Aerodynamic Design of Axial Flow Compressors and Fans
Professor Chetankumar Sureshbhai Mistry
Department of Aerospace Engineering
Indian Institute of Technology, Kharagpur
Lecture 02
Introduction (Contd.)

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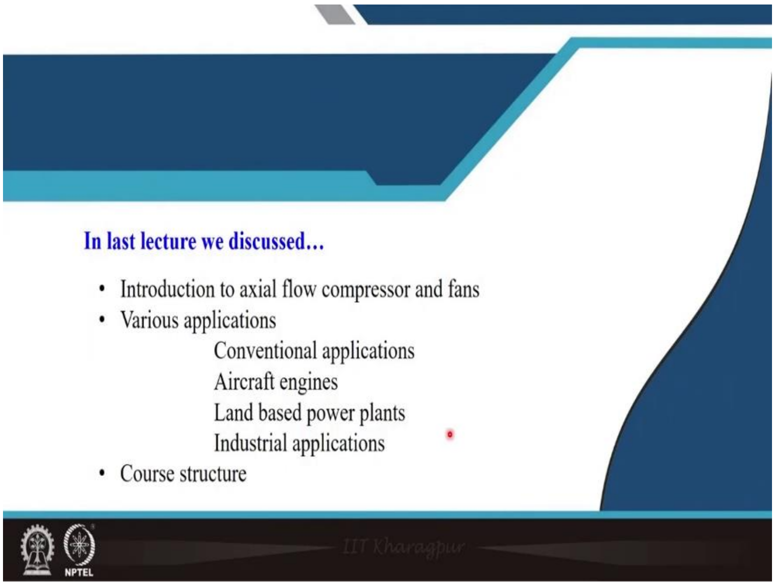

Hello, and welcome to the second lecture on Aerodynamic Design of Compressors and Fans! So, in last lecture, we were discussing about the introduction to axial flow compressors and fans. We have discussed about various applications, which are ranging from, say… conventional application, if you look at ceiling fan, cooling fan, we have discussed about the heating, ventilation and air conditioning fans. Then, we have discussed about the special application of the fans, application to your propulsion devices. We have discussed about the application to aircraft engines. We have discussed about the application to land based power plants and various industrial applications, which are ranging from supercritical CO_2 towards the application for different process industries in oil and gas.

Then we have discussed about the course structure, and as we have discussed, we are having this course that's what has been designed with say… 12-week structure. And we also have discussed about say… different references. That's what is required for this course. Now, let us move ahead with the next.

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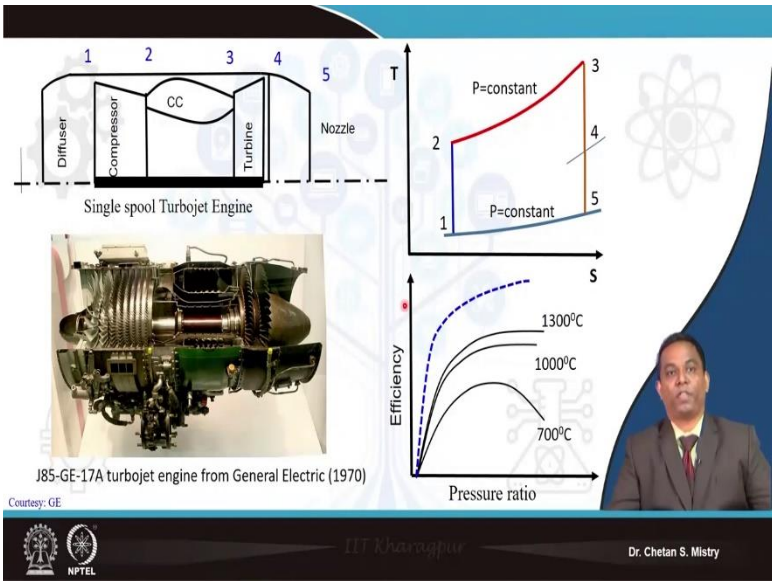

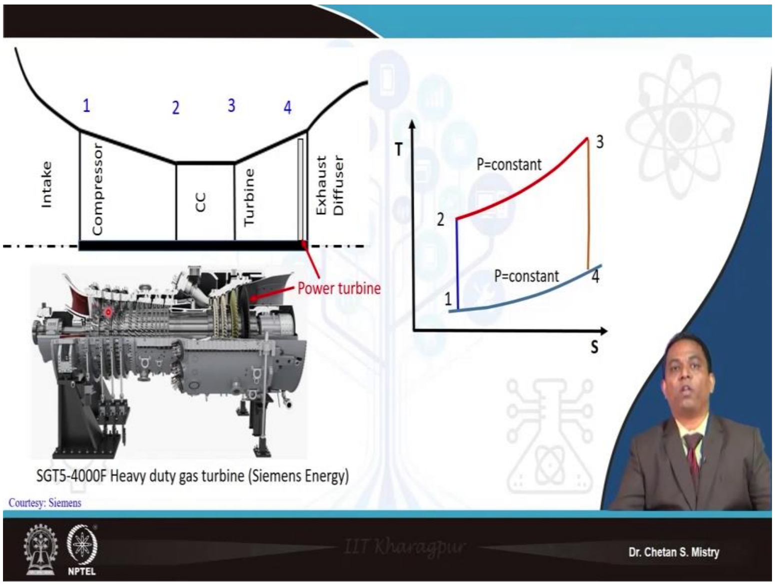

So, this is what is representing the cut section of single shaft turbojet engine. This turbo jet engine, that's what is comprising of the diffuser. Next component is your compressor that's what is the axial flow compressor; we are having combustion chamber, that's what will be followed by the turbine, and in the exhaust, I will be having nozzle. So, here, this engine, that's what is been used for the propulsion purpose. Propulsion, I mean, that's what is generating the thrust.

So basically, in order to have the movement of our aircraft in forward direction, we are looking for the component of force, that's what is called thrust, and that thrust that's what will be generated by all these components. And the flow that's what is coming out from my exhaust of the nozzle. Now here, if you look at, I am putting them at different stations, say station 1, 2, 3, 4, 5. I can represent the whole process in say… thermodynamic cycle.

So, if you look at, suppose, say… this is what is my entry pressure. Now, if I am looking this is what is say my station 1. The first process that's what we are representing as a compression process. So, we can say, this compression ideally it is isentropic process. So, I will be putting this as a station 2, so you can say, I will be having the rise of pressure from station 1 to 2.

We have next coming component that's what is, say… combustion chamber, the combustion that's what is taking place in our gas turbine engine, that's what we can safely assume as, say… constant pressure combustion. Now, it will be raising my temperature to, say… stage 3, that's what is a maximum turbine entry temperature.

Now, from 3 I will be having, say… expansion process, that's what is taking place in turbine. So, we can say, turbine – it is an expansion device in which my pressure that will be reducing. So, that's what is represented by station 4. Now next component, what we have is our exhaust nozzle. So, there is an expansion process that's what has been taking place in the nozzle, and that's what has been represented here, from process 4 to 5.

We can say, the exhaust that's what will be coming out from this engine, it will be going to the atmosphere. So, here, this is what is a fundamental idea of your gas turbine engine that's what is applicable for say… aero application. So, many of you are having the background of mechanical engineering, just try to look at what all are the components here. Now, if you look at on the downside, that's what is representing my pressure ratio versus efficiency curve.

And as I told, people, they are more focusing, say… being engineer we are always interested in terminology, that's what is called, say… efficiency. We are always looking for the things to be highly efficient. So, we are moving in that direction only. So, here, if you look at, this is what is a line, which is representing my turbine entry temperature. So, over the year, in order to meet higher thermal efficiency, people they have increased the temperature of my turbine entry, that's what is ranging from 700 to 1300.

And if you look at this blue line, that's what is representing maximum turbine entry temperature; as on today, that's what is reached approximately to 2000 K to 2200 K. So, you can say, my expectation of my pressure ratio, expectation of my efficiency that's what is demanding for the special kind of application for aero engines. So, this is what is we say, the aero engine - gas turbine engine, that's what has been used for the generation of my thrust.

Now, if we look at, this is what is representing the cut section of the engine. Here also, you can see, we are having the entry of my flow from one end that will be followed by, say… your axial flow compressor, my combustion chamber and here on the rear side we are having, say… turbines that will be followed by one more turbine, that's what we are defining as a power turbine. So, the process of the cycle, thermodynamic cycle, that's what is similar to what we have discussed for, say… aero engine.

So, here also, from station 1 to 2, we are having the rise of pressure, that's what is my compression process, I will be having constant pressure heat addition process, I will be having, say… isentropic expansion process, that is what is from station 3 to 4, okay. Now, just look at carefully, here the construction that's what is totally different from your gas turbine application to aero engine.

The purpose here is for the generation of power, and that is the reason rather than your exhaust, that's what will be going straightaway to the nozzle, here this high temperature gas that will be striking on this power turbine; and that power turbine that is what will be connected with the generator and that's what is generating my power, okay. Electric power; what we are looking for, okay! So, the purpose here for the gas turbine is for the power generation. So, do not get confused with the gas turbine engines.

People, they are having idea, say… you know, when we are discussing about the gas turbines application to your aero engines, we are talking about the thrust; when we are discussing about say power plant, we are talking in sense of my power generation that may be in terms of Mega-watt, okay! So, there is no straight way relation between your power generation and thrust generation. So, please do not get confused with these terminologies.

Now, you must understand any mechanical engineering students they may be having this idea. So, here let me discuss, say here, what turbines we are having, that's what has been used to rotate your compressor. So, in line to your aero engines, this turbine - this turbine what we are having, these turbines they are being used to rotate my compressor. So, there is nothing called power generation for my aero engine application. If we look at for, say… our power generation or land-based power plant, we are having additional turbine that's what is say a power turbine this is what has been used for the generation of my power, okay. So, with this fundamental background, let us move ahead.

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Now, let me move, say… this is what is, say a representation of my gas turbine cycle; we used to say this as a Joule cycle. So, this is what is, say… comprising of two isentropic processes, that’s what is compression process and expansion process; we are having these two constant pressure heat addition and heat rejection process. So, if I am representing this, I can represent that cycle like this.

So, here if you look at, this is nothing but it is representing one of the Joule cycle, where we are having, say… compression process, constant pressure heat addition process, expansion process and this is what is my exhaust. Let me put this as say… my cycle ‘A’. Now, you may understand, you may think, Sir, why do not we increase the pressure of my compressor such that with the background of your thermodynamics, you can say we will be able to reduce the amount of heat supply.

So, let me consider this as a cycle. What it says, we are raising our pressure from 1 to 2’. This is nothing but by compression process. I will be adding some amount of heat maintaining the turbine entry temperature to be constant. And if we look at, this is also one of the Joule cycle; this is also representing one of the gas turbine cycle.

Now, if you look at, you will say; Sir, why do not we increase this pressure, further? Yes, we can! If you look at, this is what is representing my third cycle where I am raising my pressure too much. So, here, in this case, you can understand my compression ratio for a compressor, that’s what is increasing; my amount of heat addition, that’s what is say… decreasing. Now, this is what is our requirement. So, let me put this on my required cycle, say… you know, over the time people they are looking for increasing the efficiency of gas turbine cycle; and this increase of gas turbine efficiency of gas turbine cycle that's what is possible by increasing the turbine entry temperature.

Now, this turbine entry temperature, that has a big limitation for our application, because metallurgical constraints that's what is coming into the picture. If my temperature, that's what is too high, it may be possible that, that will burn the my gas turbine blades. And this is what is also one of the major area of research these days; people they are talking about blade cooling technologies! Okay.

Now, let me represent this, in sense of my pressure ratio and useful work. If I am representing this as say… pressure ratio and useful work, I can represent all these cycles like 'cycle A', 'cycle B' and 'cycle C'. So, if you look at, with increase of pressure ratio, my useful work that's what is going to change! Let me tell you, we have our fundamental understanding, say the area under the curve on T-S diagram, that's what is representing my work done capacity, Okay!

So, now you will say, Sir, this is what is not giving useful work. Our expectations, that's what is say… different; we are looking for some other concept. So, that is the reason why over the time, over the years, people they have increased this requirement of useful work. Because they are looking for higher power generation; people they are looking for high thrust generation. So, this is what is representing the increasing trend for your pressure ratio in relation with your useful work.

Now, somewhere here, your turbofan engines -they are working. Now concord engine, what we are having, you know, this is what is engine, that's what has been used for your fastest or say, the flight, or your aircraft, that's what is moving at Mach 2! Okay! So, for that, the requirement of my work done that's what is very high, okay. So, with this fundamental understanding of your thermodynamics, gas turbine cycle and your thermodynamic process, let us move forward towards the next.

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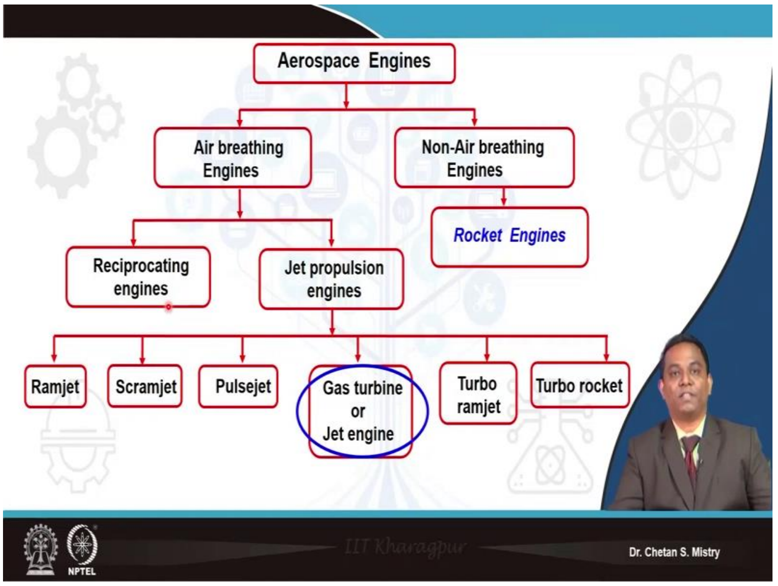

Now, when I say, we are having the background of say… aero application. So, let me discuss, say… if you look at my aerospace engines; they are being classified in a two way, that's what is say… air breathing engine and non-air breathing engine. Let me tell you this non-air breathing engine, that's what is different from your air breathing engine, because for air breathing engine, you are using your working fluid that's what is air; and for non-breathing engine, our working fluid, that's what is say in order to have combustion within engine, we are looking for separate fuel; we are looking for separate oxidizer. While in the case of air breathing engine, we are taking our atmospheric air.

So, you may be having background of your reciprocating engine which we are using for our two-wheeler, we are using for our four-wheeler that's what is working on a principle of reciprocating engine. Earlier aircraft engines, they were flying with this reciprocating engine with the constraint of size and weight; later on, people they move with the gas turbine engines.

So, if you look at, that's what has been classified as jet propulsion engines. Now, in the jet propulsion engine, we are having further classification say… ramjet engine, scramjet engine, pulsejet engine, we are having gas turbine engine, turbo ramjet engine, turbo rocket engine. We are focusing mainly on the gas turbine engine, okay.

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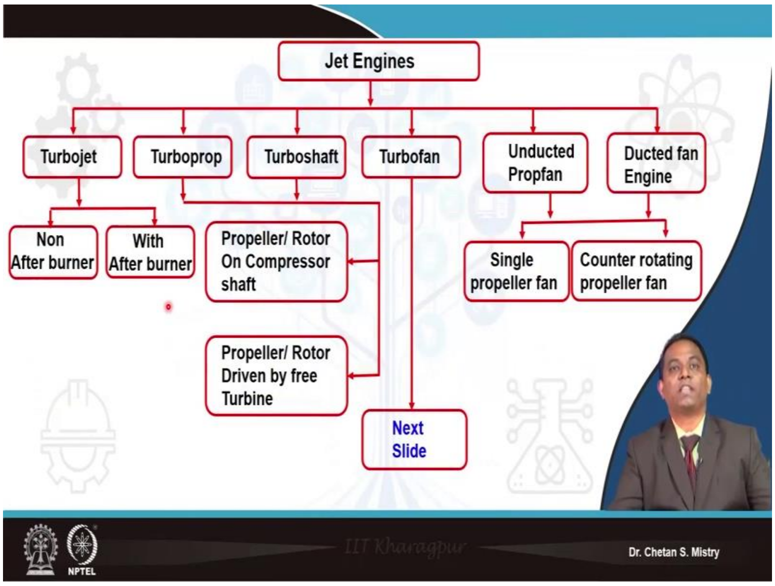

Now this gas turbine engines, that's what is further been classified as, say… turbo jet engine, turboprop engine, turboshaft engine, turbofan engine, un-ducted propeller fan, ducted propeller fan. Further, if I am classifying turbojet engine that's what is with after burning, without after burning. So, they are having the special applications. Let me tell you, say… these engines for aero application, they are being used for two different purposes: one it is for your commercial airline, second, that's what is for your military application.

When I am talking about the military application, that's where we are looking for higher thrust in order to do different kinds of maneuvers. And that's what is required after burner to be incorporated. If I am talking about, say… commercial application, that's what is flying in the range of Mach number 0.8 or 0.85; there we are not looking for higher amount of thrust or we are not doing any maneuvers.

So, there is no requirement or we are not applying any afterburner for this application. So, here if you look at, for say… the turboprop engine, we have discussed this turboprop engines they are being used to rotate your propellers. So, we are having these days so a propeller and rotor that's what has been placed on common drive or say maybe propeller that's what has been connected with the turbine.

So, you know, we have discussed this say… turboprop and turboshaft engine that's what is similar to your land-based power plant; where your shaft power that's what has been used for the rotation of your wheel. This wheel for aero application maybe propeller and for, say…

application for your land-based power plant that's what is to rotate your generator. Now, let me move towards the next slide.

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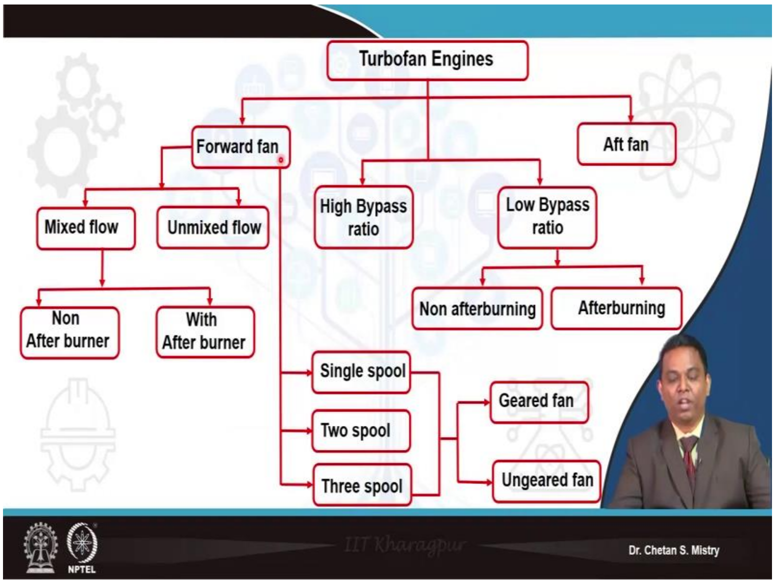

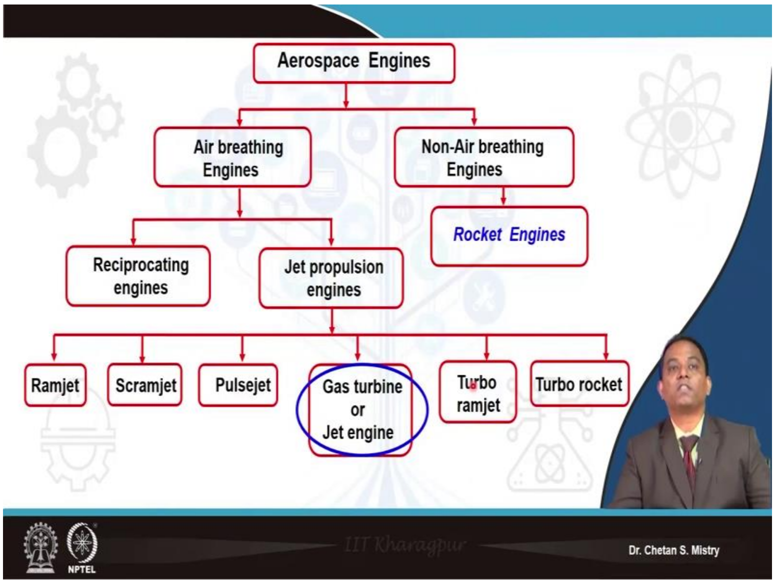

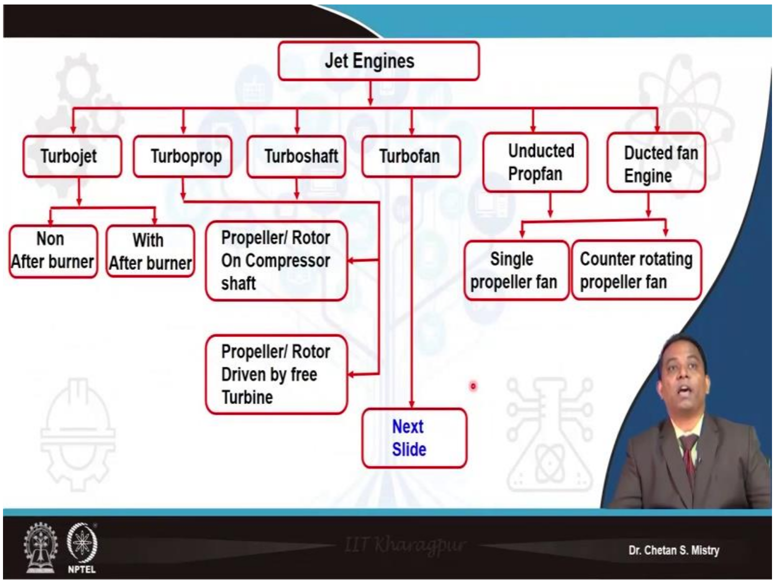

So, here if you look at, this is what is a classification for, say… turbofan engine, where you will be placing your fan in forward direction; maybe you will be using that on the rearward direction; they are having special advantages and disadvantages. Since this is what is a course which is related with the design, that is the reason why these all what we are discussing is of important! Okay!

This forward fan, they maybe of say… a mixed flow configuration, unmixed flow configuration. This mix flow configuration further can be accommodated with your afterburner; so it is say… afterburner - with afterburner, without afterburner. This forward fan, that's what is having say… single spool configuration, two spool configuration, three spool configurations.

Let me tell you, there are many engine manufacturing companies for, say… aerospace application; initially they were talking about the single spool configuration. Later they moved with say… two spool configuration; Rolls Royce is a company they are working or they are making their engines with the three spool configuration.

These days, a recent trend that has come up with a geared fan. Now, Pratt and Whitney, they are the first who has developed the geared turbofan engine. Now looking to the benefit of this turbofan engine with geared or geared turbofan, now, almost other companies they are also started with. So, you know, like whole purpose of putting this classification here is you can understand this application of your gas turbine engines for different aero engine in depth requirements.

Now, if you look at, there are many companies, name a few say… GE, Pratt and Whitney, Rolls Royce, MTU engines, Siemens, Honeywell; they all people they are working on development of these engines. And these engines, they are having the special application. So, they are having categorically different engines. So, all these companies, they are having their old engines, they are having these existing engines, and let me tell you, these people, they are working for the development of new kind of engine for the future!

So, this is what is giving you overall picture, what is the scope of having learning of this course on aerodynamic design of compressors and fans! So, this is what is multibillion-dollar business a year, and this is what is the fastest growing industry for, say gas turbine applications, okay! So, the background or what all we will be discussing, that is what we will be focusing mainly on aero applications.

Let me discuss here, say we are having the application of gas turbine for as we have discussed, they are different; say… land-based power plant. We can understand, where we are having a whole lot of space; that's what is available in order to accommodate our engine, where I am not having any constraints with the size of the engine, where I am not having any constraint with the length of my engine!

When I am talking for the application for aerospace, I am having big constraint in sense of my size, I am having big constraint in sense of my weight, okay! So, my design strategies for aero engine that's what is most challenging. It does not mean people those who are working on land-based power plant they are not focusing on.

So, now most of the companies those who are making the aero engines, they are also dealing with the engine development for say gas turbines, that's what is applicable for land-based power plants. So, understand one thing; like our application for this design that's what will be catering the requirement for the future, okay.

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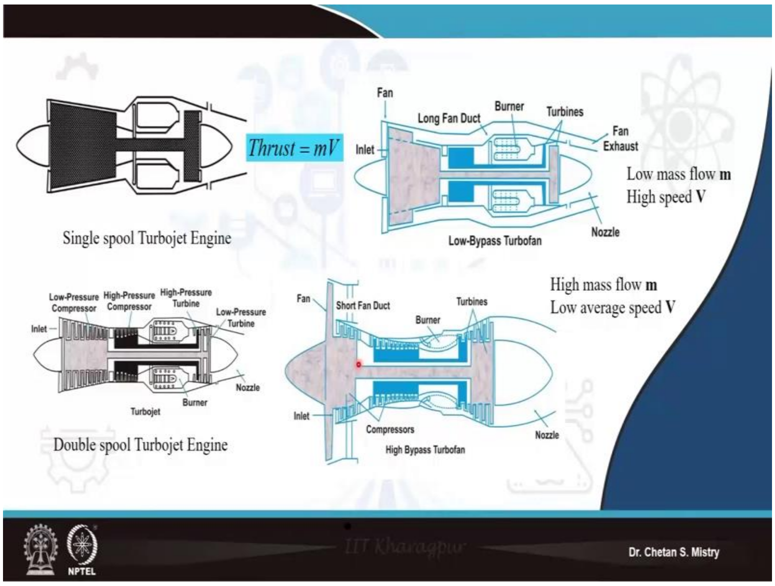

Now, let me show you, this is what is representing my single scale, single spool turbojet engine. So, on the front side, what you are looking at, that's what is representing my compressor; further component as we have discussed is my combustion chamber and downside I will be having turbine.

Now, you know, like this is not because it is looking nice, that is why we have kept this picture. Just look at, this is what is representing my length of the axial flow compressor is large. And if you are comparing the length of my turbine stage, that's what is say lower; and you can understand there is a special reason behind this! Okay. So, this engine, that's what is generating my thrust. So, according to yours, Newton's law; we can say thrust generation, that's what has been represented by "$\dot{m}$ ", that is nothing but the mass flow rate and V that is nothing but my exhaust velocity from the nozzle.

Now, earlier days, people they were happy with the single spool configuration. Later on, with the requirement of higher thrust, they people they have, they are looking for, say higher thrust that means they are looking for higher pressure ratio for the compressor! We have seen that part, okay. Now, when I say, I am looking for say… higher pressure ratio, that means my number of stages required for this axial flow compressor that will be larger, that will be increasing the length of my engine.

Now, that's what is a constraint for my arrow application, okay. Second option, you may be aware of the fundamental equation that's what is called Euler's equation, which we will be discussing in later stage. That’s what is say, my power generating capacity or power absorbing capacity of turbo machinery, that’s what is a function of my rotational speed.

Here in this case, you may be argue, Sir, why do not we rotate this compressor at the high speed? If we are rotating at the high speed with less number of stages, we are able to achieve our pressure ratio, true! But at the same time, if you are looking at, my flow, that’s what is entering from the front side, that’s what is facing say… atmospheric air. Now, this atmospheric air, that’s what is at the low temperature, so you can understand there will be possibility of the formation of shock at a front stage.

Now, this shock, that’s what is acting like an aerodynamic penalty; that may lead to reduce the performance of my engine, that may lead to reduce the efficiency of my engine. Now in order to meet this requirement, people they opted with the second option, that’s what is called double spool turbojet engine. Here, if you look at, we are having two shafts; one, that’s what has been called, say… LP spool and second one, that’s what is called, say… HP spool.

Let me tell you, the front part, that’s what is called a low-pressure compressor that’s what has been connected with my low-pressure turbine. Now, here in this case, do not get confused with the terminology of say low pressure. It does not mean low pressure means it is generating the low pressure, the compressor stage that’s what is generating the low pressure, okay! You need to understand my operating pressure is low and that is the reason why this is what is called low pressure compressor.

Now, if you look at on the rear side, this spool that’s what is called HP spool, which is rotating at the high speed, okay. Now, this high-speed rotation that’s what is giving the reduction in number of stages what we have discussed earlier. Now here also, this is what is called HP compressor; do not get confused with the terminology of HP means high pressure generation. No, this is what is my operating pressure is higher, okay.

So, we are having this kind of configuration. That’s what is meeting with the requirement of my generation of my thrust. Similar kind of configuration maybe having for say land-based power plants. So, in order to avoid the possibility or the limitation of single spool, we are moving with the double spool configuration. Now, you know, like the fundamentals always says I can improve my thrust by increasing my velocity or by, you know, increasing my mass flow rate.

So, people, they are having different kind of configuration; these days they are talking of. This is what is one of the engine configurations, which is known as low bypass ratio turbofan engine. So, here if you look at, we are having, say fan, this is what is my fan; this is what is say my HP compressor, this is my HP turbine and this is what is say my LP turbine. So, this is what is giving me high mass flow rate and lower velocity at the exhaust or we can say, that's what is giving me the requirement of my thrust.

This kind of engines, they are being mainly used for your military application. Now, when they say, this is what is being used for military application, we are having major concern with the thermal signature, okay! So, this bypass duct what we are looking for this bypass duct, that's what is giving, say… it is reducing my thermal signatures, that's what is coming from the engine.

Now, for aero application, when we are talking for the big engines; this is what is say high bypass ratio engine, this is what all we have discussed earlier, we are having large size fan, okay! And, that will be followed by your LP compressor, by HP compressor, that is what will be rotated by two spool configuration. Now here also, you know, like as we discussed our major concern for aero application -for say… our commercial airlines, it is a fuel economy. And, you know, we can increase our fuel efficiency by increasing turbine entry temperature, but we have constrained with the heat transfer.

So, in order to address this part, we are having this big size fan. That is what will be giving the bypass air which can cool this particular region. And that's what is giving the additional benefit. Let me tell you, this high bypass ratio engine that's what is giving say approximately 70 percent of your thrust and that's what is a major choice. We will be discussing something that's what is called your propeller efficiency or people they started talking about thermo-propulsive efficiency. So, these engines they are having highest thermal-propulsive efficiency.

So, with this introduction part to the gas turbine engines, that's what is applicable for land-based power plant, with application for, say… aero engine development; with fundamentals of your thermodynamics and the construction feature, here I am stopping with. We will be discussing further for the design aspects for say… compressors and fans. Thank you, Thank you very much!