Jet aircraft propulsion

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Module No # 01

Lecture No # 42

Future of aircraft propulsion

Hello and welcome to this concluding lecture of this lecture series on jet aircraft propulsion. So, we are currently on the forty second lecture and this would be the concluding lecture of this lecture series. So, the purpose of this lecture, particular lecture, is to primarily give you an overview of what we have been discussing in this course over the last forty one lectures. And also, partly to also introduce you to some of the concepts of aircraft propulsion, which we might get to see in the future. So, we are going to discuss two distinct aspects of jet aircraft propulsion. One is, of course the overview of jet propulsion system that we have discussed over several lectures now. Which is what, I would be covering; I would be recapitulating topics that have been discussed during this whole course.

And, the second half of the course which is going to be handled by Professor Roy; he would be discussing about the future of jet aircraft propulsion where, he would be discussing about some of the concepts, some of the very promising concepts that might, that something that we might see in a few years from now. And, so these are some of the topics that we are going to discuss.

So, we will begin with an overview of the whole course and the course contents. Where in we will discuss about, well, where I will just basically revise and revisit some of the topics that we have discussed in very brief. And, so as you have already undergone the course during the last forty odd lectures, what is it that you have basically discussed and learnt?

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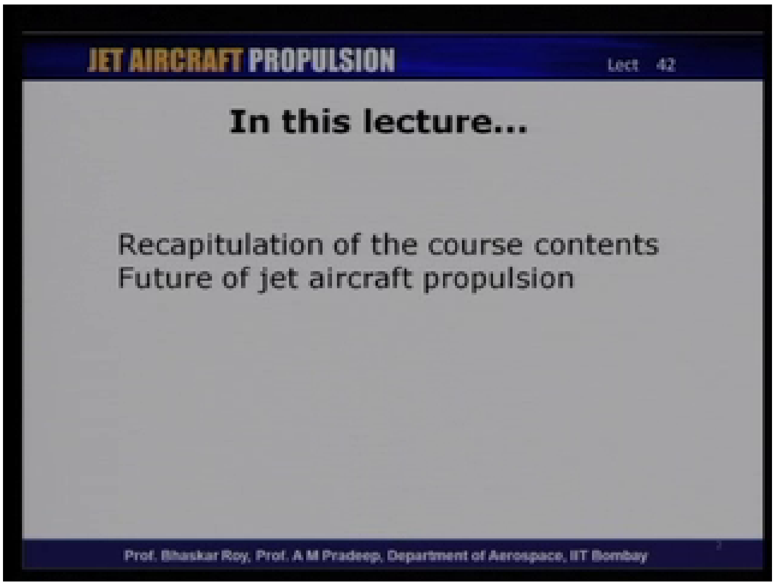

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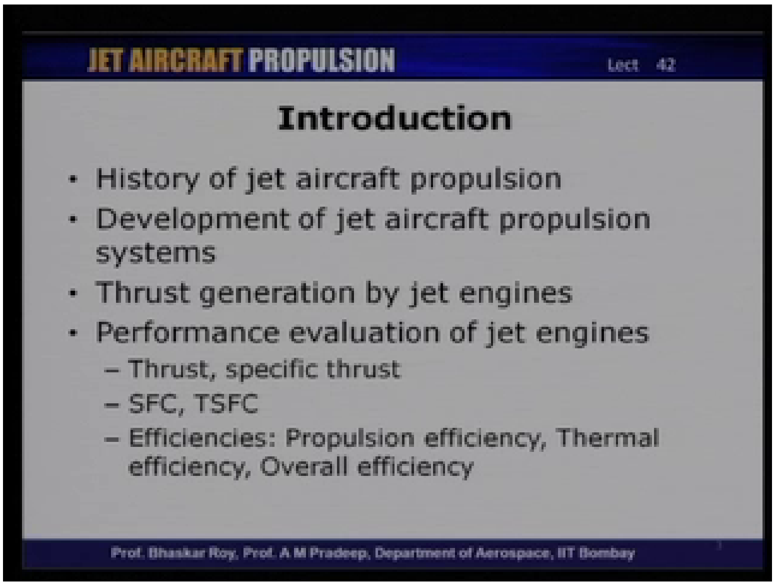

So, let us quickly recap what we have been discussing over these several, over last several lectures. So, in today's lecture as I said that, two distinct topics that we are going to discuss; one of them is, of course recapitulation of the course contents and the second part of the course is future of jet aircraft propulsion. So, the first few lectures that we had discussed in during this course were devoted to introduction to the whole concept and subject of jet air craft propulsion. We had one lecture entirely devoted towards discussing the history of jet aircraft propulsion, where we have seen how the jet engines as we see now have evolved over several years close to about sixty, seventy years of development; we have seen how jet aircraft propulsion has developed as a concept, from a concept to a fully flying jet aircraft engine; we have seen very complicated, the current modern day jet aviation engines are very complicated to, as compared to what were, what they were supposed to have been many years from now.

And, so we have seen some of these the evolution of jet evolution or jet aircraft engines over the last several decades to take a form that we see now. And, in today's second half of today's lecture we are going to see how jet aircraft engines are going to evolve or likely to evolve from now onwards. So, we go, we have primarily covered the entire spectrum of jet aircraft engines starting from its history, its inception and evolution and how jet engines have evolved to current day modern; the military as well as civil aircraft engines which are very complicated engines and devices. And, how is it that they are going to or likely to evolve over the next few years.

So, we started our course with an in-depth discussion on the evolution of jet aircraft engines. And then, we have also seen how the jet aircraft propulsion systems have developed, how is it that that jet engines have developed into an entire system which consists of several sub systems and several sub components.

Then in next few lectures, well, basically I, when I am when I am saying that jet engine as a system consists of several sub systems, what are these sub systems? In fact, we spent several lectures on each of these modules or sub systems of the jet engine as a whole. We had discussion, very detailed discussion on the components like the compressors, the turbines, combustion chambers, intakes and the nozzles.

So, each of these components constitutes the sub system of the whole system, which is the jet engine. And, it is necessary that all these components put together work as a single unit. Which is why towards the end of the course, we also had some discussion on matching of these components; because its, the design and development of individual components are done by separate groups.

And eventually, if they all have to put in if they all have to be put into a single engine and the engine has to successfully run and develop a certain the designed thrust, then it is very much necessary that all these components work together as a unit and not as an individual components; because as designers of… let us say the compressor, the compressor group would obliviously try to maximize the efficiency of the compressor. And, that is true for all other components as well. But, ultimately when they are all put together, it is not the individual efficiencies that alone matter, but how these components match with the other components. And all of them put together, generate the required thrust and also with a high amount of efficiency. So, that is why we had to discuss these components in detail.

Now subsequent to this, we discussed about some of the fundamental equations that we were using throughout the course. This is what to do with the performance of jet engines themselves.

How do we evaluate a jet engine? Now that we have designed a jet engine, how we can evaluate and say that this jet engine is going to made it is requirement. Well, there are a few basic parameters that these jet engines are evaluated based on. One of them obviously is the thrust because the primary purpose of a jet engine is to generate thrust, so that the thrust can be propelled forward.

So, thrust is one of the primary performance parameters. We derived the thrust equation, we have seen how from, starting from first principles we can derive a generalized thrust equation. And of course, we have used this equation throughout the course. Basically, the thrust equation consists of two distinct terms. One is the momentum thrust; which is basically mass flow rate times one plus f; that is, the fuel flow rate into m dot plus into the jet exhaust velocity u e minus u. So, this is the momentum thrust.

Second component of the thrust is the pressure thrust; which is area times p e minus p a. And, of course as pressure thrust is usually much smaller as compared to the momentum thrust. So, thrust is in general the product of mass flow rate times one plus of in the u e minus u. So, we have derived this equation. And of course, we have used this equation for the different types of engines that we have discussed. And, subsequent to the thrust equation; so, thrust being one of the most important parameters, performance parameters. What are the other parameters?

So, how much fuel does an engine consume to develop the thrust? So, that is the second parameter that we have discussed. That is specific fuel consumption. And, besides fuel consumption, there are also efficiency that are come in to picture. The different types of efficiencies like thermal efficiency, the propulsion efficiency and the overall efficiency. So, these are some of the parameters we have been discussed and we have also derived equations for determining how we can calculate these parameters.

So, in the first two or three lectures, we have discussed on some of these topics with the history of propulsion, development of jet aircraft propulsion systems, the thrust generation and performance evolution based on thrust in specific thrust, specific fuel consumption and TSFC or thrust specific fuel consumption and the efficiencies; the propulsion efficiency, thermal efficiency and overall efficiency. Subsequent to this, we had an overview of the different types of engines; how can we classify engines based on certain parameters. One of the ways of classifying engine is based on the number of spools or shaft that the engine has. So, you see an engine could have a single spool in which all the rotating components like the compressors and turbines and fans and all of them are mounted on the same shaft. So, that is known as a single spool engine.

On the other hand, a multi pool engine would have multiple number of shafts; that is, there would be a compressor, high pressure compressor driven by a high pressure turbine, then the low pressure compressor driven by a low pressure turbine and so on. And, so there would be multiple number of these shafts or spools. Typically, there could could be, they could be either two spool or three spool, when not more than that. So, you could have engines which have either a single spool or it could be two spool or three spool. Of course, in principle it is possible to have more number of them. But practically, it is known that having more and more number of spools does not really help. So, that was one way of classifying the set of engines. The other classification is based on the type of engines themselves.

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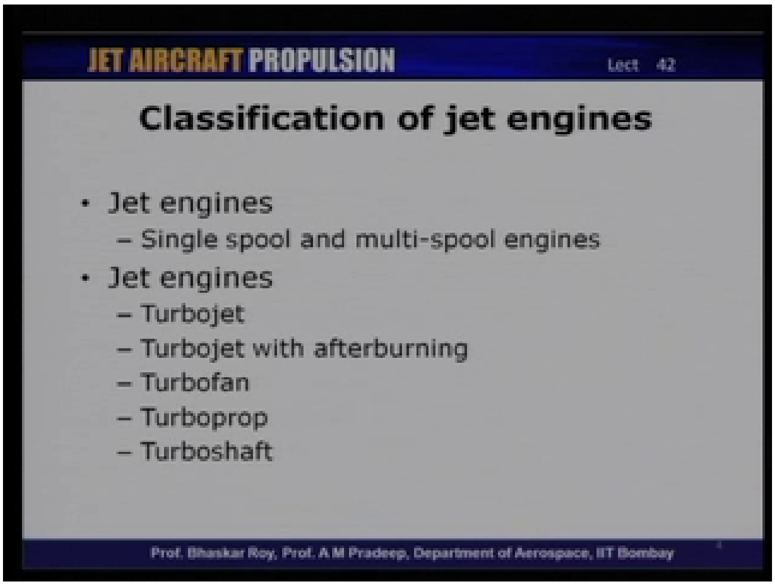

So, the most fundamental form of engine that we know is the turbojet engine. So, turbojet engine is probably the simplest of the jet engines; besides, of course the ramjet and pulsejet. So, those engines which have rotating components, turbojet is the simplest of them. Turbojet engine typically consists of a compressor, then the combustion chamber, turbine and nozzle. And of course, there is an intake ahead of the compressor. Turbojets may operate with or without reheat or after burning. So, a turbojet engine with afterburning is used normally in military aircraft, where these aircraft would have to operate at supersonic speeds. So, if an aircraft has to operate at supersonic speeds, we would need to use afterburning or reheat, so as to enable the engine to generate additional thrust and accelerate it to supersonic speeds.

So, besides the turbojet with afterburning, the most common form of civil aircraft engine that is used is the turbo fan engine. So, most of the modern day, larger sized engines or aircraft would be flying with a turbo fan engine. A turbo fan engine is very similar to turbojet, besides the fact that ahead of the compressor we would also have a fan. So, a fan generates a bypass mass flow. It is a cold mass flow. And, again a turbofan might be either mixed mode or an unmixed mode. And, so there is a cold stream which may or may not mix with the hot exhaust before it exits from the engine. So, turbo fan is very commonly used engine for the civil aviation.

And then, the other commonly used form of engine for civil aviation is turboprop engine. That is, we have a propeller which is driven by a turbine. And, so it is like a turbojet with a propeller in front of it. So, turbo prop engines primarily generate thrust using the propellers. But, they may also have some component of jet thrust. Then, the other variant of the jet engine is the turbo shaft engine. Turbo shaft engines are used in helicopters. So, there is no jet thrust here. So, the entire, one of the turbines is exclusively meant to drive the main rotor blade of the helicopter. And, so such engines are called turbo shaft engines; because they generate shaft power and not jet thrust. So, we had some discussion and overview of these different types of engines.

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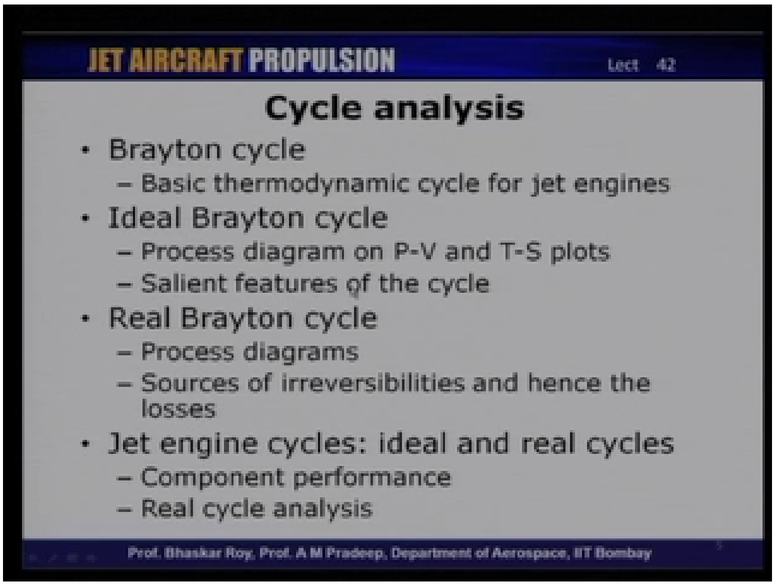

And, we saw what is it, how is it that we can distinguish between these different types of engines. Subsequent to that, we started the thermodynamic analysis of jet engines. We had discussed about the basic thermodynamic cycle of jet engines. We have seen that the basic thermodynamic cycle based on which an engine operates is the Brayton cycle. So, we have seen what is a Brayton cycle and how we can represent a Brayton cycle; an ideal Brayton cycle on process diagram based on pressure volume or temperature and tropyh plots. So, we have seen an ideal Brayton cycle and represented its process on P-V and T-S plots. We have also seen the salient features of the cycle that, what are the different processes which constitutes a Brayton cycle.

An ideal Brayton cycle consists of isentropic compression, then constant pressure, heat adhesion, isentropic expansion and constant pressure heat rejection. So, these are different processes which constitute an ideal Brayton cycle. We have also have seen the real Brayton cycle and the process cycle, process diagram for a real Brayton cycle. We have seen the sources of irreversibilities. And, what makes an real Brayton cycle? That is, there are irreversibilities in the compression, expansion process. There could be pressure loss taken place in the heat adhesion process and so on. We have then discussed about the extension of the Brayton cycle to jet engines. Brayton cycle forms the basic thermodynamic cycle, and how can we extend that to an actual jet engines. So, actually all jet engines operate based on Brayton cycle. But of course, there are modifications or the differences between the pure ideal Brayton cycle as compared to jet engine cycle.

The fundamental difference is that a Brayton cycle is the closed loop or close loop cycle, whereas the jet engine cycle is an open cycle. Of course with the air standard assumptions, we still use; we can still approximate the jet engine cycle to be a Brayton cycle.

So, we have carried out, we have carried out very detailed analysis of these thermodynamic cycles, in terms of cycle analysis for both the ideal version of the jet engine as well as the real version of the jet engine. Cycle analysis as we have seen, involves calculating properties across individual components which will eventually give us the thrust, hence fuel consumption.

There are certain parameters which are fixed design parameters like the ambient conditions, then the compressor pressure ratio, turbine inlet temperature. And, these are some of the parameter which are fixed apriory. And, based on these parameters and using cycle analysis we can evaluate or judge the performance of jet engines from a cycle analysis.

We have done this for both the idealized version as well as for the real version. Real version also includes efficiencies which are introduced as a result of irreversibilities in various components like intake efficiency; because compression in an intake can be non-isentropic. Then the compressor efficiency, isentropic efficiency of a compressor, then there could be the efficiency of the combustion, pressures law in the burner or combustion, turbine efficiency and the nozzle efficiency.

So, we have associated efficiencies with all the components because in an actual, in actual practice we know that none of these components are going to perform ideally or in isentropic manner, like the compression or expansion process are never isentropic. So, we have associated efficiencies with all these components. Once you associate efficiencies, we can still carry out the cycle analysis in a very similar manner as for an ideal cycle. But, we have these efficiencies inbuilt into them. But, cycle analysis helps us in the sense that it is probably the starting point of the design of the jet engine itself. Based on the cycle analysis, we can evaluate whether the jet engine is going to deliver the performance that is being required for this particular application, like in the terms of thrust and efficiency and fuel consumption. So, cycle analysis is a means for achieving some of these preliminary designed parameters.

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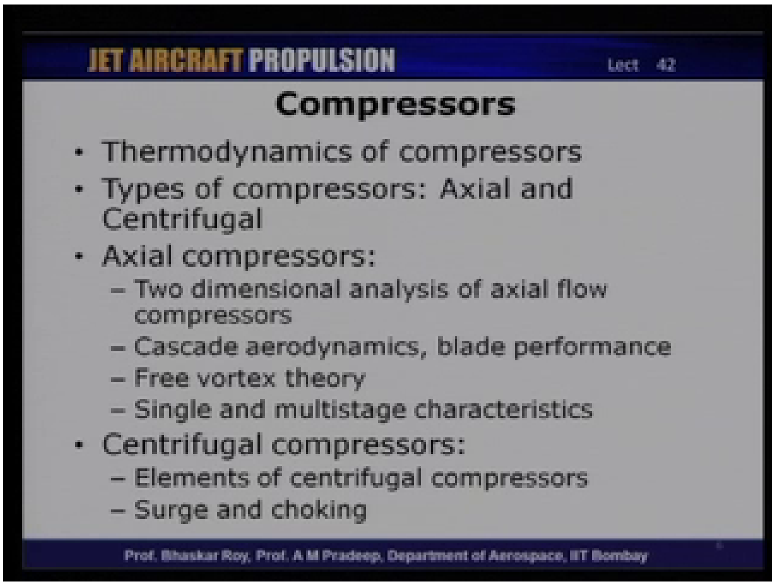

So, after cycle analysis we started our discussion on individual components. We have several components which constitute jet engine. One of the components, one of the important components is the compressor. So, first we discussed about the rotating components. So, there are two distinct rotating components in jet engine; the compressor and the turbine. We first discussed about these two components and then we took up the non rotating component like the combustion chamber, intakes and the nozzles.

So, in compressors we first started off with the thermodynamics analysis compression process itself or the thermodynamics of compression. We have seen how we can explain compression process taking place through a rotor stator combination and how the pressure rise is achieved as a flow passes through a compressor. Then, we also saw that there are two distinct types of compressors; the axial compressor and the centrifugal compressor. We have had very detailed discussion on both these types of compressors. We started off with the axial compressor, where we had discussion on a two dimensional analysis; a simplified two dimensional analysis of flow in or an axial compressor stage; that is, a rotor and the stator combination.

So, we first started off with the two dimensional analysis and then we discussed about what is known as Cascade Aerodynamics. Cascade Aerodynamics is basically method by which one can evaluate test compressor blades on a two dimensional scale before taking it to complicated rotating ring.

We have then seen what are the different performance parameters for evaluating a blade performance. We then discussed about the free vertex theory, which is something that is used for evaluating for designing the compressor stage. Where, basically the product of the radius times the tangential velocity is equal to a constant. Based on that, we can design a blade from the hub to the tip. We then discussed about the performance characteristic of single and multi-stage axial compressors. That, that is when we discussed about the instability mechanisms like rotating stall and surge. And, that is why performance characteristics would typically have a surge line, beyond which on the left hand side; which will be the compressor performance is unstable.

Subsequent to axial compressors, we discussed about the centrifugal compressors. And, in centrifugal compressor, we have seen the different components of centrifugal compressor like it has inducer; it has an impeller and diffuser. We had the detail discussion on these individual components and how we can analyze flow passing through the inducer and impeller and finally the diffuser. So, we have seen different components of a centrifugal compressor. We have also discussed about instabilities that can occur in centrifugal compressor like surging and another limit to mass flow that is choking. So, centrifugal compressor performance in relation to these two limits of operations; the surge line on one side and choking line on other side. These two limit the performance of compressors in general.

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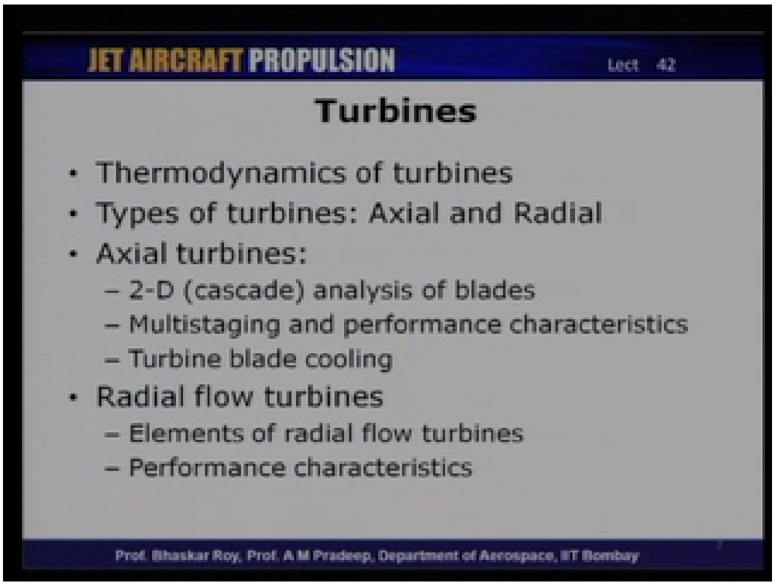

So, this was about compressors. We had spent a few lectures on discussion on these topics on both types of compressor; the axial as well as the centrifugal compressor. Now subsequent to compressor, we took the turbine. That is the next rotating component. So, in turbine, again we had similar procedure followed. We started off with the Thermodynamics of turbines. We have seen how turbines can generate work output by expanding hot combustion products through them. Thermodynamics of turbines was discussed in detail in one of the lectures. And then, we discussed about two distinct types of turbines; the axial turbine and the radial turbine. In axial turbine, again we have discussed two dimensional analysis of blades or cascade analysis of flow through these blades.

We have then discussed about multi staging of axial turbines and performance characteristics of turbines. And unlike compressors, there are no instabilities that the limit performance of turbines like surge or stall. But, they do have a performance characteristic. Then, very important aspect of turbine is the turbine blade cooling; because we have seen turbine inlet temperature is a limiting parameter. But, higher the turbine inlet temperature; better is the performance. So, how come we increase the turbine inlet temperature and without exceeding the material limits. So, one of the ways of doing that is, by cooling the turbines blades. So, we have seen in detail what are the methods available for blade cooling in turbines. And using that, how we can improve the turbine inlet temperature, therefore increase the performance of the engine as a whole.

Then, we have discussed the radial turbines which are less popularly used; axial turbines are commonly used. Even in the case of compressors, axial compressors are normally used in larger sized engines, whereas centrifugal compressors tend to be better options for smaller sized engines. In turbines, on the other hand the axial turbines are more commonly used in both larger as well as the smaller sized engines. But, radial turbines are also sometimes used. And, a radial turbine is exactly like very similar to that of a centrifugal compressor in terms of its appearance. And so, the components are constituents of radial turbine. We have seen the elements that constitute a radial turbine and how we can evaluate the performance of radial turbine, in terms of the performance parameters. So, these were the… distinct components, the rotating components of the jet engines; the axial compressors and then, well, axial compressors, centrifugal compressors; similarly turbines; axial and radial turbines.

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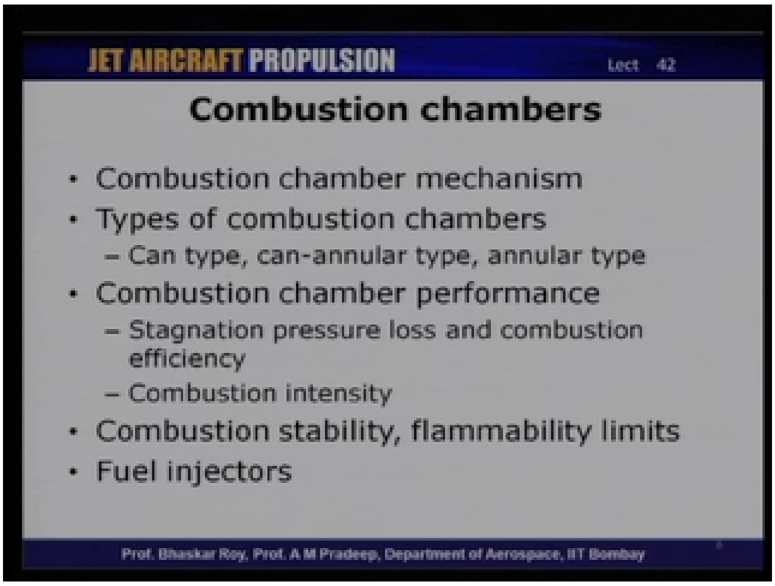

And, after we discussed about the rotating components, we then took up the non-rotating components. And so, we started off with the combustion chamber. That is one of the non rotating components. So, combustion chamber is the heat adhesion unit of… If we look at the Brayton cycle, there is one process which involves heat adhesion. So, combustion chamber is the part of that Brayton cycle, where heat adhesion takes place. we have seen the mechanism of combustion chamber itself.

And, what are the different types of combustion chambers? They are can type combustion chamber; they are can-annular type of combustion chamber and annular type of combustion chamber. So, we have seen in detail the geometric construction of these three types of combustion chamber. And then, we also discussed about the performance of combustion chamber. How we can evaluate performance using the stagnation pressure laws. That is one of the performance parameter. The combustion efficiency is an another parameter and also the combustion intensity. So, using three of these parameters one can evaluate the performance of combustion chambers.

We also saw in some detail, how we can evaluate stability of combustion as well as the flammability limits. Which is why, one has the peculiar design for a combustion chamber to ensure that the combustion is stable within the limits of the combustion chamber. We also had brief discussion on the fuel injection mechanism in combustion chamber and how we can inject fuel in an efficient manner; so that, the fuel and air mix efficiently before the combustion begins. So, we had rather detail discussion on the combustion chamber on all of these aspects and we have seen what are the advantages and disadvantages of these three different types of combustion chambers that we have discussed.

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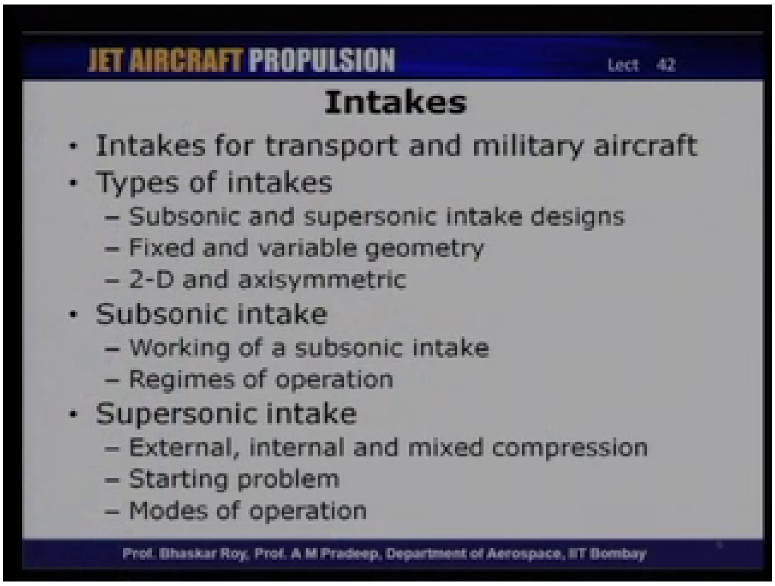

So, subsequent to combustion chamber, we had couple of lectures or on intakes. Intakes constitute the first component of jet engine. And, so we had some detailed discussion on types of intakes and their performance as well.

So, we have discussed intakes that are used for transport as well as military air craft and what are the different types of intakes. One may have subsonic intakes, supersonic intakes. We have seen their designs. Intakes could either be fixed geometry or variable geometry. We also seen what is two dimensional and an axial symmetric intake, we then took up a discussion on subsonic and supersonic intakes separately. We have seen the working of subsonic intake and the operation of subsonic intake in different operating conditions like take off or cruise.

In supersonic intakes, we had discussion on three different types of intakes, the external compression, the internal compression and the mixed compression intake. We have discussed about the starting problem associated with supersonic intakes and also the modes of operations of supersonic intakes like sub critical, the critical and super critical modes of operation of supersonic intakes.

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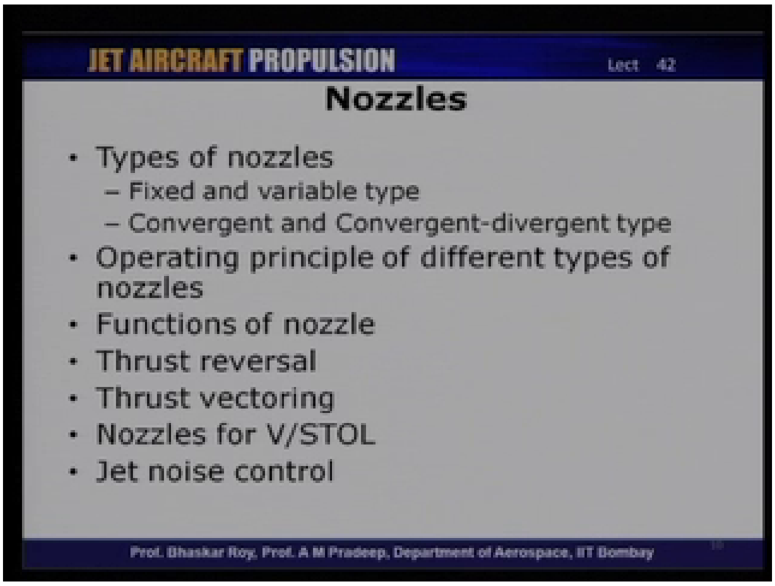

So, after intakes with the other component that we had for discussion, the last component of a jet engine, that is the nozzle. So, similar to intakes we also classified the nozzles in different types. We could have fixed nozzles, a variable type nozzles; one may have the conversion type of nozzle, convergent-divergent type nozzles.

We have seen the operating principle behind these different types of nozzle; like convergent nozzle is used for subsonic flows, whereas cd nozzle or convergent divergent type nozzle is used in supersonic flows. And, why is that we need to use these two types of nozzles for separate types of flows; we have seen the operation of these nozzles. We have also seen different functions of nozzle that, besides of course generating thrust, there are other functions that the nozzles have to satisfy in modern jet engines like thrust reversal, thrust vectoring in combat aircraft. And, nozzles are also used for vertical or short takeoff in landing by the deflection of nozzles appropriately. We have also seen one of the functions of modern day jet engine nozzles is also for controlling the jet noise to some extent by appropriately shaping the nozzle exit area. And so, nozzle jet noise, jet noise control also happens to you; one of the functions of modern day jet engines.

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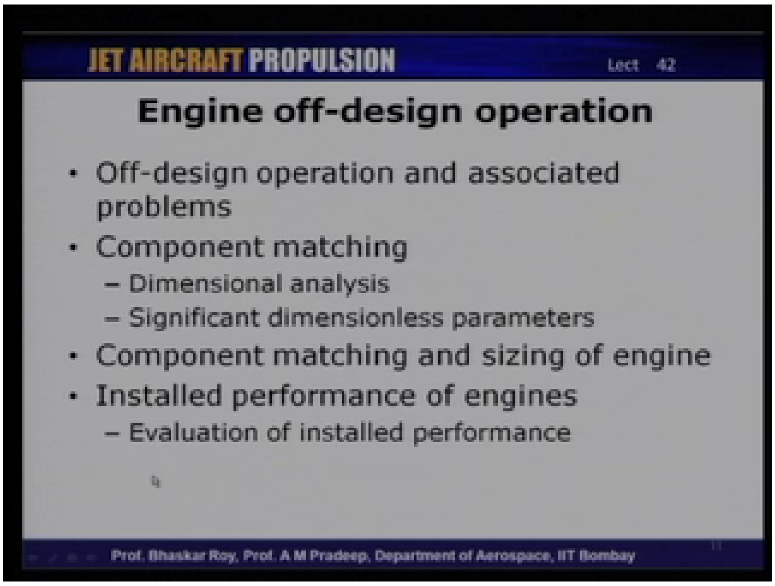

And so, after we have completed all the discussion on different components, we had some in depth discussion on the engine off-design operation. So, these engines are designed to operate under certain conditions. Obviously, we know that they have to undergo operation under all other kinds of design, other other kinds of conditions or which are referred to as off-design operations.

So, we have seen what are the associate, problems associated with off-design operation of an engine and why is it important that we have a proper matching of different components. And, we have seen in the beginning of the lecture; I mentioned that even though these components are designed as individual units by separate teams, eventually they all have to put we put in place in a single engine. So, they have to operate efficiently on one unit. So, component matching is very important aspect. So, we have seen a dimensional analysis which can be done to identify significant, non dimensional parameters which can be used for component matching.

Then, we have also discussed about matching as well as sizing of jet engines. And then, we have seen the installed performance and how we can evaluate installed performance of engines; because engines may be designed to develop certain performance level, but once they are installed in an aircraft, the performance would be different from what they have been designed for. So, how we can evaluate performance of the installed performance engines?

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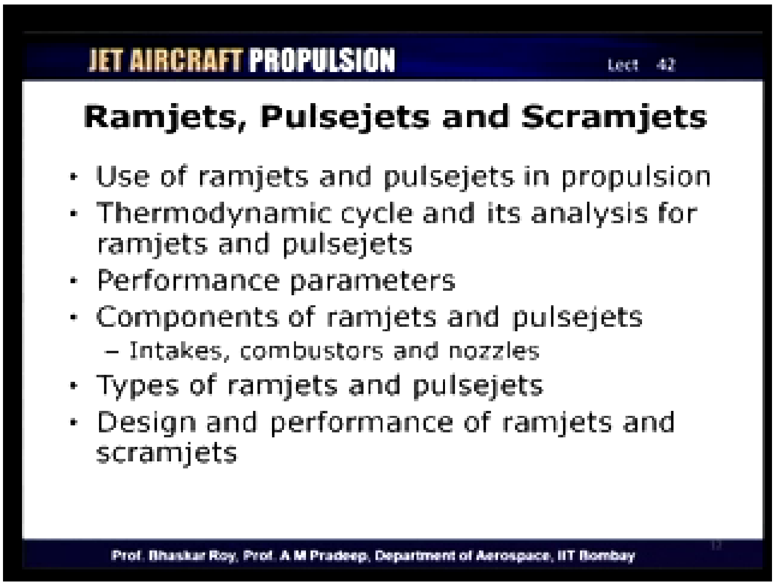

Then towards the end of the lecture series, we had some discussion. We have spent some few lectures on discussing about some other types of engines, which are obviously very simple, at least in design on paper they are very simple like ramjet, pulsejet and scramjets; because they do not have any rotating machinery. And, so we have discussed about what are the uses of ramjets and pulsejets. We have seen the thermodynamic cycle of ramjet and pulsejets. And, we have seen how we can evaluate performance of ramjets and pulsejets based on cycle analysis. We have then taken up detail desired discussions on the components that constitute these engines like the intake, the combustion chamber and the nozzle and how we can go about designing some of these components.

We also have discussed about different types of ramjets and pulsejets that, like we have we may have the solid fuel ramjets or liquid fluid or gaseous fluid or it might have integral rocket ramjet combination or one may have some of the other forms of ramjets; the ejector ramjet and so on. So, we have discussed in brief about these some of the concepts and also different types of pulsejets like valved and valve less pulsejets as well as the conceptual engine, the pulse determination engines. So, we also had a few slides on discussion on design aspects of ramjets as well as scramjets. So, these were some of the topics that we took up for discussion towards the end of the lecture series in the last few lectures.

And so, what we have discussed in, just now is an overview of the different topics that we have been discussing during the last forty one lectures that we have had so far. And, I have just given you an overview of the different topics, different chapters that we have covered over several of these lectures. So, in the next part of the lecture which will be taken up by professor Roy, he will give you an overview of where the aviation, the aircraft jet propulsion is taking us to and future of jet aircraft engines and what are the different types of engine that we are likely to see in the future and in few years from now. So, some of these topics will taken up for discussion by Professor Roy in the next part of the lecture.

Over these lecture series, we have been taking about various kinds of jet engines for powering aircraft to flight. We just had an overview of what we have covered in a little more than forty lectures in this lecture series by professor Pradeep. I will try to give a very brief glimpse to you of what the future holds for us in this area of jet engines for powering aircraft to various kinds of flight situations. We have seen over the last lecture series; in this lecture series, over the last few lectures that there are various kinds of engines that take us all the way up to hypersonic speeds. The man, of course started flying at very low speed with the Wright brothers flying about hundred and seven years back and that was very low speed flight. Over the years, we have learnt what are the possibilities, what are the options that we have, what kind of jet engines are good and fuel efficient and which are the ones which are probably not that efficient, the once which are not very efficient, have kind of fallen on the way side. And, we are now looking at various kinds of options that are available. Not only which are fuel efficient, but also which has possibility to take us to higher flight speeds and probably flying at various kind of operating conditions.

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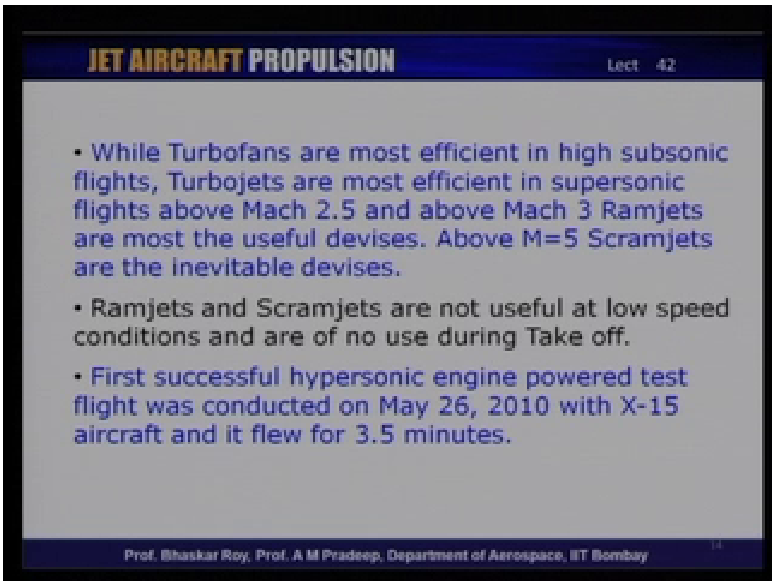

Let us take a quick look at what are the options that we have for various kinds of jet engines. You see; when you have the turbofans which are operating at subsonic speeds to high high subsonic speeds, to transonic speeds let us say. They are the most efficient devices of jet engines for powering aircraft. However, it is generally felt that once you cross about Mach 2 or 2.5, the turbofans probably would become less and less efficient. And, top pure turbojets would actually be the more efficient device.

In view of the fact that, the aircraft that fly at very high altitude also be experiencing very high drags. So, the drag penalty for the thrust creation become a little prohibitive with turbofans. And then, pure turbojets essentially became more useful devices. However, once you cross Mach 3.5, you all looking for devices that are even more efficient in terms of less drag penalty and reasonable thrust production. And then, you are looking at devices like ramjets. Now, these ramjets will take you to up to Mach 5 or so. And, at about mach five or so, even the ramjets become problematic because the flow which is highly supersonic outside. Once they are inside, they have to make subsonic in ramjet for the combustion purpose.

And then making them subsonic, it becomes a highly loss making proposition. And then, the scramjet come into picture, where you have to make them subsonic and they can remain supersonic. And, you have supersonic combustion. That allows you to go through scramjets and allows you to go through hypersonic speeds up to Mach 10 or so. Now, this is the spectrum which mankind has already conquered. We already have flights through the entire spectrum from very low subsonic to hypersonic speeds. Hypersonic flight X-15 and X-15 a has been successfully flown last year.

And, this clearly tell us that various kinds of jet engines that we have been talking about are indeed already flying and successful devices, however there are some riders. These riders are that the ramjets and scramjets, even though they are very good at very high supersonic speeds, you cannot use them for taking off. They are not good at low subsonic speeds. They are, really speaking; they are of no use when the aircraft is taking off. So, when an aircraft cannot take off when powered by ramjets or scramjets. As I mentioned the first powered flight of hypersonic aircraft has taken off last year. And, it flew for about three point five minutes, three and half minutes, which is more than what is Wright brothers flew hundred and seven years back in the low subsonic first flight of mankind.

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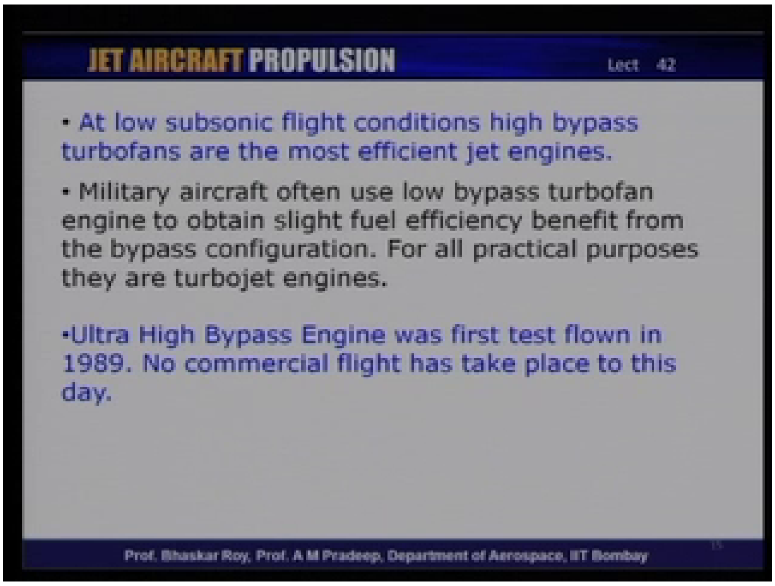

So, let us look what are the options that we have for various kinds of flight situations. At low subsonic, flight conditions is pretty much understood that high bypass turbofans are the most efficient devices. We have covered all the bypass engines and it is pretty much understood now that unless you have a high bypass turbofan engine, the flights under subsonic flow conditions are not going to be very efficient. So, high bypass and higher the bypass, more efficient they are, more fuel efficient they are. So, that is the option we have for low subsonic to medium subsonic flight conditions. However, the military aircraft which often fly under high subsonic to transonic and low supersonic speeds for various military operations have started using low bypass turbofan engine.

Even though for a long time, they were using only turbojet engines. They have now started using low bypass turbofan engines, and that gives them the slight fuel advantage. Turbofan of the bypass always gives a certain slight fuel advantage over a pure turbojet. And, this slight fuel advantage has been used by the military aircraft engines up to Mach 2; giving them more operational flexibility, more range of operation, more time in flight. These are the things that military aircraft would be beneficial when using turbofan engines. And, these turbo engines as we have seen are essentially very low bypass; low bypass ratio not only less than one, sometimes even less than 0.5 in so far. As sometimes, they are even cold leaking bypass engines.

So, those are engines that are normally used military aircraft operations. We are mostly supersonic aircraft, the other kind of engine that is have already been talked about. And, we have introduced that to you. That is ultra high bypass engine. Now, these ultra high bypass engines are of a very high bypass. We pass the values like 6, which have been used eventual recently in Jumbo and Boeing 777 and Airbus and aircraft. However, these ultra high bypass engines were actually test flown; way back in 1989 and more than twenty years back. However, they are still not used in a big way in various commercial aircraft even today.

And, one of the reasons is that these ultra high bypass engines have two problems that and require a good solution. One is that they make a lot of noise. And, the noise regulations these days are very stringent in various aircraft around the world. The noise regulations are so stringent that in some of the airports those which are noisy aircraft or even allowed to land or take off. So, this ultra high bypass that was one of the problems that they were making lot of noise, especially during a takeoff and landing. The other problem was that they were indeed having a lot of drag penalty. You see, bigger the engine; more is the engine diameter or the fan diameter. The more is the diameter; more is the drag penalty of engine itself, which adds to the aircraft drag penalty.

And, when have together you have a lot of drag penalty, which has been talked about before. The engine itself has to overcome that extra drag. Now, this was a little problem. And, this is an another reason why the ultra high bypass engines have not yet come into being. We will talk about today one kind of ultra high bypass engine that is likely to make the commercial flight very soon, which uses new technology. Both new kind of design and of course a kind of mechanical arrangement, which allows them to go towards high ultra high bypass configuration.

The other possibilities that people are talking about is as we just mentioned the scramjets and ramjets are not good enough for aircraft to take off and land; Obviously for takeoff land; low subsonic, high subsonic.

And then, true transonic speeds or low supersonic speeds, the best option is always the turbofan engine. Now, what people have conceived is a combination of turbofan or turbojet with ramjet or scramjet. And, that combination is what is taking shape these days, which will allow an aircraft to take off, go through a low subsonic, high subsonic. Go through supersonic speeds, low supersonic speeds and then all the way flight to an ultra high supersonic speeds, that is, hypersonic speeds. And in in those phases, it will operate as various kinds of engines. It will start off as ordinary turbofan engine, then turbojet engine, then ramjet engine and finally a scramjet engine. So, we will take a look at some of these options and how they look like in in terms of what they have been conceived of, as of today.

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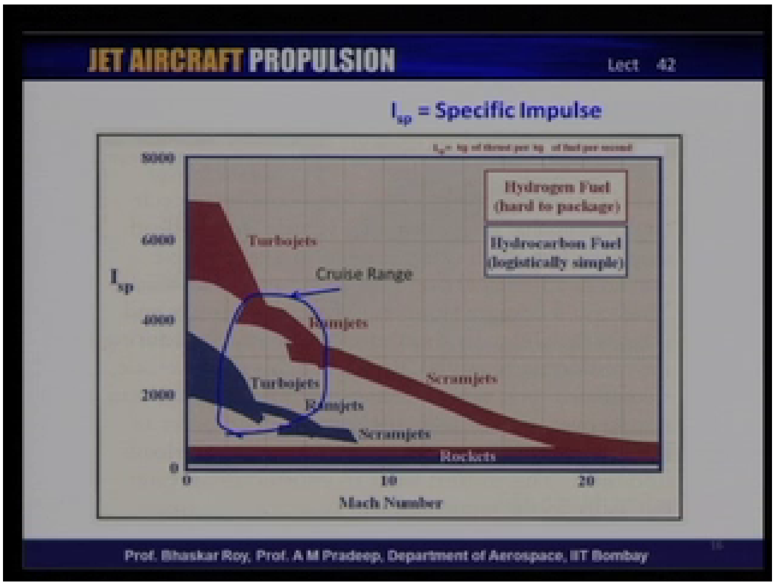

When we look at this particular diagram which tells us what the specific thrust or specific impulse is, compared to various kinds of jet engines. We can see that the normal cruise range that today we are talking about from subsonic to hypersonic speeds, it encompasses all the kinds of jet engines that we are talking about. It encompasses the turbojets, the ramjets. And, it starts to utilize the scramjets. We also see that we have a choice between two kinds of fuel; the hydro carbon fuel and the hydrogen fuel. The liquid hydrogen which is available for a long time and has been used in rockets for a long time, we can see that they can be attractive fuel for other kinds of jet engines also.

And, they indeed, actually give better specific thrust to specific impulse. The red zone; they are actually contribute or contributed by the hydrogen fuel. The trouble with them is the hydrogen fuel. Or, the liquid hydrogen is light and as a result carrying certain mass of fuel would require more volume and hence more space in the aircraft. Now, that is something which, till today the aircraft designers and are ready to concede that extra volume or extra space to the hydrogen fuel. And, as on when that issue is resolved, it is probable that we will move from hydrocarbon fossil fuel to liquid hydrogen, which of course is indeed a better fuel by all considerations.

So, even then, we have the choice of using turbofans, turbojets and then ramjets and scramjets. So, the cruise reins that we are talking about from subsonic to hypersonic, essentially can be covered by these three varieties of jet engines. Let us take a look at what a combination engine would indeed look like, which will take one single aircraft all the way from take off to subsonic to supersonic and then to hypersonic speeds.

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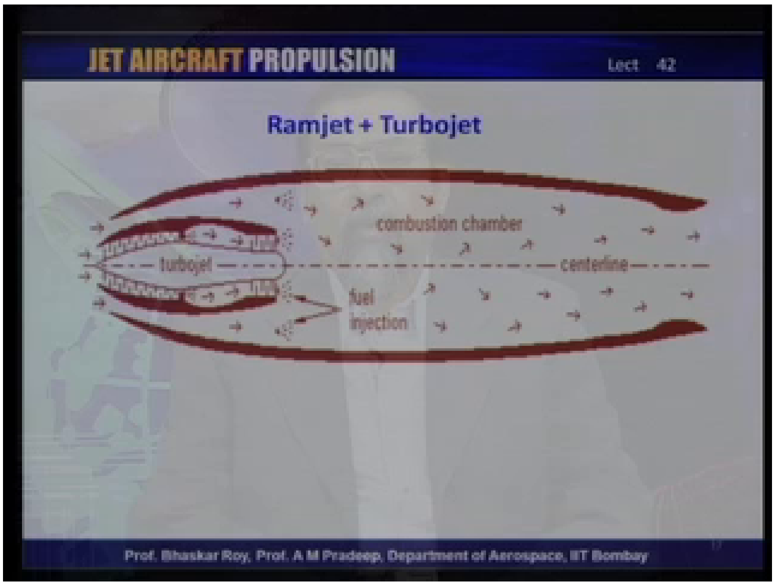

Now, this is a concept which people have been talking about for some time that you have a turbojet or indeed even a turbofan embedded inside a large ramjet engine, which is very large in size.

And, that ramjet actually would operate essentially in hypersonic or very high supersonic flight conditions. But, till such time as that, it is the turbojet or low bypass turbofan would provide the thrust for the flight of the aircraft. Now, this embedded turbojet or turbofan would be much smaller in size. It will exhaust into the combustion chamber of the ramjet. And during low speeds flights, that is subsonic or even low supersonic flights, the ramjet operation may be either suspended completely or very lightly operated to add just a little bit of fuel to the exhaust of the turbojet engine to provide a little more impetus to the thrust, the flow that is coming out from nozzle, indeed nozzle of the ramjet. So, that would provide necessary thrust for flight of the aircraft.

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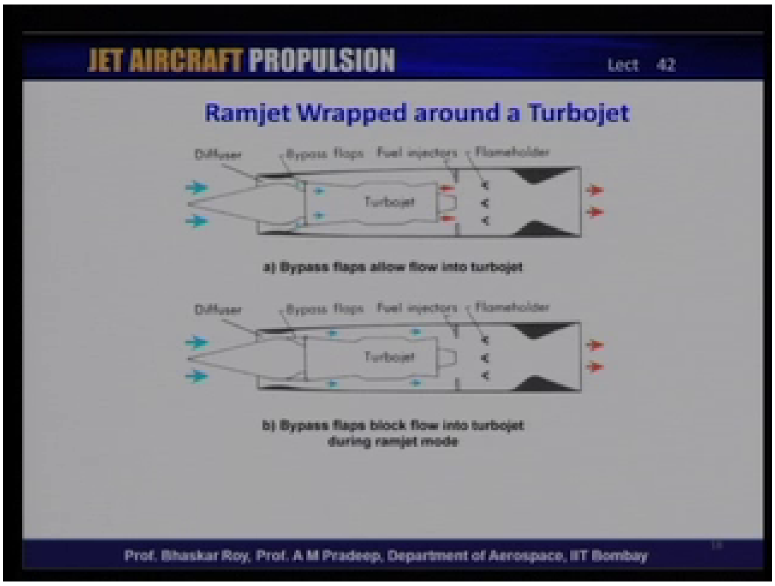

Now, that is the combination which people have been taking about. And, this is a concept which came up quite some time back, little more than twenty, twenty five years back. However, the concept has move forward a little and we can take look at what are the modern version of these concepts indeed look like. In this, the concept was taken forward; that is about fifteen years back, in which the turbojet is buried inside a sized ramjet and this was christened as ramjet wrapped around a turbojet. Indeed, the ramjet is spread around a turbojet engine and the outer periphery of the engine essentially operates like a ramjet.

And, so far as you have a diffuser over here, which allows a flow to come through the intake system into the turbojet. And then, it flies and the flows through the turbojet engine and comes out as a hot jet from the turbojet, which then may have little a bit of fuel edition here more like a afterburner. And then, the flow goes to the large nozzle of the jet overall engine as a thrust creating jet. However when the aircraft is flying at hypersonic speeds, this turbojet flow may be blocked and the entire flow coming through the intake and the diffuser system, which then would be a supersonic diffuser or intake would indeed go straight into the ramjet configuration. And, it would come through this bypass system into the ramjet combustion chamber. And, from there it will flow like a ramjet engine through the convergent-divergent nozzle that you see here; producing hot thrust for the entire flow with the combustion taking place in ramjet mode. Now, that is the kind of convertible engine, which people have been conceiving for quite some time.

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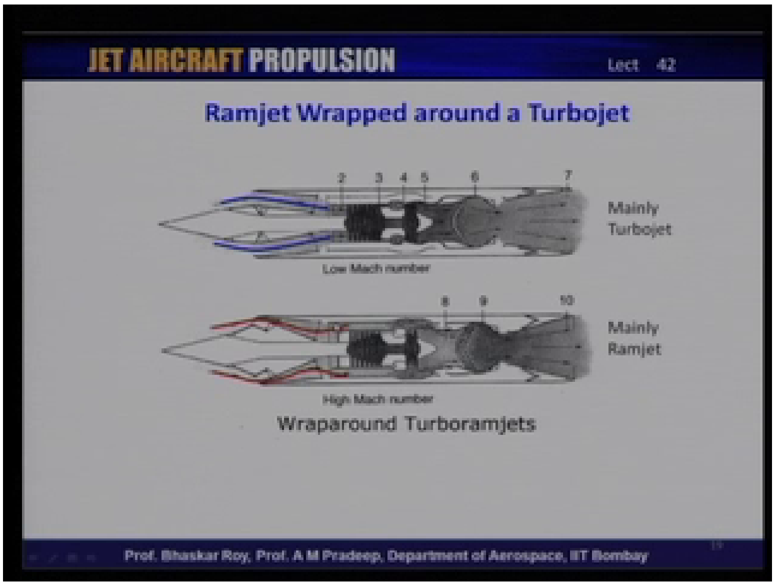

And, misconception has now taken place in a little more in a elaborate way in this form. Now in this form of the engine, the flow I have mentioned comes through intake system. And then through this intake system, it gets into the ramjet which is operating at the low Mach number either subsonic or low supersonic. And then, it goes through the normal compressor, combustion chamber and turbine or the normal ramjet, turbojet or turbofan engine configuration. And then, it goes through the jet pipe and the nozzle of the turbojet engine which is then placed in a manner pretty close to the nozzle of the ramjet engine; which then, operates in a manner that in a convenient through the turbojet engine operation; which means the flow from here could be going straight out through the nozzle without going out through the convergent-divergent nozzle. So, this nozzle could be straight out or divergent nozzle coming through the convergent nozzle from here. And then, from here onwards it is a divergent nozzle, which allows the aircraft to actually fly straight through from subsonic to supersonic flight operation. So, it could have a effective convergent-divergent nozzle; that means, the nozzle of the turbojet engine is essentially convergent. And then, through the nozzle of the ramjet it could become a divergent, producing essentially thrust for the entire aircraft.

However in high Mach number, that is, under high supersonic to hypersonic flight conditions, as you can see now the ramjet is is operational in a ramjet mode and the turbojet is completely blocked. So, the compressor turbine, combustion chamber combination of the ramjet is now completely off and effectively it is switched off or it is not operational anymore.

And, the entire flow that is coming through the system is coming from high supersonic flight conditions and as a result it comes to the system, goes into this bypass mode, goes through the entire duct and goes into the combustion chamber and then flies out flows out in a convergent-divergent mode producing thrust for hypersonic flight. So, that is the conception that is taking place. It is probably going to take a few more years to solve all the technological issues; so that, we have a convertible engine that will take mankind all the way from takeoff to hypersonic mode of flight. And, it is something which everybody is waiting for to happen. Probably it will happen in another five to ten years' time, before which we have to have different kinds of engines for different kinds of flight situations.

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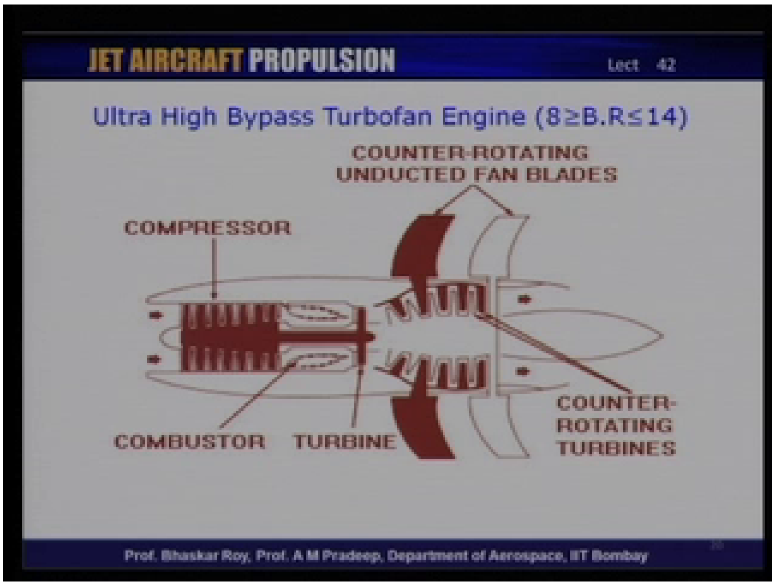

The other kind of engine that I was talking about is the ultra high bypass turbofan engine, which is taking shape now and is probably almost ready for commercial application; probably very shortly; within a couple of years, probably. And, this uses what is known as counter rotating and ducted fan blades. These counter rotating and ducted fan blades produce a ultra high bypass, essentially ultra high bypass engine. Now, here what I am showing you here is unducted fan blades, indeed it could be ducted as well.

The counter rotating fan blades allow the fan blades to run at somewhat higher speeds. In the process, the size of the thrust producing fans could actually be reduced. And hence, you can even think of ducting them. And, as a result of the reduction of the size, the mechanical complexities and some of the mechanical issues are reduced. And, and a good design and a good aerodynamic configuration has allowed to reduce the noise substantially; so that, they are now compliant with the noise regulations that are in force all over the world. So, this kind of counter rotating unducted or ducted fan blades would produce ultra high bypass turbofan engines with a bypass ratio of the order of up to even fourteen.

And, these are… as you can see here, one fan is mounted on one set of turbine. And this fan, the counter rotating fan mounted on another set of turbines. And, these turbines, rotors are counter rotating. And, they are in a certain operational mode. And, the design actually excludes all usage of stators or stator nozzles as we know essentially, these set of turbines essentially do not use any stator nozzles. They are counter rotating rotors in meshed in each other. And hence, they are stator less configurations. So, this stator less turbine configurations would probably power the counter rotating unducted or ducted and blades for the future ultra high bypass turbofan engines.

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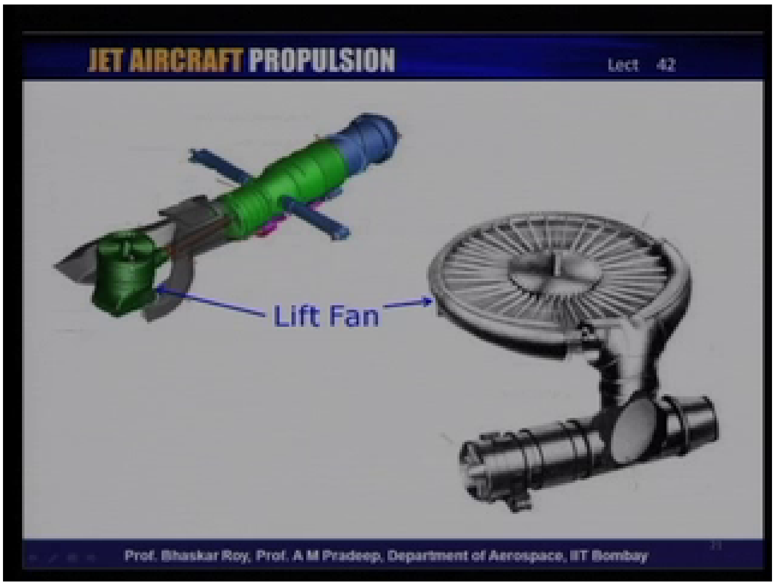

The other kind of engine that has been taking place for some time is also referred to as lift fan. And in this kind of lift fan, the lifting fan which you see here at the front of the engine can actually be tilted. So, some people even like to call it "tilt rotor". So, this provides direct lift for the lift of the aircraft allows the aircraft to have a vertical takeoff or short take off and landing, whereas this operates as a straight forward jet engine or turbofan engine providing lift for a forward thrust. Once, the aircraft is airborne and has been lifted off the ground, this lift fan can turn around by ninety degree and start providing forward thrust. So, the delivery from this lift fan would go indeed into the jet engine and provide forward thrust.

So, this lift fan is tiltable by ninety degree. So, in during takeoff and landing, it can operate to give direct lift to the aircraft; while flying, it actually provides direct forward thrust for flying of the aircraft, whereas the other picture that we see here is more of a use for vertical takeoff and landing, where the basic engine provides a mechanical power to rive this big lift fan which is embedded probably in the wing of the aircraft. And, this provides direct lift to the flight for the takeoff of the aircraft. And then, once it is taken off, this engine which you can see is much smaller; actually provides the forward motion or the forward thrust of the aircraft. So, this is more of a low speed aircraft configuration, where a small amount of forward thrust will move it forward, whereas the big lift fan provides the lifting ring meant for vertical takeoff and landing purpose.

So, these are some of the engines that have also been designed and even test flown, however they are not been commercially used for any aircraft so far. There are mechanical complexities; there are fuel efficiency complexities, which yet to be solved to satisfaction. And hence, even though they are considered to be successful engines, they have not yet been used in a big way in commercial flights in any kind of aircraft. But, some of the issues are likely to be resolved in years to come. And, we will probably some of see some of these lift fan also operation in various kinds of aircraft.

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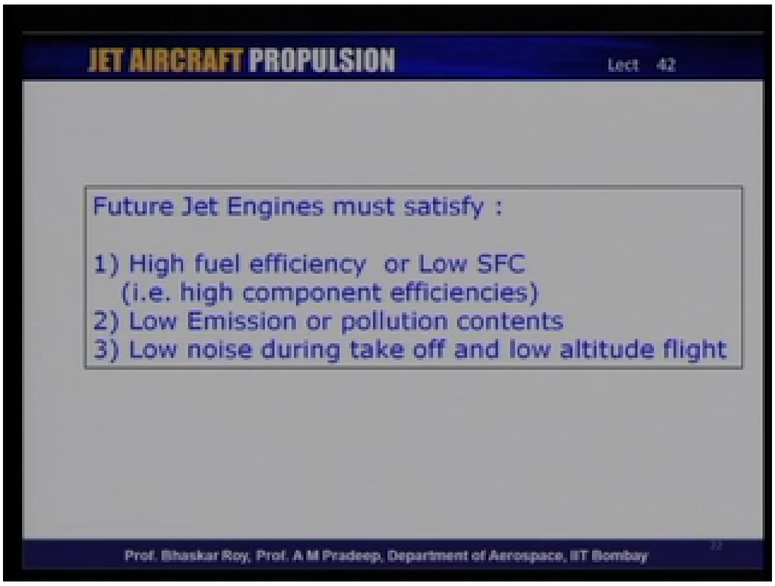

In future, for the aircraft to be successfully flown, we need to have three very important points in our mind. One, it must have very high fuel efficiency or low specific fuel consumption; which means that, every component of the engine that was the intake compressor combustion chamber turbine and nozzle, all of them should have very high efficiency of operation. That is absolutely necessary to have high fuel efficiency during all kinds of operation; not only during design point, but also during various kinds of design operating, critical operating conditions.

The other important point is the low emission or pollution content. The present regulations very clearly state that it must have lower and lower emission or pollution from the engines.

The third important point, of course is the noise. Engines have always been very noisy. The first jet engines were extremely noisy, but now the regulations very stringently stipulate that you have very low noise. So, many of the engines that have been created today are also being referred to as "green engines" because they are less pollutant and they are less noise making.

So, this "green engines" are now making the ground and more and more of the engines, we will see would be the "green engines"; make less pollution and less noise. So, that is the future that is holding out for us. And, we shall see some of these engines in new future flying around. And, I am sure some of you would be on those aircraft.

In this lecture series, we have tried to bring to you the very attractive and and very challenging field of jet engines, which has been powering aircraft for more than fifty years and taken mankind from low subsonic to hypersonic flights. I hope you have been able to enjoy some of the things, some of the theories and some of the discussions that we have had in this lecture series. And, I hope some of you would find it attractive enough to choose jet engines or aircraft jet engines as your career choice. We wish you all the luck and hope that you would find this course attractive enough to follow it up with more studies in your future career.