has to come back in and again go in axially and go out radially and you have the combustion chamber here and then the turbine, so for a compressor we have two choices.

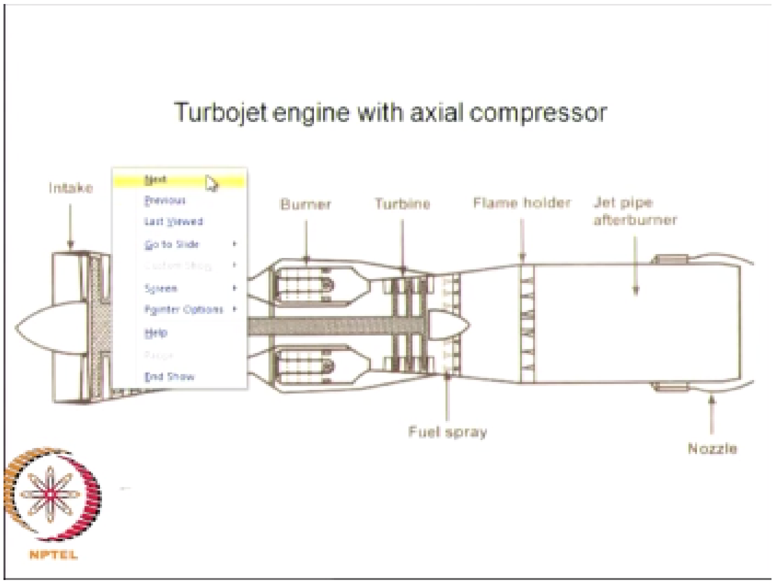
(Refer Slide Time: 20:25)



That is compressor can be either axial or centrifugal what is the difference between the two wait what do you think is the change from axial to centrifugal notice one thing that, if you take a look at this engine there is only one stage of centrifugal compressor whereas in the axial compressor there are many stages here, so one is in the axial compressor it has large number of stages and this has fewer stages okay, now typically in an axial compressor the pressurize / stage is around 1.2 whereas for a centrifugal compressor similar value is somewhere around 8.

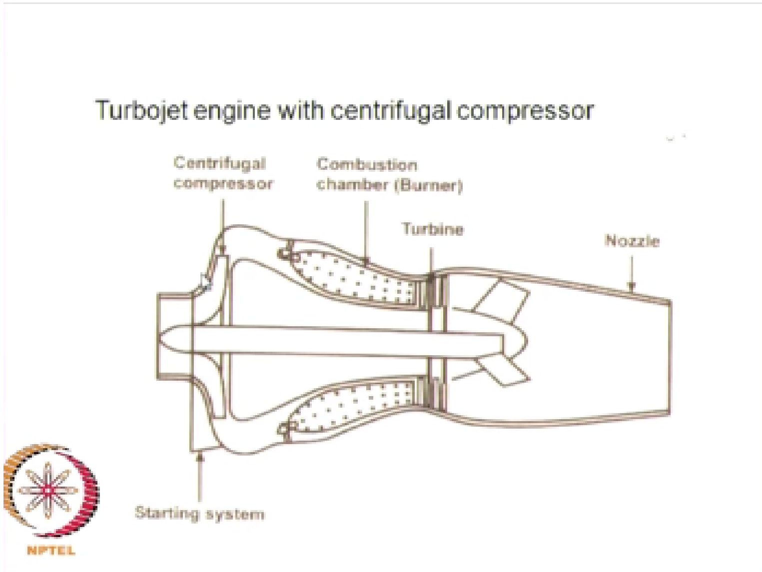
So you see that if you want a pressure rise in a centrifugal compressor you can achieve the same with fewer number of stages whereas if you go for an axial compressor you need large number of stages to achieve the same okay, now is that all the difference or is there something more to it yes typically one would most modern engines would go with axial compressors because it requires a smaller frontal area if you look at the figure here.

(Refer Slide Time: 23:05)



This requires a smaller frontal area compared to this one.

(Refer Slide Time: 23:13)



Which has a larger frontal area okay so one would go with a smaller frontal area because it reduces drag, so axial compressors compared to centrifugal compressor okay, now if you see here that axial compressor the pressure rise per stage is very small this is because if you go for a larger pressurization an axial compressor then flow separation and stall takes place therefore you are forced to look at a very small pressurized per stage whereas in a centrifugal compressor you do not have such problems.

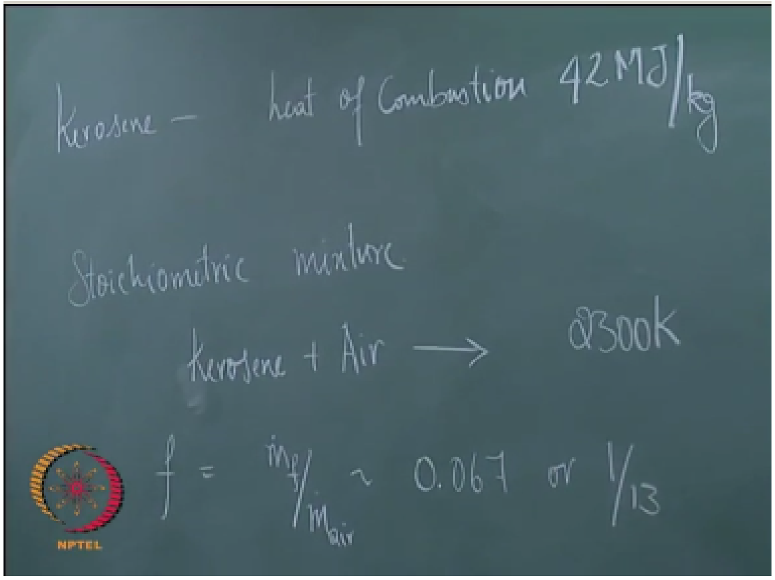
We will discuss that in detail as when we look at compressors in a low in a greater detail little later in the course, now it is also seen that axial compressors will have higher efficiency compared to centrifugal compressors because the flow distribution is much better in axial compressor if you look at centrifugal compressors if you need to have multiple stages then what you have here is flow coming in axially and then it goes out radially and again, if you have to have a second stage it has to come back in axially and then again go out radially.

So the flow distribution is not a very good in centrifugal compressors, so therefore centrifugal compressors will have a slightly lower efficiency have higher efficiency compared to centrifugal compressors now we have looked at different kinds of compresses then you go to the combustor here in the compressor there is temperature rise typically this temperature will be of the order of 400 to 750 Kelvin why am I choosing two different values one it depends on compressor pressure ratio and two it depends on altitude.

At a lower altitude the incoming air temperature is much higher and therefore it will rise to a higher temperature whereas at a higher altitude where the temperatures are much lower it will rise to a lower temperature okay, and in the combustor we have temperatures ranging from at the outlet of the compressor to something like 950 to 1600 Kelvin again it depends on compressor pressure ratio altitude and also what is known as what is the limit on turbine Inlet temperature okay.

Already is the board now if you look at the fuel that is used what is the fuel that is used in gas turbine engines or turbojet engines kerosene what is the calorific value of the fuel around 42 mega joules per kg, now if you are using kerosene right the maximum temperature that you can attain with kerosene and air is something like 200 3000K it is also known as adiabatic flame temperature.

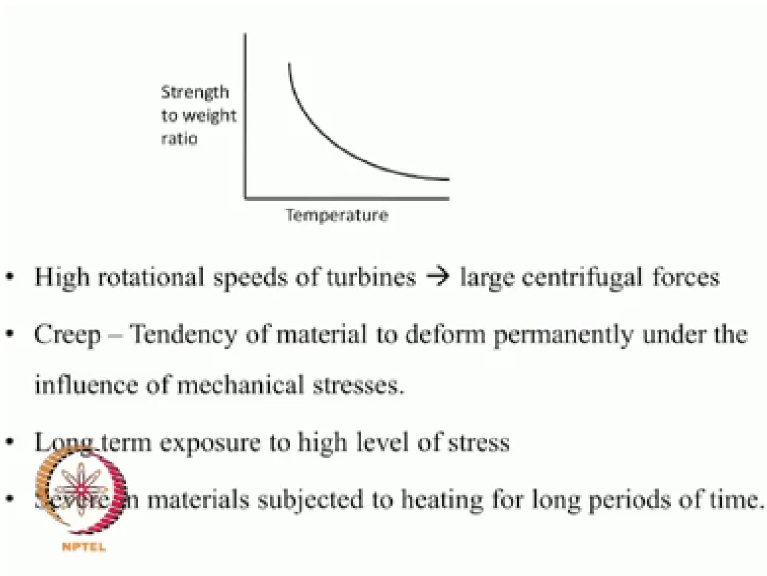
(Refer Slide Time: 29:20)



So kerosene is used and it has a heat of combustion of around 42 Mj/kg and what we know as stoichiometric mixture what do we mean by this what do we mean by stoichiometry mixture is the right amount of fuel and air that is required or it is the amount of air that is required for complete combustion of the fuel, if you use this for kerosene and air if you use stoichiometry mixture you get a temperature of around 2300K okay the stoichiometric ratio for this is F which is nothing but mass flow rate of fuel divided by mass flow rate of air this is around 0.067 or 1/ 13 for kerosene and air.

So if you have one part of you will need 13 parts of air to completely burn it and the temperature that you get at the end of the combustion process is somewhere around 2,300 T and now compare that with what we are letting this go to this is around 1600 why do you think we are letting not letting it go to such a high temperature evine inlet temperature turbine Inlet temperatures need to be lower why is it to be lower integrity in the turbine days, so you have nozzle you have compressor combustor takes that kind of temperature why do not you talk about fractural integrity there so high temperature allowing it and rip apart the casing of C okay very nearly that.

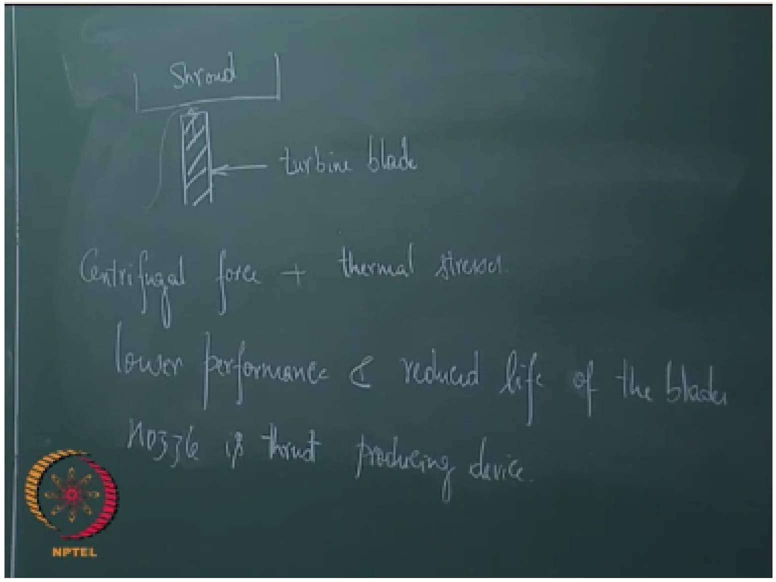
(Refer Slide Time: 32:08)



If we look at this graph here we see that the strength to weight ratio of any material will decrease rapidly with increase in temperature and in addition turbine blades are spun at very high speeds which contributes to very large centrifugal forces in addition to this there is something known as creep which is nothing, but the tendency of material to deform permanently under the influence of mechanical stresses this is caused when you have long term exposure to high levels of stress and is more severe in materials subjected to heating for long periods of time.

If you take a look at the compressor or sorry the turbine here there are turbine blades and there is an outer casing.

(Refer Slide Time: 33:16)



Let me draw that here let us, say this is the turbine blade and this is the shroud or the outer casing there is always a small gap between the two of them why do you think it should be there if you see railway tracks there is a small gap between two railway tracks why is it that the compensation due to it yes if you are during summer the temperature increases and therefore the gap reduces something similar is what you see here firstly the turbine blades are rotated at very high rpms so there is an enormous amount of centrifugal force acting on them.

Now there is a centrifugal force acting in this direction in addition to that there are thermal stresses that are developed okay, now which lead to elongation of the blade, now if you do not provide this gap then the blade will rub against the shroud and well deteriorate the performance as well as lead to a shorter life for the turbine blades what happens if we give a larger gap, so what is the big fuss about nobody wants to do work just like us air also does not want to do any work.

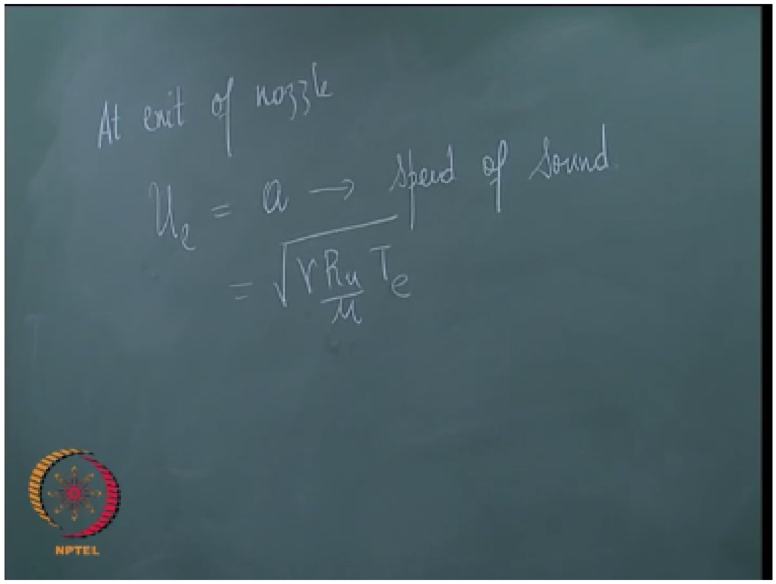
So if you give a larger gap then we most of the flow tends to go through this because this is the part of least resistance okay, so you cannot give a very large gap because most of it will anyway pass through that you have to give a small gap such that after elongation it is nearly there right, so that is why we see that we are not able to go to very high table in let temperatures although our limit is something like two 1300K, we have forced to something like thousand 600 or 1800K okay this is because of the problem that we just now discussed about.

So if the turbine blades rub on the shroud then it leads to lower performance and reduce life of the, so we have forced to compromise and look at a lower temperature we are right now at 1600 2800 because we use lots of cooling techniques to cool the blades we use bypass air from the compressor to cool the blades, so that we are able to go to higher and higher temperatures now lastly you have the nozzle here nozzle is the thrust producing device just like in the piston engine plus propeller was the truss producing.

Device here nozzle is the thrust producing device okay. if you notice the pressures after expansion in the turbine are very much lower they will be of the order of around 1.5 to 2.5 atmospheres typically, okay this depends again on the altitude and the pressure ratio across the nozzle is very small therefore we typically end up using only a convergent nozzle in an aircraft engine that is you only have a convergent portion here and the reason for that is that the pressure at the exit of the turbine are very much lower and you do not have a large pressure ratio.

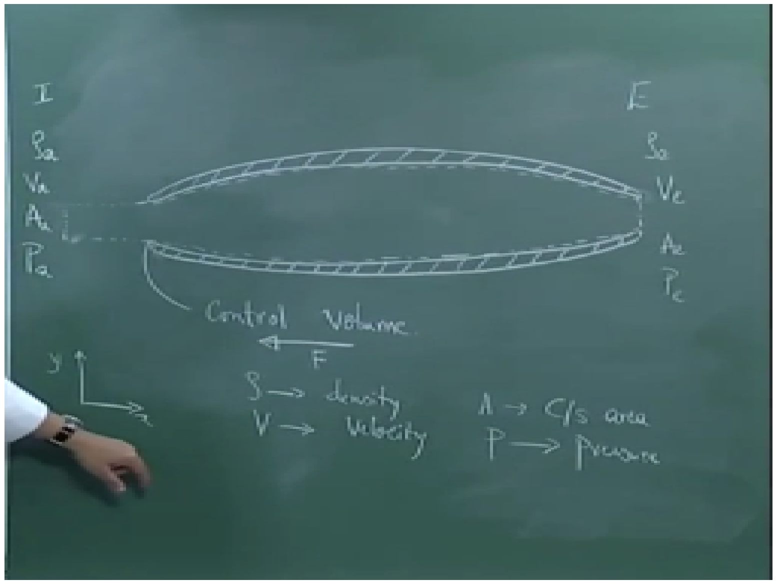
Across the nozzle so you end up using a convergent nozzle only now the flow at the end of the nozzle here is to what do we mean by that the Mach number is 1 or the flow attains the speed of a flow speed and the acoustic speed are the same.

(Refer Slide Time: 39:28)



So at the exit of nozzle Ue is equal to a which is nothing but speed of song now speed of sound is given by where γ is the ratio of specific heats Ru is the universal gas constant M is the molecular weight of gases and D is the temperature at the nozzle exit okay, so notice that Ue is directly dependent on the temperature at the exit of the nozzle Te, so if the temperature at the exit of the nozzle is large then you get a higher velocity and therefore higher thrust that is what is the reason for this to produce the thrust you have a higher temperature at the exit and therefore you get higher velocity okay now let us try and look at how to derive the thrust equation.

(Refer Slide Time: 41:38)

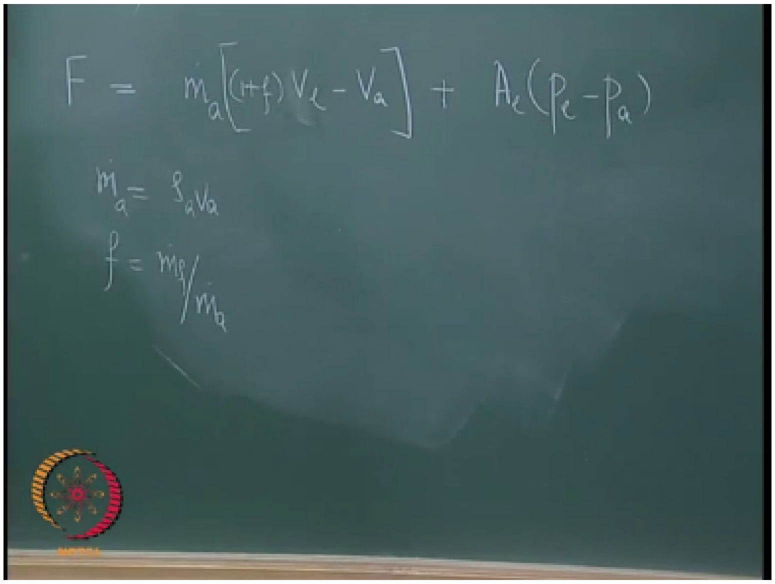


Now let me call this as the y-coordinate and this is my x-coordinate and I will assume an engine I will not look at what are all the details in here, I will look at an engine something like this you well for the time being ignore the details that are inside because all that it does is it changes flow conditions from here to here and if you look at what are the changes that it does we should be able to capture what is the thrust it is producing, now let us take a control volume this is the control volume that I take I have taken the control volume sufficiently upstream of the inlet.

Because I do not want things that are happening here two dimensional effects to come into picture we are only looking at what is the thrust in the x-direction, so what is the thrust that is produced in the x-direction is all that we are interested in okay, now let me call the parameters at the inlet as c_a V_a A_a and P a this is ρ is density V is velocity yes cross-sectional area and P is the pressure , now similar quantities at the exit section here let me call this as the intake section I and let me call this as the exit section E.

At the exit section similar quantities would be ρe Ve Pe and Pe is the pressure at the exit of the nozzle the ambient pressure is still P_A okay that is the same as this, now we want to find out what is the thrust that is produced in the X direction right, so what do we need to do in order to do this which law of motion do we need to look at Newton's second law of motion which states that force is equal to rate of change of momentum.

(Refer Slide Time: 46:21)



So σ F X or the sum of the forces in the X direction must be equal to rate of change of momentum in x-direction okay, now what is σ F_X what are the things that constitute σ F_X1 is the thrust that it is producing the other is the pressure into this area and pressure into this area okay, so σ F_X I can write it as f now I have taken PA - PA if you notice I have taken the control volume sufficiently upstream so that the pressure across the intake area does not gain much, so from here to here there is no change in pressure so this will go to 0 and the other one will be in the negative direction.

Because you are looking at force in the other direction now what is the rate of change of momentum here m dot into U_e right, so you have ρ_e V_e2 A_e - ρ_a Va2 A ρ_e V_e we know is equal to m dot Ve okay, so we get if you simplify further we get F is equal to I take this on the other side and I can write this as m dot a into 1 +F V_e – V_a + PE - PA I have taken this term to the right hand side this goes to 0, now m dot a is nothing but ρ_a V_a okay now the 1 + F constitutes remember in our earlier in the class we defined F as mass flow rate of fuel divided by mass flow rate of air.

What happens is inside the engine you are adding fuel in the combustor here you are adding fuel right, so therefore there is an increase in mass and that is why you have 1 + F when it is going out there is an increase in mass and that is why you have 1 + F. so this is the thrust equation for a turbojet we will discuss more about the turbojet in the next class okay we will stop here we will discuss next about the turbojet in the next class.

Online Video Editing/Post Production

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

Camera

Selvam
Robert Joseph
Karthikeyan
Ramkumar
Ramganesh
Sathiaraj

Studio Assistants

Krishnakumar
Linuselvan
Saranraj

Animations

Anushree Santhosh
Pradeep Valan .S.L

NPTEL Web & Faculty Assistant Team

Allen Jacob Dinesh
Bharathi Balaji
Deepa Venkatraman
Dianis Bertin
Gayathri
Gurumoorthi
Jason Prasad
Jayanthi
Kamala Ramakrishnan
Lakshmi Priya
Malarvizhi
Manikandasivam
Mohana Sundari
Muthu Kumaran
Naveen Kumar
Palani
Salomi
Sridharan
Suriyakumari

Administrative Assistant
Janakiraman. K.S

Video Producers
K.R. Ravindranath
Kannan Krishnamurty

IIT Madras Production

Funded By
Department of Higher Education
Ministry of Human Resource Development
Government of India

www.nptel.ac.in