Jet Aircraft Propulsion

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Module No. # 01

Lecture No. # 08

Cycle Components and Component Performances

Hello and welcome to lecture number 8 of this lecture series on Jet Aircraft Propulsion. As we have been discussing in the last few lectures, there are different modes or forms of Brayton cycle, which is the fundamental cycle based on which all the gas turbine engines operate. So, the Brayton cycle forming the basis of all gas turbine engines. We have been discussing over the last couple of lectures on, what are the different forms of Brayton cycle, the actual Brayton cycle and how is it that this Brayton cycle is used in an actual aircraft engine.

And we have seen the ideal analysis or the ideal cycle formed of the Brayton cycle used in the turbojet the simple turbojet engine, which is the most fundamental form of a gas turbine engine. And then, we have seen variants of turbojet engine like the turbojet with afterburning, then we have also seen turbojet, the turbofan engine which is a variant of the turbojet engine with a fan. So, as to have a lower effective jet exhaust velocity leading to better propulsion efficiencies and also fuel efficiency to some extent.

Then, we have also seen that, there are different forms of turbofan engines like the single spool, the multi spool and so on. And then, the other forms of the propeller forms of the jet engine, the turboprop, the turboshaft engine. And also a very simple form of a jet engine, the ramjet engine which does not have any rotating components. So, these are the different types of jet engines that we have been discussing over the last couple of lectures. And also we have had some discussion on the basic cycle the ideal cycle of these different modes of jet engines.

So, what we are going to discuss today are, the components that constitute a jet engine and how is it that we can evaluate the performance of these components, we are not going into discussion mode of the exact form of these components or what how is it that these components work and so on. We will just be treating these components as black boxes, but we will also look into take into account the performance parameters, which we can associate for each of these components.

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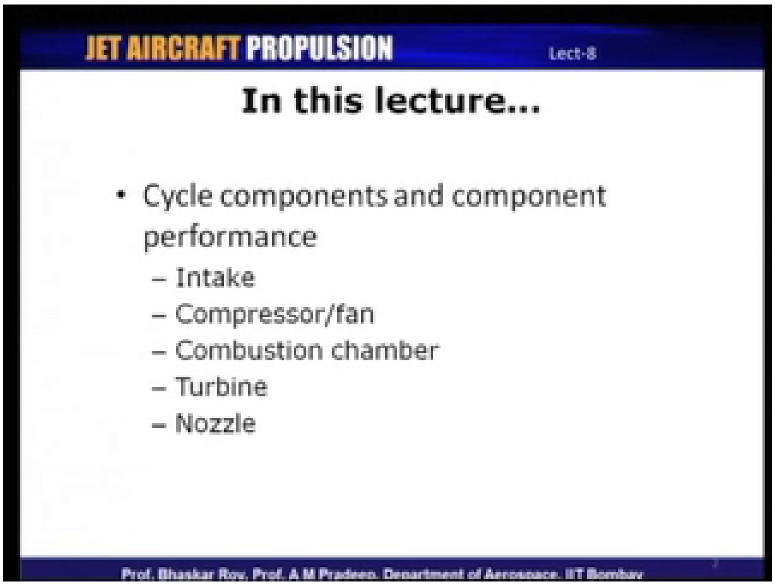

JET AIRCRAFT PROPULSION Lect-8

In this lecture…

- Cycle components and component performance
  - Intake
  - Compressor/fan
  - Combustion chamber
  - Turbine
  - Nozzle

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So, what we are going to discuss in today’s lecture are, the following will be beginning our discussion with taking a look at the intake, intake is one of the first components of a jet engine. Then following the intake is the compressor or the fan, thermodynamically compressor and fan are the very same and so, the performance parameters that we define for compressor should also be valid for a fan. And then, we will discuss about the parameters, which are to be defined for combustion chamber, then the turbine, the nozzle and afterburner and so on. So, these are some of the topics that we will be discussing in today’s lecture.

And we will as I mentioned, we will not be discussing about the geometry and the design and other aspects of these components this the detail design and also the composition of these components will of course, be discussed in detail in later lectures, when we analyze each of these components one by one. Today, we are going to just treat them as black boxes and that, there is some performance penalty which we have to associate due to some irreversibilities and so on. So, let us discuss about, what are the irreversibilities that could possibly be happening the performance of these devices.

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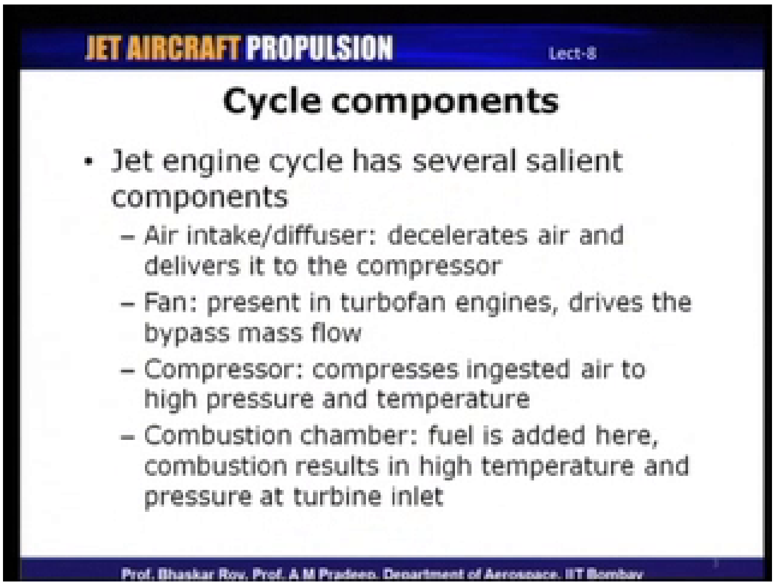

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Cycle components

- Jet engine cycle has several salient components
  - Air intake/diffuser: decelerates air and delivers it to the compressor
  - Fan: present in turbofan engines, drives the bypass mass flow
  - Compressor: compresses ingested air to high pressure and temperature
  - Combustion chamber: fuel is added here, combustion results in high temperature and pressure at turbine inlet

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So, we know that, jet engine as we have seen has several salient components. And one of the first components of a jet engine is, the air intake or the diffuser, the basic performance the basic function of an air intake or a diffuser is decelerate the air incoming air and deliver it to a compressor. So, that is one of the basic functions of an air intake, that it will decelerate the air incoming air directs it towards the compressor and in the process, it also reduces this velocity, increase the pressure at little bit. And as we have seen in the ideal cycle, compression begins with the air intake. So, part of the compression occurs in the air intake, rest of it occurs in the compressor.

The second component that follows an air intake is either a fan in the case of a turbofan engine or it could be directly a compressor in the case of turbojet engines or turboprop and so on. So, compressor or a fan as I mentioned are thermodynamically the same, because both of these increase the pressure, decelerate and so on. So, these are components, which are thermodynamically the same and there function is to increase the pressure and in the process, they also increase the temperature of the incoming air and then, it is deliver to the next component, which is the combustion chamber.

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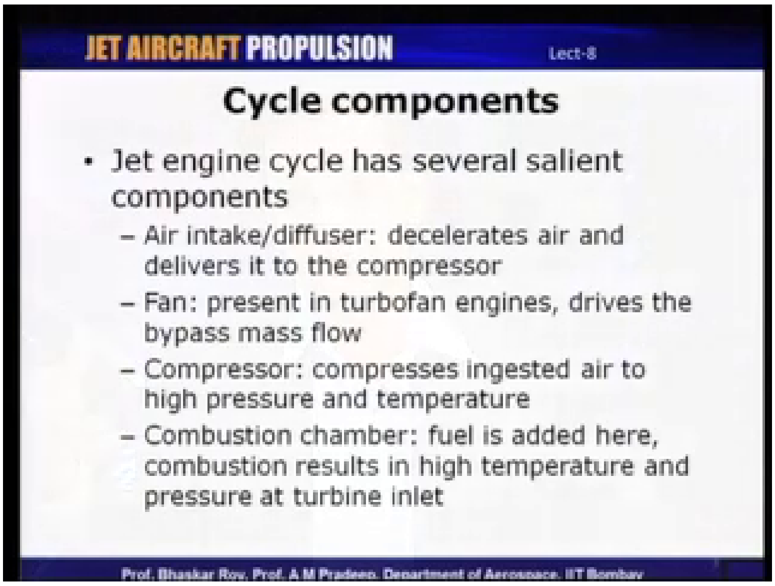

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Cycle components

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So, combustion chamber is the component, where fuel is added in the engine and combustion takes place releasing a lot of temperature and energy and at the end of the combustion chamber we have the air and the combustion products, which are at high temperature and pressure at the turbine inlet. So, at the turbine inlet we would want combustion products or air to be at very high pressure and temperatures, so that this can be expanded through the turbine and in the process we can extract energy from such a system.

So, combustion chamber delivers hot products, which are at high temperature and pressure at the turbine inlet, and then the turbine expands this and in the process, it will deliver a shaft work. And the function of a turbine in a pure jet engine is, nearly to drive the compressor. So, turbine does not have any other function, it is meant only to drive the compressor, but whereas, in certain other forms of engines like in a turboprop for example, turbine besides driving the compressor also drives the propeller.

So, in in such engines as we have discussed in the last lecture, there is a separate turbine unit which is known as the power turbine or the free turbine, which drives the propeller. So, such units exist only in those engines, where we need let say, propeller power output and so on. After the turbine depending upon the nature of the engine let us say, if it is a turbojet engine with an afterburner, then afterburner would follow a turbine that is, the combustion products from the turbine would still have a lot of energy in it and also, it is at high temperature and pressure at the same time, there is substantial amount of oxygen still left in the combustion products.

So, it is possible for us to add additional fuel after the turbine exhaust, raise the temperature even further and therefore, the pressure as well, so that there is an additional pressure available for expansion in the nozzle. So, this is used in the engines, where we need additional thrust for example, if we have to accelerate and the cross the sonic barrier reach the supersonic speeds and also (( )) at supersonic speeds, then it is essential that, turbojet engines also have an afterburner, so that this can be achieved.

So, nozzle is the last component of the jet engine, combustion products are expanded through the nozzle and generates the required thrust that the engine is supposed to deliver. So, what we will discuss today each of these components and how can we evaluate or judge the performance of these units. Will start with the diffuser and will first take a look at what are the sources of losses that are possible in in a diffuser or an air intake; and how can we estimate the performance of such devices.

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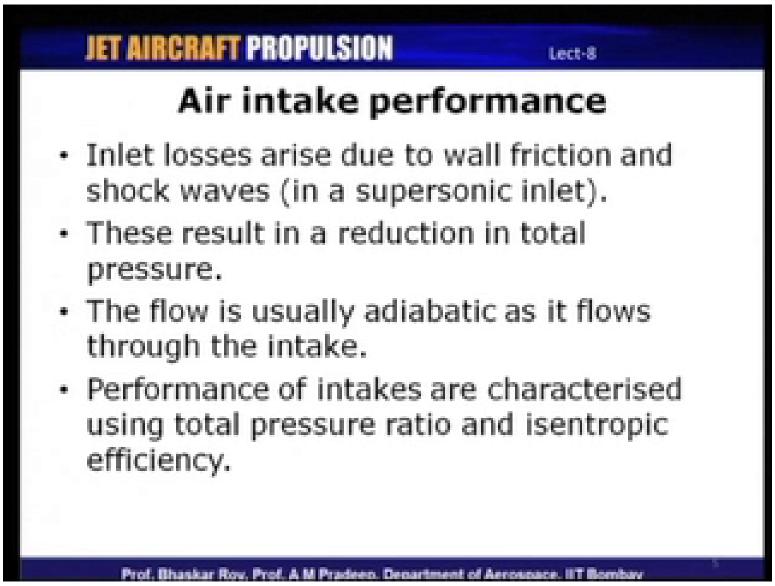

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Air intake performance

- Inlet losses arise due to wall friction and shock waves (in a supersonic inlet).
- These result in a reduction in total pressure.
- The flow is usually adiabatic as it flows through the intake.
- Performance of intakes are characterised using total pressure ratio and isentropic efficiency.

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So, let us take a look at the air intake performance first. Now, there are two sources of losses in an air intake, one is wall friction which is present in all in fact, all the components, and the second possible source of loss are shock waves, but this is valid only for a supersonic intake.

So, a supersonic intake may also have shock losses in addition to wall friction losses and so, how does it affect the performance? It obviously, results in reduction in the total pressure at the exit of the diffuser and also, there is an efficiency penalty associated with this. And so, we will be defining what is known as an isentropic efficiency. And the flow through intakes can always almost always we assume to be adiabatic, because there is hardly any heat transfer that takes place across the diffuser boundary. So, it is, it can be safely assumed to be adiabatic.

And so, there are two parameters that will define the performance of air intakes, one is the total pressure ratio which will basically tell us how much frictional losses has taken place, this can also be expressed in the form of what is known as an isentropic efficiency of the diffuser. So, both these parameters are usually used to evaluate or access the performance of air intakes.

And so, how do we arrive at a definition for let us say, the isentropic efficiency? Total pressure ratio is straight forward it is, the exit total pressure divided by the inlet total pressure and sometimes, this is also referred to as pressure recovery; that is total pressure ratio across the diffuser is it gives us an indication of how much pressure, how much total pressure has been lost, and so how much is higher the total pressure ratio betters the pressure recovery of such an intake, so total pressure recovery is one of the parameters.

Now, to define the efficiency of intakes you will have to take a look at the temperature entropy diagram of the intake in a little more detail, so that we are able to define a performance parameter, which is basically the isentropic efficiency.

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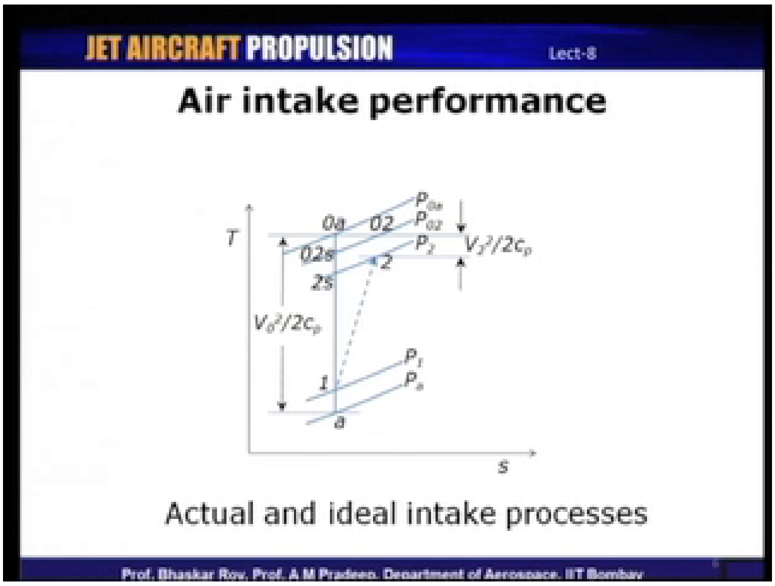
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Air intake performance

Actual and ideal intake processes

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So, what I have plotted here is, a temperature entropy plot of an intake process, but unlike what we have been plotting earlier this is lot more details are shown here, on what actually happens during an intake process. So, let me explain this in little more detail, so we have ambient air, which is at station a, which is at an ambient pressure of P subscript a, and then this is compressed all the way upto the total pressure at the exit, that is P 02.

And station 1 is the entry of the intake, if you recall the intake when we are discussing about the cycle analysis of turbojet I had shown that, there are two distinct points, one is corresponding to the ambient condition and the second one that is station 1, which corresponds to the inlet entry the geometric entry of the intake. So, this means that, there is already some compression which is taking place which is shown by the increase in static pressure here. So, there is an increase in static pressure, but because this is outside the intake boundary, there are no losses associated with this process. So, the first compression process that is known as the external compression or precompression, as it is denoted by in some literature.

So, precompression does not suffer from any losses, because there are no solid surfaces which bound free compression, but from point 1 all the way upto point 2, there are sources of losses, because of the friction effects and so, there is an increase in entropy as you can see, it is no longer and isentropic process, process from a to 1 is always isentropic, process from 1 to 2 is not isentropic. And so, this is the static pressure at the exit of the diffuser that is given by point 2 (Refer Slide Time: 12:37), whereas 2 s denotes the temperature on the pressure line, if the process were to be isentropic.

Now, what are the corresponding total pressures? Now, the total pressure corresponding to point 2, which is the actual total pressure will be equal to P 2 plus V 2 square by 2 C p and that is the static pressure plus dynamic pressure, that is P 2 is static pressure plus half rho V square will give us the total pressure, that is P 02. And what should have been the total pressure, if there were no losses it would be equal to the static pressure here P a plus V not square by 2 and that is given by P 0a.

So, P 0a corresponds to the total pressure of the intake, if there were no losses at all, whereas, P 02 corresponds to the total pressure in the presence of loses which means that, P 02 is always less than P 0a and for all engines, P 02 will be less than P 0a. So, how do we define an efficiency based on this? So, the efficiency that we have going to define will be based not on the pressures essentially, but it is on the temperatures or enthalpy corresponding to this line. So, we will define the difference in enthalpy for an actual process divided by an ideal process.

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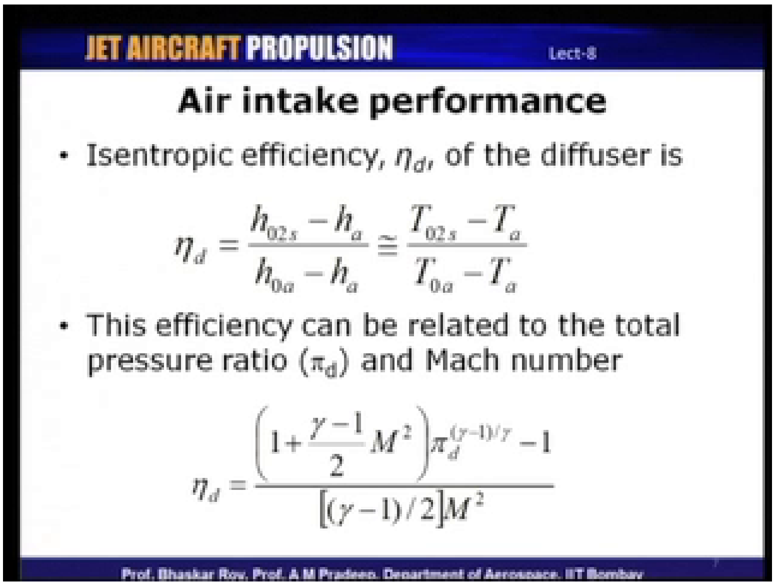

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Air intake performance

- Isentropic efficiency, η_d, of the diffuser is

$$\eta_d = \frac{h_{02s} - h_a}{h_{0a} - h_a} \cong \frac{T_{02s} - T_a}{T_{0a} - T_a}$$

- This efficiency can be related to the total pressure ratio (π_d) and Mach number

$$\eta_d = \frac{\left(1 + \frac{\gamma - 1}{2} M^2\right) \pi_d^{(\gamma-1)/\gamma} - 1}{[(\gamma - 1)/2] M^2}$$

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So, based on what we have discussed now, the isentropic efficiency of the diffuser can be define as, h 02s which is the total stagnation enthalpy for the isentropic process minus h a, which is the static enthalpy at the ambient condition divided by h 0a minus h a. So, let us go back to the TS diagram and see that, look at the definition once again (Refer Slide Time: 14:34), so h 02s is as this point (Refer Slide Time: 14:40), which is the stagnation enthalpy on the total pressure line actual, if the process were isentropic. So, h 02s minus h a divided by h 0a which is the stagnation enthalpy on the process line, if it were entirely isentropic, so this goes all the way up to p 0a, so h 02s minus h a divided by h 0a minus h a.

So, this is the isentropic efficiency of a diffuser, if you were to assume that the static pressures are at the inlet and exit are the same, then this can also be expressed in terms of the corresponding temperatures (Refer Slide Time: 15:12). So, we get T 02s minus T a divided by T 0a minus T a. So, enthalpy difference which enthalpy difference between those two points that is one corresponding to the total pressure line actual minus the ambient enthalpy divided by total pressure stagnation enthalpy for the isentropic process all the way up to p 0a minus stagnation enthalpy minus the ambient enthalpy.

So, this defines an isentropic efficiency of a diffuser based on temperature. So, what you should notice here is that, the isentropic efficiency has been defined based on temperatures, but it is due to the pressure loss, there is no loss in stagnation temperature occurring across a diffuser. So, this is one point, which you have to keep in mind that, there cannot be either an increase in stagnation temperature or a decrease in stagnation temperature, unless there is either heat addition or heat removal.

So, if we assume that, the process is adiabatic which is true then, there is no change in stagnation temperature, but there is definitely a change in stagnation pressure, because of frictional losses. So, this efficiency that we have defined is, because of the loss in stagnation pressure and that we have expressed in terms of stagnation temperatures. So, adiabatic efficiency of a diffuser is basically T 02s minus T a divided by T 0a minus T a. So, this can also be expressed in terms of the stagnation pressure ratios and so on.

So, if you want to simplify this expression that we have seen (Refer Slide Time: 17:08), we can relate the efficiency to the to the total pressure ratio, that is pi subscript d and the Mach number, so if you do a simple simplification of this what we have seen that is T 02s divided by T 02 is T 0a is can be expressed in terms of the corresponding pressure ratios and so on, because its isentropic.

So, if you want to simplify that, what we get is? Eta d, which is diffuser efficiency is 1 plus gamma minus 1 by 2 M square multiplied by pi d, which is the stagnation pressure ratio raised to gamma minus 1 by gamma minus 1 divided by gamma minus 1 by 2 M square. So, here M is the free stream Mach number. So, what we can see is that, the diffuser efficiency can be easily expressed in terms of the Mach number that is the flight Mach number and the stagnation pressure ratio. So, these are two parameters which based on which we can actually determine the diffuser efficiency.

So, we have seen that, the diffuser efficiency is something that we can estimate based on Mach number and the pressure ratio. And remember that, pressure ratio itself is one of the parameters or stagnation pressure ratio is in by itself, one of the parameters which define one of the efficiencies of the diffuser. So, based on what we have discussed we should able to now access the performance of diffuser based on the pressure loss, which is also expressed in terms of temperature difference and therefore, we get an adiabatic efficiency or isentropic efficiency of a diffuser.

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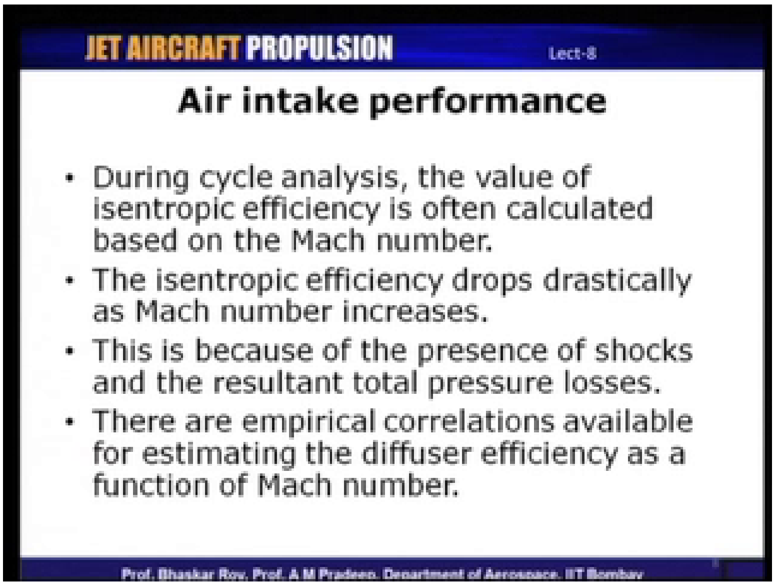

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Air intake performance

- During cycle analysis, the value of isentropic efficiency is often calculated based on the Mach number.
- The isentropic efficiency drops drastically as Mach number increases.
- This is because of the presence of shocks and the resultant total pressure losses.
- There are empirical correlations available for estimating the diffuser efficiency as a function of Mach number.

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So, when we do a cycle analysis, which is what we will do in late the next lecture. We will basically be using the efficiency definition based on what we the flight Mach number. And what is seen is that, the isentropic efficiency drops drastically as the Mach number increases, because as we increase Mach number, there would be the presence of shock waves and therefore, the resultant total pressure losses would be substantially higher.

And in fact, there are empirical correlations, which are available for estimating efficiency of a diffuser as a function of Mach number. So, there (( )) available which you can look up on in some text books, which define the efficiency based on or as a function of Mach number and so, some of these definitions could be used when we are doing a real cycle analysis of jet engine.

So, having discussed about intakes, let us move on and take up the next component which is of interest that is the compressor or the fan. Now remember, I mentioned that, compressor and the fan are thermodynamically same, so whatever efficiency definitions that we going to define for the compressor will also be valid for a fan.

So, in the case of compressor we are going to define, what is known as a isentropic efficiency. We have already seen this in one of our earlier lectures for turbine and compressors; will take a relook at how these efficiencies are defined.

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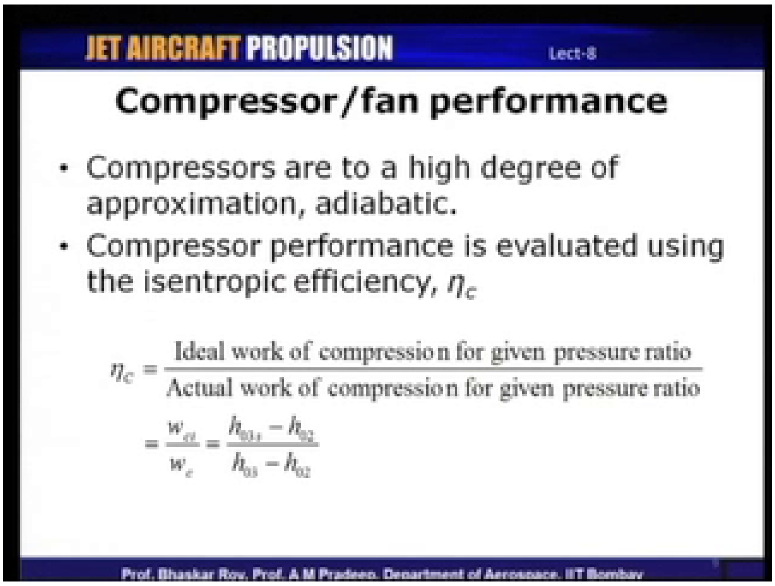

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Compressor/fan performance

- Compressors are to a high degree of approximation, adiabatic.
- Compressor performance is evaluated using the isentropic efficiency, η_c

$$\eta_c = \frac{\text{Ideal work of compression for given pressure ratio}}{\text{Actual work of compression for given pressure ratio}}$$

$$= \frac{w_{ci}}{w_c} = \frac{h_{03s} - h_{02}}{h_{03} - h_{02}}$$

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Now, as we have approximated in the case of intakes, compressors are also to a high degree of approximation, adiabatic. And so, how do we evaluate the performance? Compressor efficiency, isentropic efficiency is basically defined as the ratio of ideal work of compression for a given pressure ratio divided by the actual work of compression for a given pressure ratio.

So, this ratio that is ideal work divided by actual work for the same pressure ratio will defined the compressor efficiency which means that, ideal work of a compressor would be the difference between the ideal stagnation enthalpy at the exit of the compressor minus the inlet stagnation enthalpy divided by actual stagnation enthalpy minus the inlets stagnation enthalpy.

So, compressor efficiency, the isentropic efficiency of a compressor will be equal to h subscript 03s minus h 02 divided by h 03 minus h 02, so this basically defines the efficiency of a compressor based on what should be the ideal work that, the compressor requires divided by what is the actual work that the compressor is needing; which means that, ideal work of the compressor obviously will be lower than the actual work that the compressor requires. So, to understand this, let us look the TS diagram of a typical compressor and take a look at, how we can define an isentropic efficiency.

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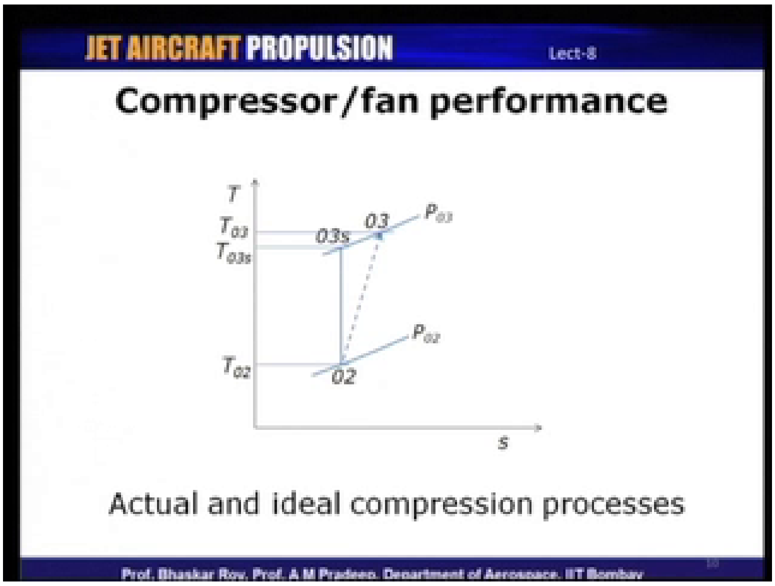
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Compressor/fan performance

Actual and ideal compression processes

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So, what you shown here is, the TS diagram for a compression process both the actual and ideal compression processes are shown here. So, the compression begins at 02, which is the inlet of the compressor, p 02 is constant pressure line corresponding to the inlet compressor pressure, the corresponding temperature is T 02. Now, an ideal process would be an isentropic process as straight line shown here, going all the way up to 2 03s. So, T 03s corresponds to the stagnation temperature, at the compressor exit. And what is the actual temperature? Actual temperature is T 03 which is on this non isentropic line. So, you can immediately see that, T 03 is is greater than T 03s and therefore, the actual work is greater than the ideal work.

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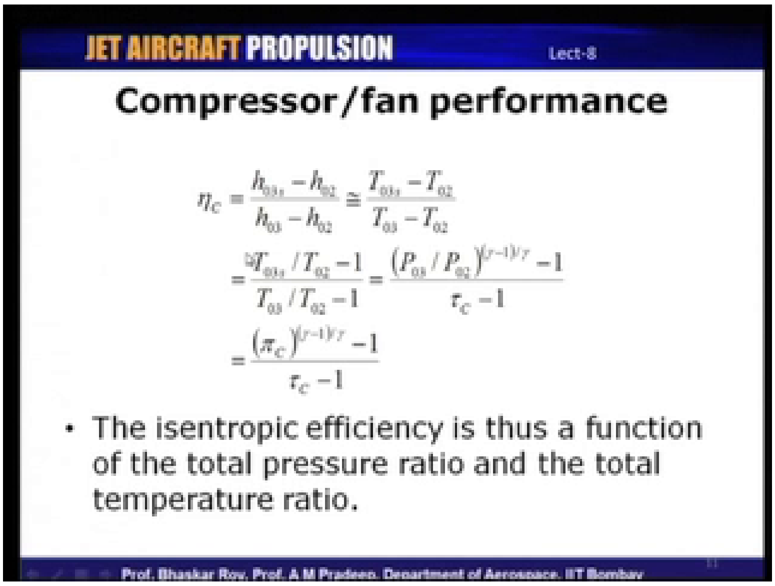

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Compressor/fan performance

$$\eta_c = \frac{h_{03s} - h_{02}}{h_{03} - h_{02}} \cong \frac{T_{03s} - T_{02}}{T_{03} - T_{02}}$$

$$= \frac{T_{03s} / T_{02} - 1}{T_{03} / T_{02} - 1} = \frac{(P_{03} / P_{02})^{(\gamma-1)/\gamma} - 1}{\tau_c - 1}$$

$$= \frac{(\pi_c)^{(\gamma-1)/\gamma} - 1}{\tau_c - 1}$$

- The isentropic efficiency is thus a function of the total pressure ratio and the total temperature ratio.

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So, based on this, if we define the compressor efficiency we have h 03s minus h 02 divided by h 03 minus h 02, which can be approximated. Assuming that, this specific (( )) at constant pressure is a constant, then we get T 03s minus T 02 divided by T 03 minus T 02, lets us simplify this now.

So, this we can express as temperature ratios, we get T 03s divided by T 02 T 02 minus 1 divided by T 03 divided by T 02 minus 1. So, the first term that you see here, that is the stagnation temperature ratio, one of them is isentropic can be expressed in terms of the corresponding pressure ratios from isentropic relations that is, T 03s divided by T 02 is equal to p 03 divided by p 02 raise to gamma minus 1 by gamma. And p 03 by p 02 is the compressor pressure ratio, which is pi subscript c.

So, isentropic efficiency of the compressor can be expressed are in terms of the stagnation pressure ratio that is the compressor pressure ratio, pi c raise to gamma minus 1 by gamma divided by tau c, which is the stagnation temperature ratio that in this case, it is T 03 divided by T 02. So, based on the expression that we have seen here, this basically relates the compressor efficiency, that is isentropic efficiency related to two distinct parameters, one is the compressor pressure ratio that is pi c and the other is the temperature ratio, tau subscript c.

So, isentropic efficiency can actually be expressed in terms of some of the design parameters. In this case, the design parameter happens to be the stagnation pressure ratio. So, depending upon, what is the design parameter for the compressor, in for a compressor it is always the compressor pressure ratio. You can express the compressor pressure ratio I mean you can express the efficiency as a function of the compressor pressure ratio and the temperature ratio.

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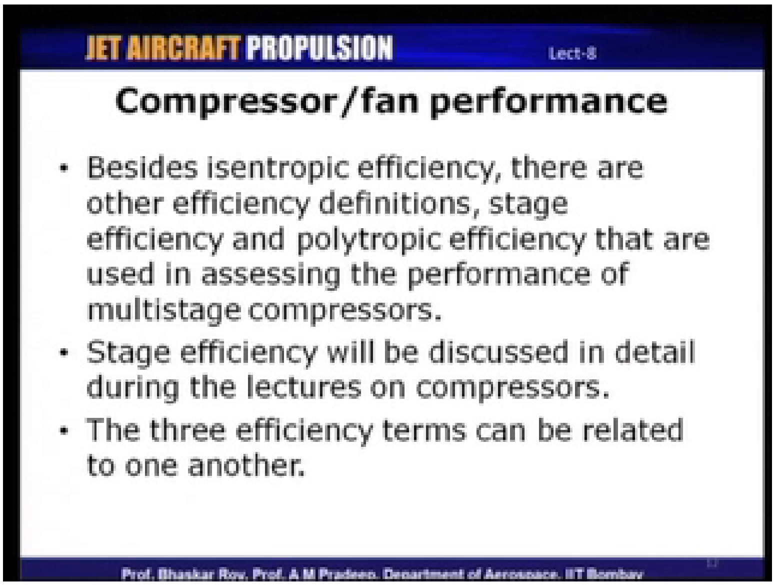

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Compressor/fan performance

- Besides isentropic efficiency, there are other efficiency definitions, stage efficiency and polytropic efficiency that are used in assessing the performance of multistage compressors.
- Stage efficiency will be discussed in detail during the lectures on compressors.
- The three efficiency terms can be related to one another.

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So, besides the efficiency definition, that is the isentropic efficiency, there are other efficiency definitions that are possible, some of them are stage efficiency and polytrophic efficiency and these are basically used, when we take a look when we when we try to approximate when we try to take a look at the actual nature of the compressor itself. Compressor as we known in gas turbine engine is usually a multistage compressor and therefore, there is the compressor process is not a signal process as we know it now, it is it constitute it is constitute of several infinity several compressor processes.

So, one of the ways of trying to estimate the efficiency of such process is to use ,what is known as a polytrophic efficiency. So, will discuss about stage efficiency little later, when we take up the compressor analysis in detail. And today, will discuss about the polytrophic efficiency, what exactly is polytrophic efficiency and it is to be remember here that, all these three definitions are efficiency terms are related to one another.

And today will be relating the isentropic efficiency to the polytrophic efficiency. Similarly, the other term that is stage efficiency can also be related to these two definitions as such, but that will discuss later on.

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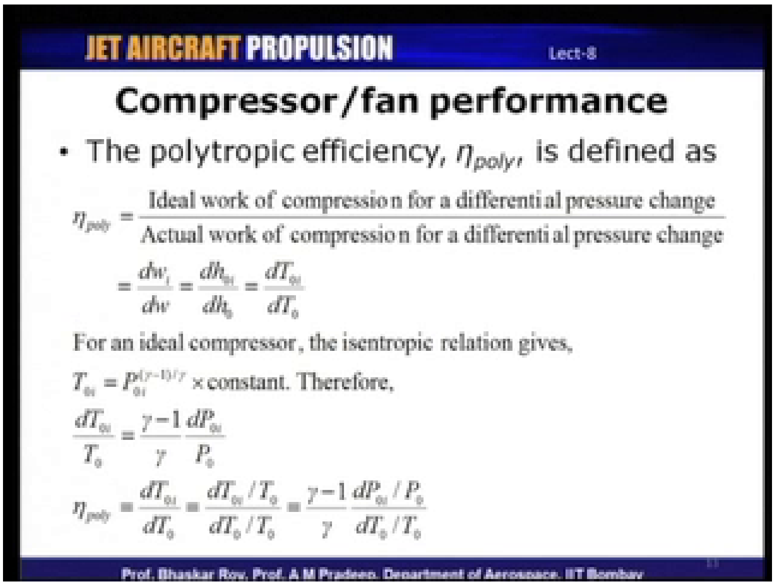

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Compressor/fan performance

- The polytropic efficiency, η_{poly}, is defined as

$$\eta_{poly} = \frac{\text{Ideal work of compression for a differential pressure change}}{\text{Actual work of compression for a differential pressure change}}$$

$$= \frac{dw_i}{dw} = \frac{dh_{0i}}{dh_0} = \frac{dT_{0i}}{dT_0}$$

For an ideal compressor, the isentropic relation gives,

$T_{0i} = P_{0i}^{(\gamma-1)/\gamma} \times$ constant. Therefore,

$$\frac{dT_{0i}}{T_0} = \frac{\gamma-1}{\gamma}\frac{dP_{0i}}{P_0}$$

$$\eta_{poly} = \frac{dT_{0i}}{dT_0} = \frac{dT_{0i}/T_0}{dT_0/T_0} = \frac{\gamma-1}{\gamma}\frac{dP_{0i}/P_0}{dT_0/T_0}$$

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Now, let us take look at what is polytrophic efficiency? Polytrophic efficiency is defined as, the ratio of ideal work of compression for a differential pressure change divided by the actual work of compression for a differential pressure change. Now, isentropic efficiency if you remember was defined in the same way, but that was not for a differential pressure change, it was defined for just a given pressure ratio.

So, this reduces to a differential work ideal divided by differential work actual, which is equal to the d h naught I, which is differential enthalpy change ideal divided by d h naught, which is the differential enthalpy raise actual, this is again approximated as, d T naught I divided by d T naught. Now, for an ideal compressor we know that, T naught I is related to P naught I raise to gamma minus 1 by gamma into a constant, because temperature ratios can be related to pressure ratio using the isentropic relation.

So, this we can by Binomial expansion we can express this as d T naught I divided by T naught is equal to gamma minus 1 by gamma into d P naught I by P naught, this is from the first approximation using binomial expansion. So, if you use this in the polytropic efficiency definition, then we get eta poly which is the polytropic efficiency, this is equal to d T naught I divided by d T naught, which is again equal to d T naught I by T naught divided by d T naught by T naught. Somewhat, we defined earlier, this can be simplified as polytropic efficiency is equal to gamma minus 1 by gamma into d P naught I divided by p naught divided by d T naught by T naught we will simplify this further again; that is polytropic efficiency we have go now going to express that in terms of a parameter, which we can very easily use in the isentropic efficiency terms.

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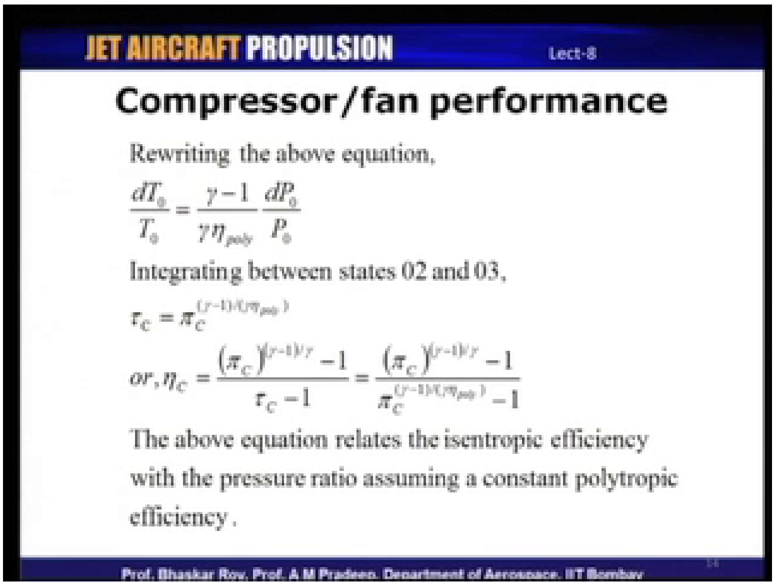

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Compressor/fan performance

Rewriting the above equation,

$$\frac{dT_0}{T_0} = \frac{\gamma - 1}{\gamma \eta_{poly}} \frac{dP_0}{P_0}$$

Integrating between states 02 and 03,

$$\tau_c = \pi_c^{(\gamma-1)/(\gamma\eta_{poly})}$$

$$or, \eta_c = \frac{(\pi_c)^{(\gamma-1)/\gamma} - 1}{\tau_c - 1} = \frac{(\pi_c)^{(\gamma-1)/\gamma} - 1}{\pi_c^{(\gamma-1)/(\gamma\eta_{poly})} - 1}$$

The above equation relates the isentropic efficiency with the pressure ratio assuming a constant polytropic efficiency.

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So, the if you rewrite the equation that we have just seen we get d T naught by T naught is equal to gamma minus 1 by gamma eta polytropic into d P naught by P naught. So, if we integrate this between states 02 and 03, which are the inlet and the exit of the compressor, then we get tau subscript c is equal to pi subscript c raise to gamma minus 1 divided by gamma multiplied by eta polytropic.

Now, thus we can again use in our efficiency definition that we have just now seen, therefore, isentropic efficiency of a compressor eta c is equal to pi c, which is the compressor pressure ratio raise to gamma minus 1 by gamma minus 1 divided by tau c minus 1, this is also equal to pi c raise to gamma minus 1 by gamma minus 1 divided by, since tau c is expressed in terms of pi c raise to gamma minus 1 by gamma into eta polytropic that we can substitute here (Refer Slide Time: 29:50).

So, what we have here is a very interesting equation, which relates three parameters, it relates the isentropic efficiency to the stagnation pressure ratio and the polytropic efficiency. So, this means that, if we know the polytropic efficiency and of course, the compressor pressure ratio, we should be able to get a better estimate of the isentropic efficiency and vice versa.

Suppose, we know the isentropic efficiency, we also know the compressor pressure ratio we can find out what should be the polytropic efficiency for such a process. And this is something which you are going to use very frequently during this cycle analysis that is something will take up with the next lecture during the tutorial. So, during cycle analysis, what we will discuss is, how we can use some of these performance parameter terms in our analysis, so that we get a realistic estimate of the performance of these gas turbine engines.

So, compressor performance evaluation involves the compressor pressure ratio, which is a design parameter, then it involves the isentropic efficiency and the polytropic efficiency. We also seen, how we can relate the isentropic efficiency to the polytropic efficiency and the compressor pressure ratio. And the other term that we are going to use is stage efficiency as I mentioned, but this we will defined little later, because that requires little understanding of the working of this compressors systems, that we will discuss when we take up the compressor analysis in detail.

Now, the next component that we are going to discuss about is the combustion chamber or the combustor or the burner, so different books called it in different ways.

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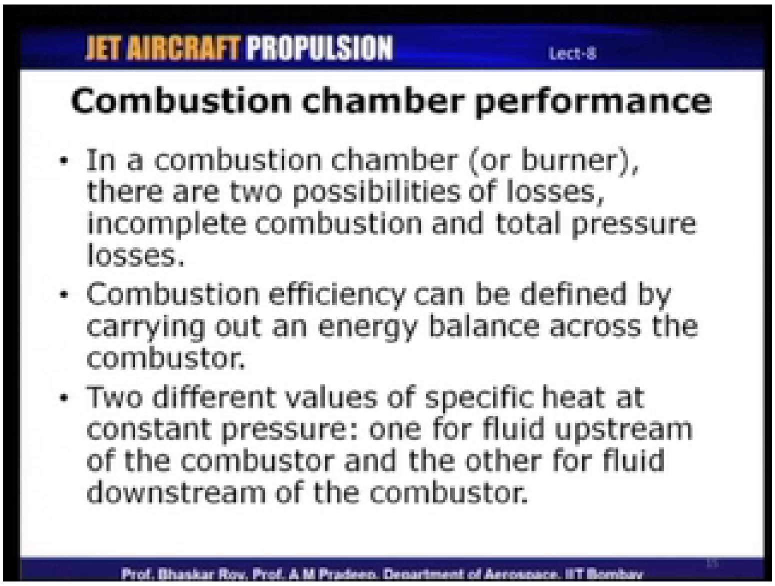

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Combustion chamber performance

- In a combustion chamber (or burner), there are two possibilities of losses, incomplete combustion and total pressure losses.
- Combustion efficiency can be defined by carrying out an energy balance across the combustor.
- Two different values of specific heat at constant pressure: one for fluid upstream of the combustor and the other for fluid downstream of the combustor.

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Now, in a combustion chamber, there are basically two possibilities of losses, in a combustion chamber there are two possibilities of losses one is the incomplete combustion and the other is total pressure losses. So, these are two different sources of losses that can affect the performance of combustion chamber. One is related to the combustion efficiency which state that, given a certain amount of fuel how much of that as actually taken part in combustion whether the entire fuel has been converted to work output or so on or (( )) released or so on.

The other parameter is the pressure loss, because combustion chamber involves certain amount of total pressure loss and the two again sources of total pressure loss, one is the viscose loss and the other is the pressure loss due to combustion occurring at finite Mach number. Something we have discussed, you might have learned about during your studies on heat addition on a constant area ductance, so on.

So, based on our understanding of the energy balance across the combustion chamber, we should now be able to defined, what is the combustion efficiency? Because, we we know the combustion chamber outlet conditions, we know the temperature there and so we know the enthalpy our energy content at the combustion chamber exit, we also know the energy content at the inlet, because we know the compressor exit conditions, we also know what is the amount of fuel that is added. So, based on all this, if you carry out an energy balance we will know, what is the efficiency associated with this combustion products.

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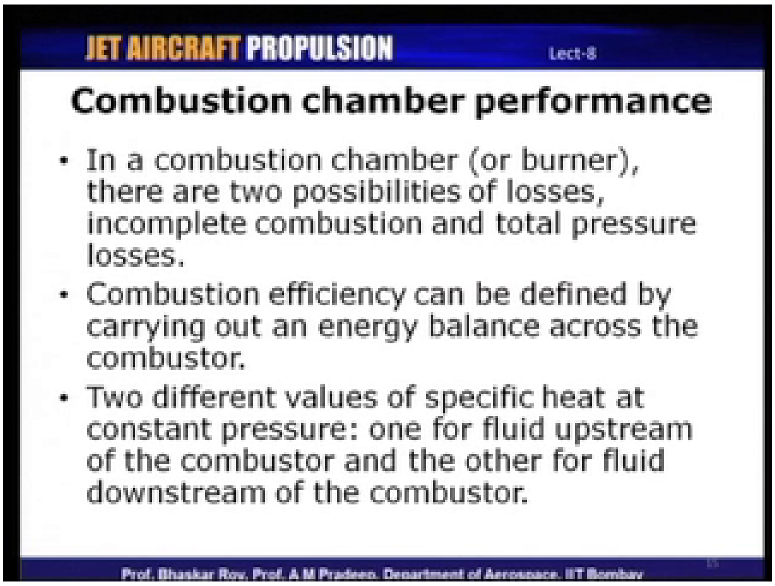

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Combustion chamber performance

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So, in combustion efficiency we can basically define by carrying out an energy balance. And only thing that, we have to remember here is that, in a combustion chamber we will no longer be using the same specific heat across that, because the temperature differential between the inlet and exit is substantial and so, we can no longer use the same specific heat at constant pressure for the inlet and exit. So, we are going to use one specific heat for the of fluid which is up stream of the combustor and the other value of specific heat for fluid, which is downstream of the combustor.

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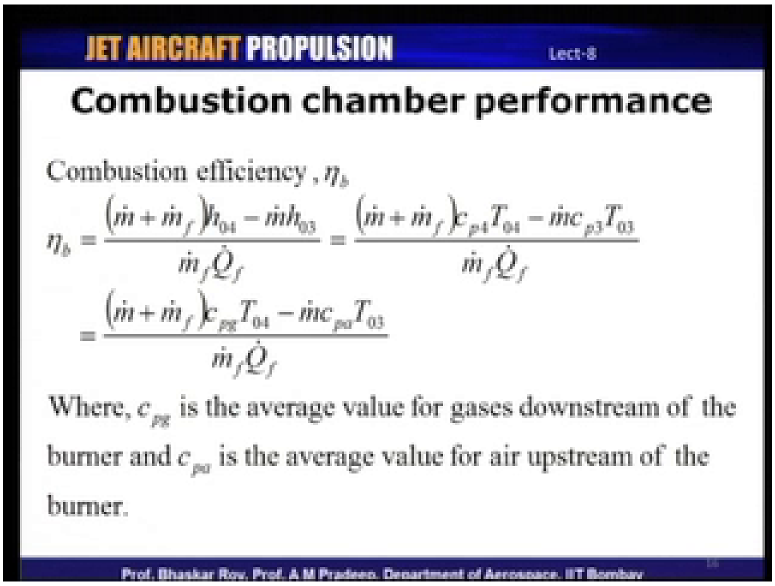

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Combustion chamber performance

Combustion efficiency , η_b

$$\eta_b = \frac{(\dot{m}+\dot{m}_f)h_{04} - \dot{m}h_{03}}{\dot{m}_f\dot{Q}_f} = \frac{(\dot{m}+\dot{m}_f)c_{p4}T_{04} - \dot{m}c_{p3}T_{03}}{\dot{m}_f\dot{Q}_f}$$

$$= \frac{(\dot{m}+\dot{m}_f)c_{pg}T_{04} - \dot{m}c_{pa}T_{03}}{\dot{m}_f\dot{Q}_f}$$

Where, c_{pg} is the average value for gases downstream of the burner and c_{pa} is the average value for air upstream of the burner.

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Now, combustion efficiency, which is denoted by eta subscript b, where b stands for burner is defined as the following. So, this will be the ratio of the difference in the inlet, difference between the exit enthalpy minus the inlet enthalpy divided by the fuel added. So, this means that, if the efficiency was equal to 1, then we have the exit enthalpy which is m dot which is mass flow rate of air plus mass flow rate of fuel multiplied by the enthalpy equal to inlet mass flow that is mass flow rate of air multiplied by the corresponding enthalpy plus the mass flow rate of fuel into the heat release Q dot f is the heat release rate of the fuel or heating value of the fuel.

So, combustion efficiency is equal to m dot plus m dot f into h 04 minus m dot into h 03 divided by m dot f into Q dot f, this we can simplify as m dot plus m dot f into C p4 T 04 minus m dot C p3 T 03 divided by m dot f Q f. Now, C p4 is basically the C p at station 4, C p3 is C p at station 3. So, this we will denote by C pg which is C p for the combustion products of the gases, this is the average value of gases downstream of the burner C pa is the average value of air upstream of the burner. So, combustion efficiency is one of the parameters that we can define to evaluate or access the performance of combustion chambers.

Now, what is the other parameter we have discussed? The other parameter we have discussed is the total pressure loss, so there could be some amount of total pressure loss taking place across the combustion chamber. And what causes these total pressure losses? One reason is of course, the viscose losses, the frictional losses in the combustion chamber; the other reason is that, when combustion occurs at a finite Mach number that usually leads to some amount of total pressure loss, so both of these parameters put together lead to loss in total pressure across the combustion chamber.

So, loss in total pressure would be given by the ratio of corresponding total pressure that is P 04 divided by P 03 will be less than 1. So, in an ideal cycle we had assumed that, it is a constant pressure process P 04 is equal to P 03 that is no longer true, so that it would be less than 1.

In a combustion chamber (Refer Slide Time: 36:40), the combustion efficiency are usually very high, because we know that the air to fuel ratio is combustion chamber in gas turbine engines are very high. And so the combustion efficiency are usually very high is of the order of 9.95 96 even as high as 0.99. We will see some estimates or values of these losses towards the end of this lecture. So, in real cycle analysis, we are going to use both these parameters, that is the efficiency as well as the total pressure loss. Now, having looked at the performance analysis of three different components, now we have looked at the intake, we looked at compressor and the combustion chamber.

The next component that we shall be analyzing is turbine. Now, turbine will be performance will be defied very much the same way as we defined the compressor. And so, we will be defining an isentropic efficiency for the turbine in pretty much the same way as we define for a compressor, we will also then be defining a polytropic efficiency for the turbine.

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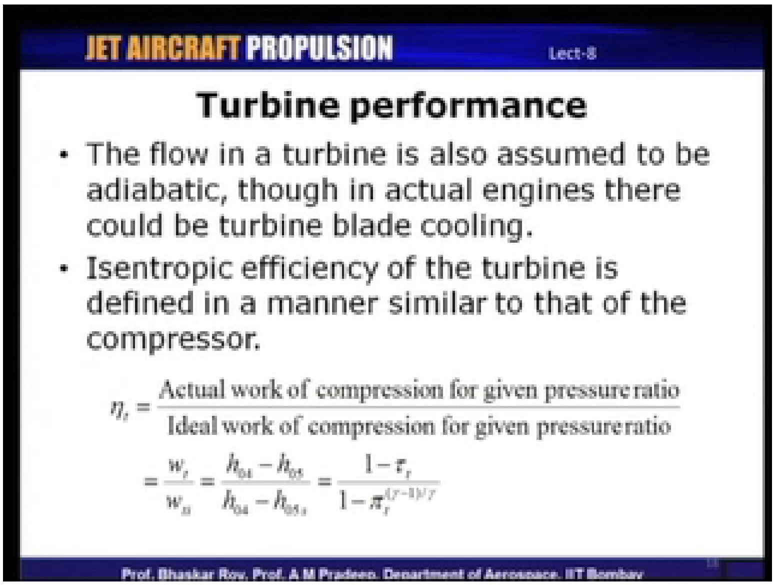

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Turbine performance

- The flow in a turbine is also assumed to be adiabatic, though in actual engines there could be turbine blade cooling.
- Isentropic efficiency of the turbine is defined in a manner similar to that of the compressor.

$$\eta_t = \frac{\text{Actual work of compression for given pressure ratio}}{\text{Ideal work of compression for given pressure ratio}}$$

$$= \frac{w_t}{w_{ti}} = \frac{h_{04} - h_{05}}{h_{04} - h_{05s}} = \frac{1 - \tau_t}{1 - \pi_t^{(\gamma-1)/\gamma}}$$

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So, in turbine a performance we will again be assuming that, the flow through the turbine is adiabatic. And so, in in a actual engine of course it is not really adiabatic, because there would be turbine blade cooling and therefore, there is actually a heat transfer taking place there, but we are going to assume, where that is negligible here.

So, isentropic efficiency of a turbine will define the same way as we define compressor this in the case of turbine, the actual work of for a turbine would be equal to the actual work that is developed by the turbine divided by the ideal work developed by the turbine for the same pressure ratio; that is w t actual divided by w t ideal, which is equal to h 04 that is inlet enthalpy minus h 05 that is exit enthalpy divided by h 04 minus h 05s, this can be simplified the same way as we did for compressor, this would be equal to 1 minus tau subscript T, which is the temperature total temperature ratio across the turbine divided by 1 minus pi T, which is the pressure ratio across the turbine raise to gamma minus 1 by gamma.

So, the turbine efficiency can be defined as we have seen its very similar to that of a compressor, but just that efficiency definition is reverse that is in in the case of turbine, the actual work output is less than the ideal work output; whereas, in compressor the ideal work is actually less than the actual work, that is why the efficiency definition are reversed as in the case of compressor and turbines.

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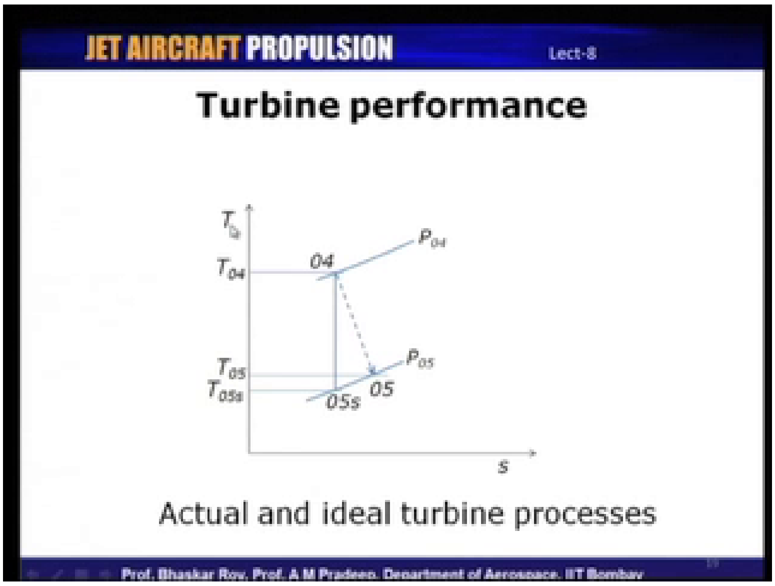

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Turbine performance

Actual and ideal turbine processes

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Now, we will take look at TS diagram of a turbine, actual and real turbines, so that we can understand the efficiency definition little better. Now, a TS diagram of a turbine is what is shown here, we have temperature and entropy on y and x axis respectively. So, turbine begins to the expansion process or turbine process begins at 04, which is turbine inlet, 05 is the actual point corresponding to the turbine exhaust, 05s corresponds to the isentropic condition that is, if the process were to be isentropic, P 05 is the pressure constant pressure line and so, 04 to 05 is the actual process.

So, turbine efficiency is defined as, h 04 minus h 05 divided by h 04 minus h 05s, this also can be expressed in terms of temperatures, that is T 04 minus T 05 divided by T 04 minus T 05s. Now, we also now define a polytropic efficiency very much the same way as we define for a compressor, because turbine also involves multi stages or expansion process is occurring in Multi stages. So, we can actually define polytropic efficiency for a turbine as well, exactly the same way as we defined for a compressor with the corresponding changes that is, because of the nature of the process itself.

So, the polytropic efficiency for a turbine is basically define by the actual work output of the turbine for a differential pressure change divided by the ideal work output for the process for a given pressure ratio or a for a differential pressure change. We have defined the same way for a compressor as well, for a differential pressure raise here, it is again for a differential pressure drop.

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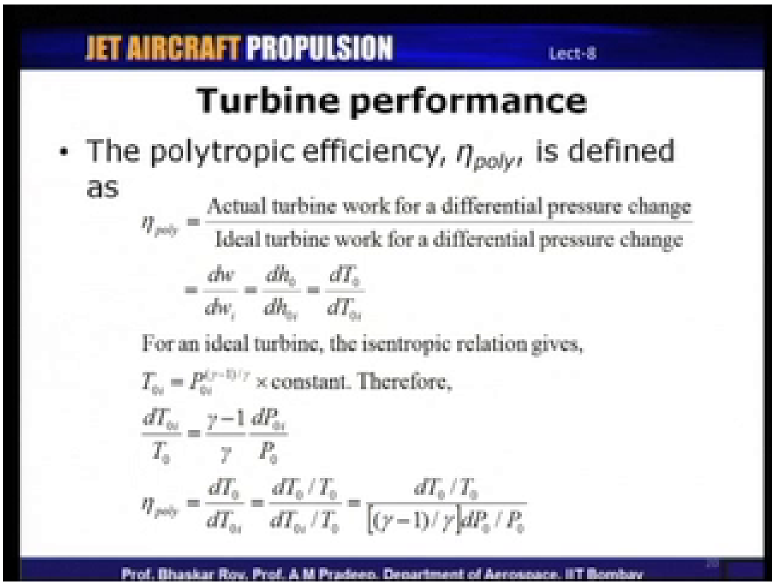

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Turbine performance

- The polytropic efficiency, η_{poly}, is defined as

$$\eta_{poly} = \frac{\text{Actual turbine work for a differential pressure change}}{\text{Ideal turbine work for a differential pressure change}}$$

$$= \frac{dw}{dw_i} = \frac{dh_0}{dh_{0i}} = \frac{dT_0}{dT_{0i}}$$

For an ideal turbine, the isentropic relation gives,

$T_{0i} = P_{0i}^{(\gamma-1)/\gamma} \times \text{constant}$. Therefore,

$$\frac{dT_{0i}}{T_0} = \frac{\gamma-1}{\gamma}\frac{dP_{0i}}{P_0}$$

$$\eta_{poly} = \frac{dT_0}{dT_{0i}} = \frac{dT_0/T_0}{dT_{0i}/T_0} = \frac{dT_0/T_0}{\left[(\gamma-1)/\gamma\right]dP_0/P_0}$$

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So, polytropic efficiency will be equal to dw, which is the actual work for differential which is actual differential work divided by ideal work d w I, this is in turn equal to dh naught divided by dh naught ideal, which is again equal to d T naught divided by d T naught ideal. Now, using the same simplification that we did for a compressor, we can and using the binomial expansion which wherein we define this ratio d T naught I divided by T naught in terms of gamma minus 1 by gamma d P naught I by P naught.

So, we get the polytropic efficiency, eta poly is equal to d T naught divided by d T naught I, this is again expressed in terms of the temperatures d T naught by T naught divided by gamma minus 1 by gamma into d P naught by P naught.

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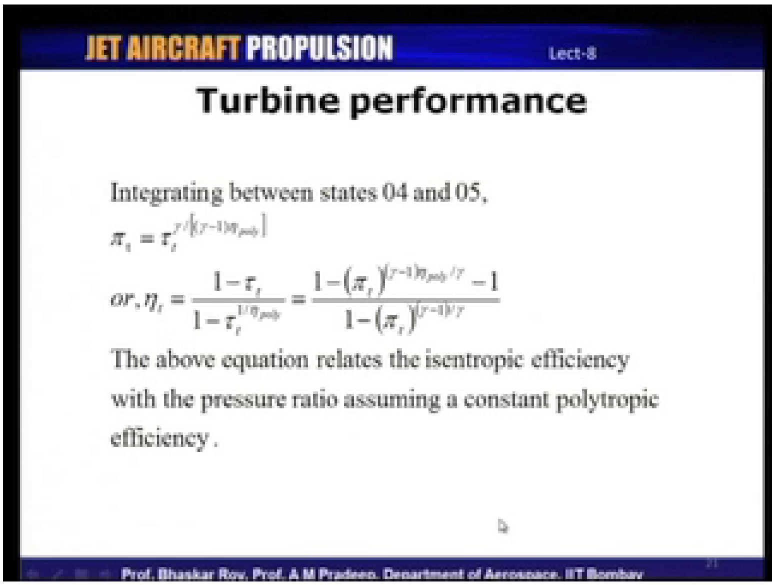

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Turbine performance

Integrating between states 04 and 05,

$$\pi_t = \tau_t^{\gamma/[(\gamma-1)\eta_{poly}]}$$

$$or, \eta_t = \frac{1-\tau_t}{1-\tau_t^{1/\eta_{poly}}} = \frac{1-(\pi_t)^{(\gamma-1)\eta_{poly}/\gamma}-1}{1-(\pi_t)^{(\gamma-1)/\gamma}}$$

The above equation relates the isentropic efficiency with the pressure ratio assuming a constant polytropic efficiency.

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So, if you integrate between states 4 and 5, which is corresponding to turbine inlet and turbine exit, then we get a definition of isentropic efficiency of a turbine in terms of the pressure ratio and the polytropic efficiency. So, we have eta T, which is the isentropic efficiency of a turbine, which is equal to 1 minus pi T which is pressure ratio raise to gamma minus 1 into eta polytropic divided by gamma minus 1 divided by 1 minus pi T raise to gamma minus 1 by gamma.

So here, we have an expression for the turbine efficiency the isentropic efficiency, which is again expressed in terms of the pressure ratio and the polytropic efficiency, very similar to what we had define for a compressor as well, where we had related the isentropic efficiency to the pressure ratio and the polytropic efficiency.

So, this is how we would evaluate the performance of turbine. Considering, the turbine has a black box and remember that, (( )) this analysis that we have been discussing, we have not really gone into the mechanical construction or the geometric details or the design of the any of these components, because thermodynamically all that does not matter, what matters is, what is that goes into this component and what is that comes out of this component, and how we can evaluate the losses that are occurring within the component. We will take up detail discussion of the analysis of this component extra in later lecture.

Now, the next component that we shall evaluate is the nozzle. Now, again as I think I mentioned earlier that nozzle is thermodynamically very similar to a turbine, because a turbine expanses the flow, nozzle also expanse the flow. But, the fundamental difference between the nozzle and the turbine is that, the turbine generates a work output, nozzle does not generate any work output in that way, it generates a reaction to thrust.

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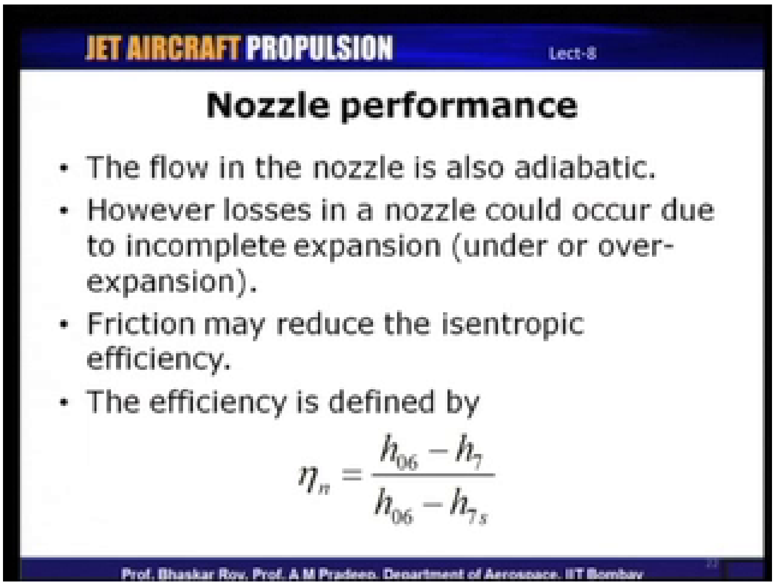

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Nozzle performance

- The flow in the nozzle is also adiabatic.
- However losses in a nozzle could occur due to incomplete expansion (under or over-expansion).
- Friction may reduce the isentropic efficiency.
- The efficiency is defined by

$$\eta_n = \frac{h_{06} - h_7}{h_{06} - h_{7s}}$$

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So, flow in a nozzle again we are going to assume to be adiabatic, which is very much true for a nozzle because, the enthalpy drop across a nozzle is much higher than enthalpy changes occurring due to in heat transfer. So, what are the sources of losses in a nozzle? Losses in nozzle could occur due to one is, incomplete expansion, it could be either under expansion or over expansion; the second source of loss could be, friction and friction also can reduce the efficiency of a nozzle.

So, how do we define a efficiency for a nozzle? Nozzle efficiency can be defined by h 06 minus h7, where h 7 corresponds to the nozzle exit divided by h 06 minus h 7s, which is the stagnation of which is the enthalpy at station 7 for an isentropic process.

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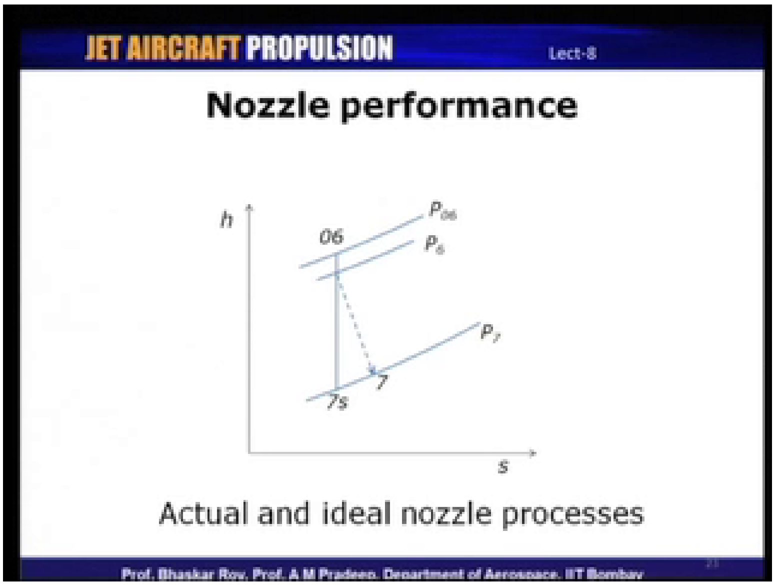
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Nozzle performance

Actual and ideal nozzle processes

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So, this will be clear, if you look at this enthalpy diagram enthalpy entropy diagram or the equivalent is temperature entropy diagram. So, T 06 corresponds or h 06 corresponds to the nozzle entry conditions, that is right here and on the pressure line that is P 06. And so, this expanse all the way up to 7 that is the nozzle exit static condition, p 7 is the a nozzle exit static pressure line. If the process were to be isentropic, then it would expand from 06 all way to 7s and so since, the process is non isentropic expansion goes all the way only up to 7. So, the efficiency is defined as h 06 minus h 7 divided by h 06 minus h 7s, so this defines the nozzle efficiency.

So, besides this some of the books also use pressure ratio across the nozzle as one of the other parameters, but in this course we just going to limit the nozzle performance based on the efficiency. So, efficiency of a nozzle is one of the terms that we are going to use for assessing the performance of a nozzle. Now as we have seen, the way we can define the efficiency is by looking at stagnation conditions at the inlet that is h 06 minus the static enthalpy at the exit h 7 divided by h 06 minus h 7s, so based on this we can define in efficiency of the nozzle.

Now, the other component that of course is not true for all the engines, but it is present in the case of let say a turbojet with after burning. So, what is an afterburner, and how can we define the performance of an afterburner? Now, if you recall I had mentioned that, afterburner is is basically a combustion chamber and therefore, performance parameter that we have defined for a combustion chamber should also be valid for an afterburner.

So, combustion efficiency and total pressure loss across the afterburner define the very much same way as we define for it the combustor should be valid for an afterburner. So, if an afterburner is used to an engine, performance of the afterburner will be evaluated the same way as we did for a combustion chamber.

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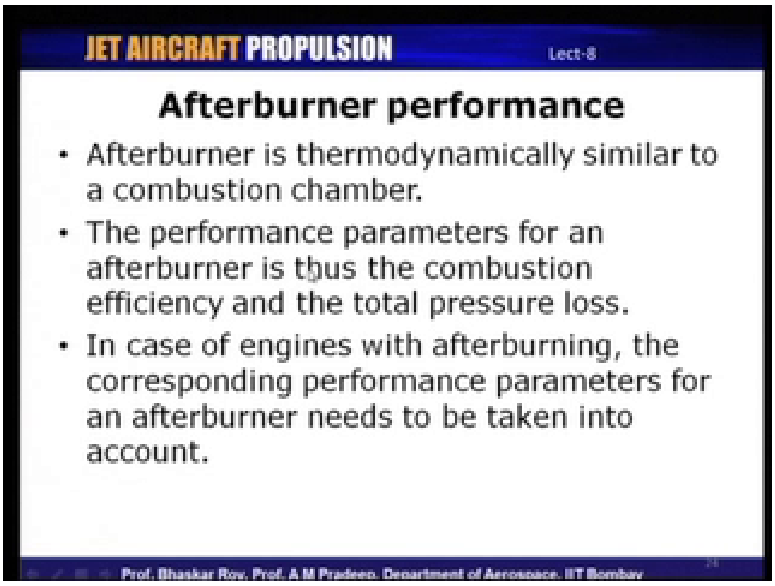

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Afterburner performance

- Afterburner is thermodynamically similar to a combustion chamber.
- The performance parameters for an afterburner is thus the combustion efficiency and the total pressure loss.
- In case of engines with afterburning, the corresponding performance parameters for an afterburner needs to be taken into account.

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So, an afterburner performance parameter would be, the combustion efficiency and the total pressure loss. So, in those engines, which have afterburning the the corresponding parameters for afterburner, that is the efficiency as well as the pressure loss will need to be taken into an account, when we are carrying out a cycle analysis. So, during this cycle analysis, a real cycle analysis of an engine with afterburner these two parameters also will come into picture.

So, these are some of the components that we have defined the performance parameters associated with all this components, the intake, the fan or compressor, combustion chamber, turbine, nozzle and afterburner. So, is there any other source of loss in an engine, well in some case we would also consider losses due to the transmission of power through a shaft.

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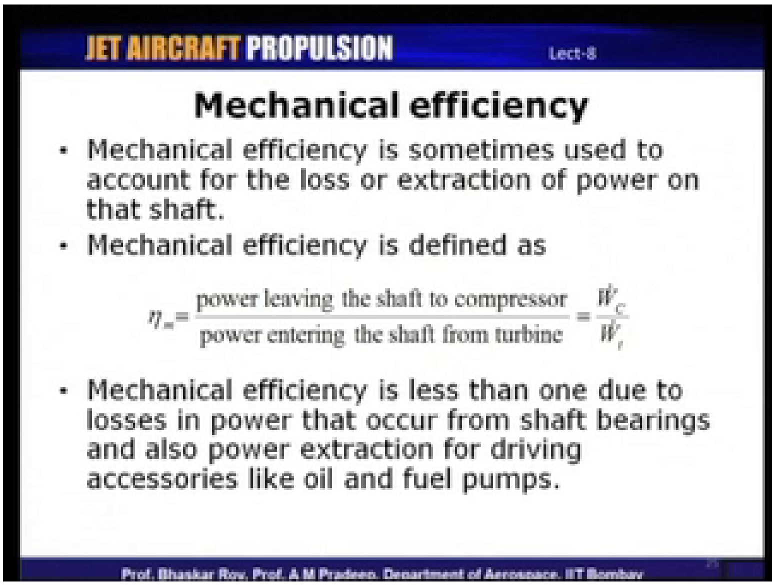

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Mechanical efficiency

- Mechanical efficiency is sometimes used to account for the loss or extraction of power on that shaft.
- Mechanical efficiency is defined as

$$\eta_m = \frac{\text{power leaving the shaft to compressor}}{\text{power entering the shaft from turbine}} = \frac{W_c}{W_t}$$

- Mechanical efficiency is less than one due to losses in power that occur from shaft bearings and also power extraction for driving accessories like oil and fuel pumps.

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So, Mechanical efficiency is one more loss parameter that is used sometime defined when we carry out a real cycle analysis. So, how do we define a mechanical efficiency? Well, mechanical efficiency is basically defined as, the ratio of the power leaving the shaft to the compressor divided by power entering the shaft from the turbine, that is the work output of the compressor to work output of the turbine.

So, if these two are equal, obviously the mechanical efficiency is equal to 1 and why it is less than 1, it is less than 1, because of loss of power due to the bearings that are present. So, when a shaft that connects the turbine and compressor; obviously, there are several bearings, which hold the shaft and so there are numerous losses taken place through this bearings. Other source of loss is that, some power is also used for driving accessories like fuel pump and oil pump and so on. So, that much power that is developed by the turbine does not actual reach the compressor, because it is used by these accessories. So, these are two different sources of losses, which may lead to some amount of mechanical losses or mechanical efficiency.

So, having looked at all these difference sources of losses, you may now wonder, how much would be a typical value for any of these efficiency or pressure losses, how do I know what what loss to take? So, I have now listed some of the typical ranges of this efficiency, which are seen in a modern day jet engine. And typical component efficiency for all of them I have listed down here of course, this is just a range, there could be engines which are out of this range, but this is typically for modern day jet engines.

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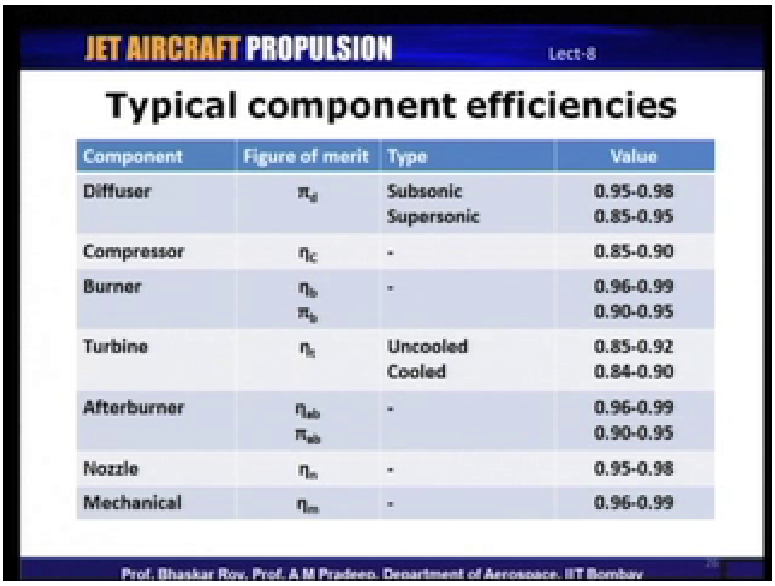
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Typical component efficiencies

Component	Figure of merit	Type	Value
Diffuser	π_d	Subsonic Supersonic	0.95-0.98 0.85-0.95
Compressor	η_c	-	0.85-0.90
Burner	η_b π_b	-	0.96-0.99 0.90-0.95
Turbine	η_t	Uncooled Cooled	0.85-0.92 0.84-0.90
Afterburner	η_{ab} π_{ab}	-	0.96-0.99 0.90-0.95
Nozzle	η_n	-	0.95-0.98
Mechanical	η_m	-	0.96-0.99

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So, let us take a look at the a typical values of component efficiency. Now, diffuser is defined by the diffuser pressure ratio as well as the efficiencies and so, if it is an this efficiencies can be different depending upon whether it is subsonic or supersonic; In supersonic intakes typically intake efficiency are lower, because of the presence of shock waves, which is by you can see for subsonic intakes the value vary from 0.95 to 0.98 for supersonic, the diffuser efficiency is vary from 0.85 to 0.95, so it is lower than this subsonic component.

Compressor efficiency, the isentropic efficiency of a compressor typically varies between 0.85 to 0.90. For combustion chamber or the burner, the burner efficiency combustion efficiency are usually as I mentioned very high, varies from 0.96 to 0.99. Burner pressure loss can be vary from 0.9 to 0.95 depending upon the nature of the burner or combustion chamber.

Turbine efficiency can be different depending upon whether it is uncooled or cooled, for an uncooled turbine typically it varies between 0.85 to 0.92, for a cooled turbine, it is slightly lower, it varies from 0.84 to 0.9. For an afterburner efficiency are pretty much identical to that of combustion chamber 0.96 to 0.99, burner pressure loss 0.9 to 0.95. Nozzle efficiency is usually vary from about 0.95 to 0.98, mechanical efficiency is again vary from 0.96 to 0.99.

So, these are some of the typical component efficiency value just to give you an idea, as to how much can this losses be, it is as you can see varies between about 10 to 10 to about 1 to 10 percent depending upon what the nature of the loss is. And so, these are some of the components efficiency, which of course we will be using when we carry out some cycle analysis later on. So, let me summaries today's lecture.

So, today's lecture was devoted to taking look at the different components that constitute gas turbine engine; and how we can evaluate the performance of each of these components by defining pressure loss and efficiency. So, we had taken a look at the intake performance, the combustion chamber, the compressor or the fan, the combustion chamber, the turbine, the nozzle, afterburner and also the mechanical losses. So, having discussed about this losses and how we can evaluate this losses.

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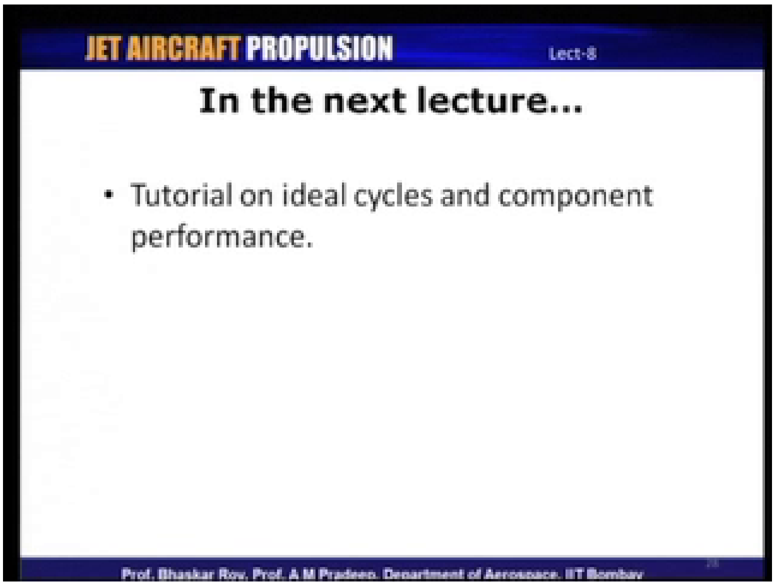

JET AIRCRAFT PROPULSION Lect-8

In the next lecture...

- Tutorial on ideal cycles and component performance.

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We will devote the next lecture for a tutorial, where we will discuss about the ideal cycle analysis a little bit and also, how we can evaluate the component performance in some detail. So, that will take as a tutorial, when we solve some problems on this topic during the next lecture.