Jet Aircraft Propulsion

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Lecture No. # 40
Performance and Design of Ramjet and Scramjet Engines

We are talking about jet engines of a different kind. We have been talking about ramjets, pulsejets, and we will be talking about scramjets which is a variant of ramjets. Now, as we see the jet engines we are talking about now in the last few lectures a different from the kind of jet engine that we have been talking about earlier in this lecture series. The present jet engine that we are talking about the ramjets, the pulsejets, and the scramjets in terms of mechanical configuration are very simple kinds of jet engines. Now, these simple jet engines do have some complication or certain issues that need to be looked at very closely both during the process of design as well as during the process of their performance prediction.

Now, we have done in the last a couple of lectures, you have done the analysis, the thermodynamic analysis, how they perform, and they are component analysis in some detail. So, you have some idea now how the jet engine functions - the ramjets, the pulsejets, and the scramjets, how they function what their cycle analysis are… And the various components of these jet engines; how they are put together into one single operating unit. Today, we will look at the performance of ramjets in some detail, and then we will go on to look at how these ramjets are put together as a design entity, in fact, how they are design. And what do you do to actually design the various components of the ramjet engine, what are the fundamental theory or functions that you may like to make use of to design such ramjet engines.

So, that is what we will be doing today. we will look at we will start from where you have been in the last couple of lectures, in terms of cycle analysis will start from there which I at this moment I would believe you know very well, and so we will start from what you know, and then move on to a few things. And then finally do what needs to be done to design such ramjet engines from simple principles, without getting into complicated issues like using a big C f d code or something. So, without getting into those issues we will use the fundamental theories that you are already aware of, and how to use those theories to essentially design a ramjet engine. So let us take a look at what the fundamental issues are, and how we can go about calculating the performance of a ramjet engine.

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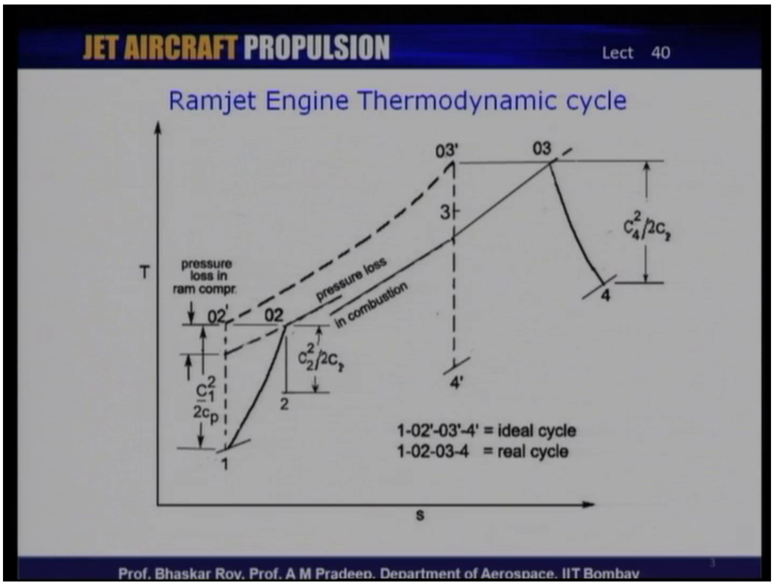

Now, you are aware of the fact that the ramjet engine goes through a thermodynamic cycle. Now, this cycle is something you are familiar by now and you are aware that in the process of intake, it incurs certain amount of really a large amount of pressure loss in the process of intake, which we call ram compression and after the ram compression, which is the only kind of compression it actually undergoes the combustion is initiated and there is a certain amount of pressure loss through the combustion process and then finally, the combusted product the air and the gas mixture is finally let out through a jet pipe and into the nozzle for a creation of the exhaust jet, which finally aircraft creates the thrust.

It starts off with a velocity field which is let us say C 1 square to begin with and then inside the combustion chamber. It has a somewhat lower velocity field which is of the order of C 2 from there heat is added so the temperature goes up from 0 2 to 0 3 that is amount of heat that is added in the combustion chamber and in the process certain amount of pressure is lost so it loses the pressure line 0 2 to and settles down to a pressure line 0 3 by the time the combustion is over and then from there, the gas is let out through the nozzle which is normally convergent divergent nozzle and it finally goes out with a velocity of the order of C 4.

Now, here again you see the ideal cycle and you see the real cycle the ideal cycle is given in dotted lines and the real cycle is given in the solid lines. As, you are aware that the areas subtended by this cycle diagram. Essentially, represents the work done by the cycle, so one can see here that the dotted line, which creates the ideal cycle the work done, would be somewhat less than the area created by the solid line. As a result of, which it stands to reason that the amount of heat energy that one needs to burn to do certain amount of work would be more in a real cycle than in a ideal cycle. So, we will take up from there the cycle analysis, which you have done in some detail in the earlier lecture and look at what needs to be done with this knowledge to estimate a performance of a typical ramjet engine.

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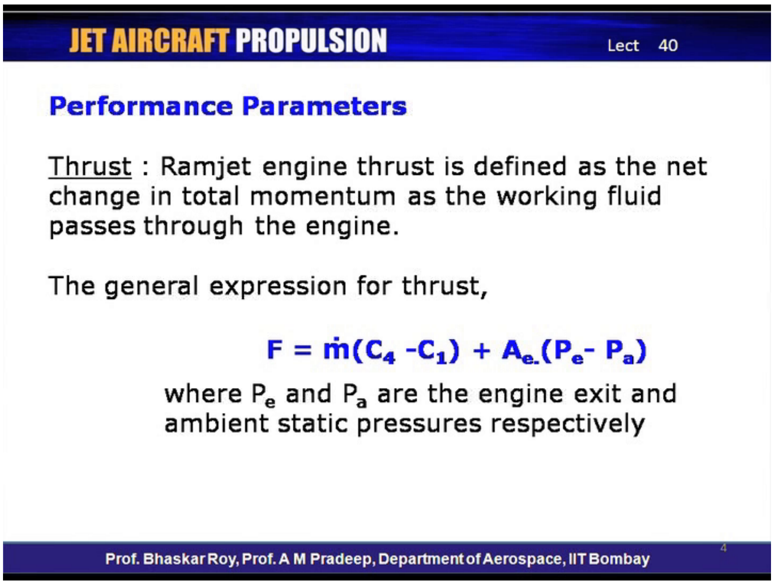

We look at the performance parameters again; I believe you are familiar with the performance parameters that we are talking about the simple performance parameters are essentially defined as thrust specific thrust and the fuel efficiency. We will look at the thrust first: The thrust of any jet engine, as you know is essentially the change of momentum that happens as the working medium that is air enters the engine and then passes through the engine and in the first process of passing through the engine. It acquires a higher momentum and this momentum change is the major contributed to the thrust making. So the thrust here is given in terms of the expression here. Now, this expression essentially gives you the thrust; the second term is the pressure thrust, which again you are familiar with because of the residual pressure at the exit phase.

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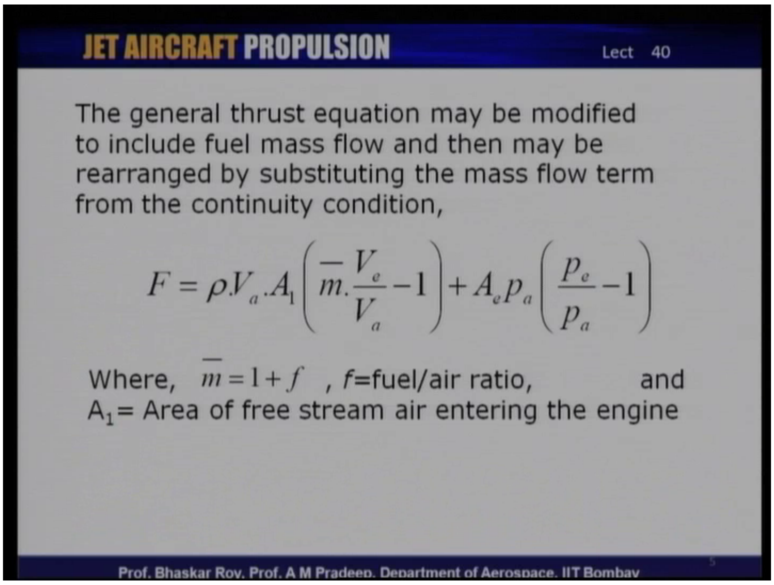

Now, this thrust then can be converted to a more encompassing thrust equation in which the mass flow, there is now substituted by row V a, A 1 which are the density, the incoming velocity and the area at the entry of the intake which is metering the mass flow coming into the engine. So the mass flow term, here is substituted from the continued equation by row V a and then you have the correction factor m bar which is one plus f, f being the fuel air ratio and that enters the equation here as a correction. In the earlier simple equation that was not taken into account and the second term is the area into the pressure thrust.

Now, this pressure thrust is a residual pressure, which is carried at the exit of the engine. If the residual pressure is zero that means the exit pressure is same as the ambient pressure, there would be no pressure thrust entire thrust would be created by the momentum thrust. So, if you look at this equation there are number of parameters here, which contribute to the thrust making one is first is the mass flow; which is coming through the engine and higher the mass flow higher is the thrust making capability of the engine and then the next is the ratio of V exit to V a. Now, it stands to a reason from this equation very clearly that higher is this ratio higher would be the thrust making capacity of the engine.

So, one of the aims of the design would be to enhance this ratio V e by V a to as high a value as possible for maximization of the thrust making. m bar, which is one plus f means that you increase the fuel air ratio. You get more thrust, which simply means your mass flow enhancement is happening; however more the fuel pumped into the engine more is the fuel consumption and hence you are essentially fuel efficiency would be going down. So, which is not quite the right thing that everybody would like to do for a short time that may be the only way to get more thrust, but that may not be the best way of increasing thrust, because you carry the fuel with you in the aircraft and if you have to pump in more fuel the amount of fuel, which would be used up in a shorter period and hence the range of the aircraft would be much lower.

So that is a parameter that one needs to be very cautious about before you decide to increase that parameter m bar. Area of the free stream air that is entering the engine is another parameter that is increasing the area of the intake. Now, the question is if you increase the area of the intake the dimension of the engine is now going up; now if the dimension of the engine is going up you remember the engine needs to be connected to an aircraft the aircraft would have a drag and typically ramjets, scramjet, pulsejet powered engines fly at very high Mach numbers at that high Mach number, if your engine size in terms of diameter is higher the engine related the power plant related drag would go up and that could be additive to the aircraft drag.

Now, this is a prohibitive proposition in the sense higher the drag more would be the thrust required and hence you reach a position very quickly, where you reach a position of diminishing return. That means; if you increase the size of the intake to take in more mass flow to get more thrust you are also creating more drag so after a certain while one can see very clearly that if you increase the dimension of the intake, the net thrust creation that is the thrust minus the drag that is being created would becomes zero and in which case there would be no point increasing the dimension of the ramjet engine anymore. Hence, one needs to hold the diameter within the certain prescribed value and beyond that it would be a losing proposition it would not be a profitable proposition to increase the size of the intake area anymore.

So that is in area which you need to be very cautious about and only after a certain amount of optimization you can arrive at that area, which gives you good thrust without actually enhancing the drag component of the aircraft anymore. So, as we see here we have a number of parameters we have the basic mass flow; we have the velocity ratio through the engine and of course, the residual pressure multiplied by the area exhaust area. So some of these things need to be looked at very cautiously the exhaust area is normally used to meter the flow for most ramjets and scramjets and pulsejets that we see the exhaust nozzle area; the exhaust area really speaking at the exhaust phase is a fix geometry.

Unlike in the other jet engine that we have done where the exhaust area is often variable so most of the aircraft jet engines the turbojets the turbo fans do have a variable geometry nozzle but, ramjets and scramjets have fix geometry nozzle. So the area at the exhaust is often a fixed area a e is often a fixed area not a variable area so that is another thing we need to optimize in the process of design that not only the intake area the exhaust area also needs to be optimized to the best value because both the areas are fix geometry they are not variable geometry.

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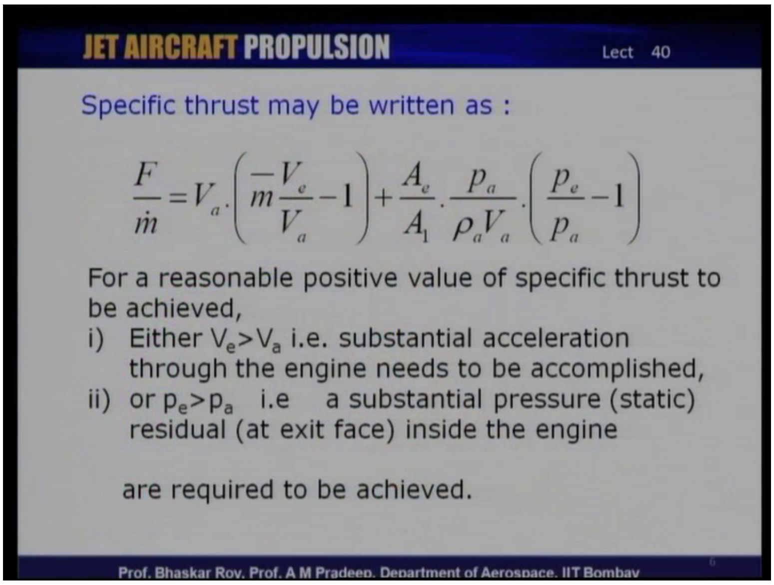

So let us look at: the other parameters that we would need to consider in calculating the performance of the ramjet engine. If you look at: the specific thrust now, which was a derivative of the thrust really, it tells us that for a reasonable positive value or specific thrust to be achieved. Either V e by V a is to be very high that is substantial acceleration needs to be done through the a jet engine or the residual pressure needs to be substantially high at the exit phase, so p e has to be substantially higher than p a inside the engine just at the exhaust phase.

Now, these two are requirements now one of the reasons is the thrust or the specific thrust that we are looking at actually requires to be made as high as possible because the drag component of the aircraft which I was talking about just a little earlier is very high at the

Mach number at which these aircraft fly. So because of the very high drag component unless one creates substantial thrust; the net thrust that is created by the aircraft engine combine is not going to be substantial for the craft to fly. Now, this is a problem typical of ramjets and more screw through more true for scramjets, where creating a positive negative thrust is often the first problem, because under certain operating conditions of the craft in flight. The net thrust could indeed, become negative and wit in which case the craft would not fly at all.

So creating a positive thrust for ramjets and scramjets is actually a fairly challenging proposition in view of the fact that the drag of these crafts is often of a very high order and you remember ramjets scramjets that we are talking about we are talking about engines that do not have compressors and turbines. Now, compressors typically help us create very high pressure ratios through the engine in ramjets and scramjets. We do not have compressors; we have only ram compression. As a result of, which creating a very high thrust becomes a challenging proposition through this kind of engines.

On one hand these are very simple engines without the complications of compressor or turbines; on the other hand it poses a challenge how to create a good positive thrust without the help of compressors. This is something which the ramjet engine designer would have to content with at the time of design and performance prediction. So you remember that you need a substantial acceleration through the engine for creating positive net thrust of the whole craft now this is something you have to remember and we will be getting into the design a little while later.

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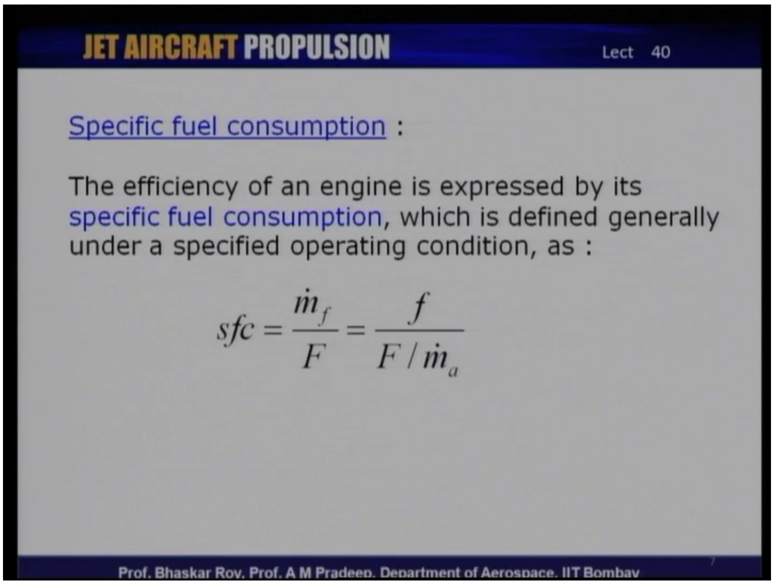

The other parameter that you would like to take a look at: is the specific fuel consumption which is of course, the figure of merit as far as the fuel efficiency of the engine is concerned. This is being over the entire lecture series, it has been defined as thermal mass flow m dot f divided by the thrust or the fuel air ratio small f divided by the specific thrust F by m dot a. Now, this is the definition which we have always used for specific fuel consumption of all kinds of jet engine and that definition still holds even for ramjet engine in so far as it is still a jet engine. Now, we see here that we need to have a good specific thrust, so that the amount of fuel carried in the aircraft is moderately used by the engine that the craft has a certain reasonable or respectable amount of range. If the specific fuel consumption is too high it will use up all the fuel very quickly and the range of the craft would be a rather a small.

So to have a reasonable range of the craft that is carrying the ramjet engine, it is necessary that specific fuel consumption be as low as possible. In view of the fact that this kind of engine do not have a compressors the cycle efficiency of these engines would invariably be some ought on the lower side, because as you remember from your cycle analysis the cycle efficiency is greatly connected to the pressure ratio of the cycle and in this kind of engines the effective pressure ratio is somewhat lower than what you can build up in a turbojet engine or turbo fan engine with the help of compressors.

As a result, the cycle efficiency of these kinds of ramjet engines is somewhat on the lower side and as a result of which the specific fuel consumption is bound to be somewhat on the higher side compared to the values that you may have come across in terms of jet engines or turbo jet engines or turbo fan engines. So keeping that in mind we have to ensure that the specific fuel consumption is held as low as possible by design so that the craft can fly over a longer distance for whatever mission it has to accomplish.

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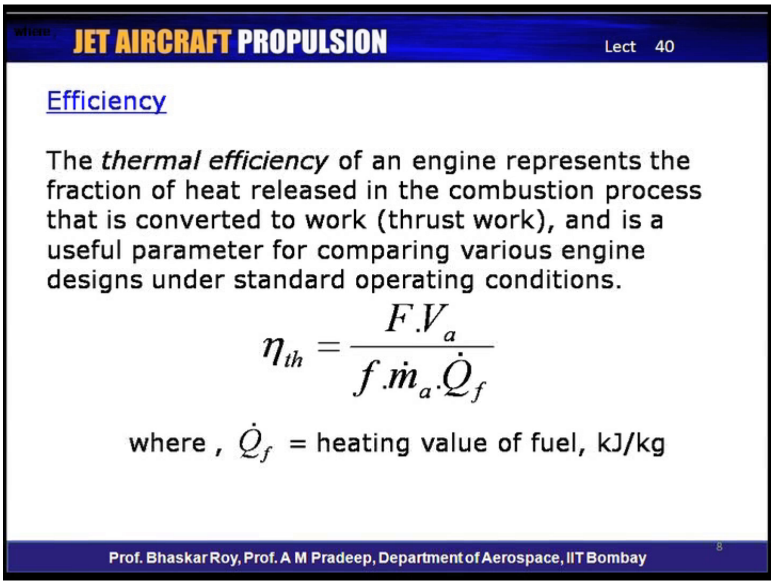

The other last parameter that you really need to look at is the thermal efficiency of the engine. This is typically a designer's parameter and it is a very useful parameter for comparison of various kinds of engines under given or a standard operating condition. Now, this is normally defined as the thrust work that is in the numerator and the in the denominator, you have the fuel energy that is burnt into the gas. So, the fuel energy that is contributed into the combustion chamber is compared to the thrust work that is done. This is a normally defined as the thermal efficiency of the engine that means how much of the energy that is put into the engine is finally, available as useful work which is thrust.

This is as I said is a typical designers parameter and it tell us in a comparative manner how good this engine is compared to some other kind of engine or some other engine in under similar operating conditions.

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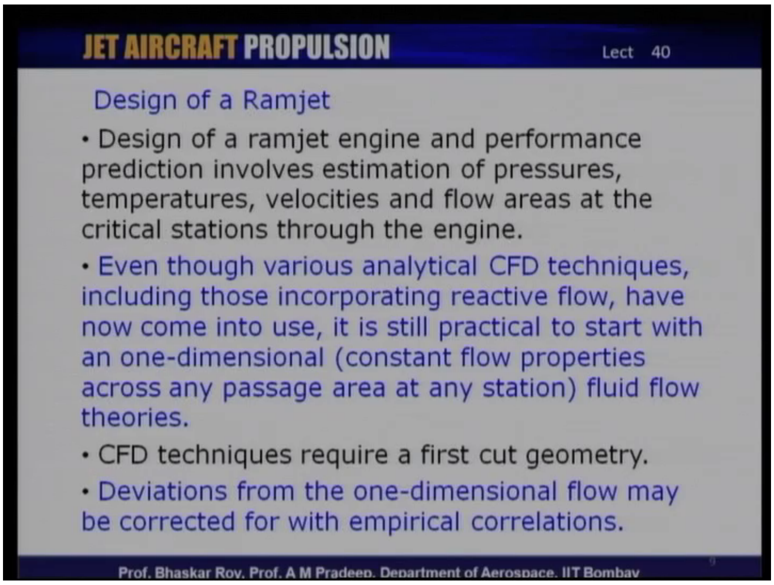

Now, what we can do is given the definition of these parameters, which are the figures of merit of a typical ramjet engine. we can now look at how these parameters can be utilized or kept in focus in the process of design of a ramjet engine. Now, design of a ramjet engine, essentially involves quick prediction of these performance parameters or the figures of merit of the particular engine under consideration and secondly finding out the various aero thermodynamic parameters through the engine. As, you can see we do not have complicated machines like compressors and turbines, the design essentially involves finding out the pressure, temperature and velocity of the fluid that is flowing through the engine from one end to another. At various stations finding out the area the local area; the area with which the flow is coming into the intake then through the intake various area changes would take place, because the diffusion needs to be ensured.

At the end of the diffusion, you have a combustion chamber again there we need to know what the area of the combustion chamber should be; what the combustion volume should be and once the combustion is effected you have a gas; hot gas, this hot gas now needs to be released through a nozzle so the entire process of carrying it from the combustion chamber through a pipe; jet pipe and then on to the nozzle which is normally convergent divergent nozzle. So, the area of the flow at every station needs to be calculated very diligently and very accurately and this accurate calculation of these areas including the local pressure, temperature and velocity gives us a full aero thermodynamic parametric numbers that allow us to finally, configure the size and shape of the ramjet engine.

So, basically the design of a ramjet engine involves calculating these aero thermodynamic parameters had various stations from the intake to the exhaust phase from the intake phase to the exhaust phase carrying all the air and then the gas through the engine and finally, exhausting it. This is what, we will be doing in the process of discussing; how to design a ramjet engine, so the design of a ramjet engine is essentially involves estimation of pressure, temperature, velocity and flow areas at the critical stations through the engine the number of such critical stations could be 5 or 8 or 10 depending on the size of the engine. At, all these station they need to be estimated with great accuracy. Those areas will tell us, where the flows are in a diverging dot; where they are in a converging dot and what needs to be done to create those shapes and sizes.

Now, even though this estimation can be done. Now-a-days through various analytical CFD techniques including some of the recent CFD techniques, which actually incorporate reactive flows; which is going on in a combustion chamber. When you do not have a an engine; when you do not know we do not even have a first cut engine you do not have a geometry at all you are still in the process of creating a first cut geometry you cannot use these CFD techniques, because they need a geometry; they need the boundaries of the geometry so that proper boundary conditions can be applied.

So, without geometry you cannot use these techniques; a modern techniques so you need to create a first cut geometry of the ram jet engine after, which you can use the modern technique so today we will discuss how to create a first cut geometry of a ramjet engine. Now, this is normally done with the help of a very simple one dimensional fluid flow theory, which we have done before in great detail and this assumes that the flow properties at a particular station; at a particular area is held constant across that area that means the properties. We are talking about the pressure, temperature, velocity is assumed to be constant across a particular area at any station.

And with this assumption a one-dimensional fluid growth theory may be used to configure a first cut ramjet geometry and size. It more detail analysis can be done later on with the help of modern techniques. The deviation from one-dimensional flow may be corrected with if there are corrections that need to be applied with the help of a certain empirical correlations which are often available, essentially for correction of certain flow properties that may need to be applied correction too. Now, one of the things we need to understand is that typically in a ramjet and also that was to in a turbojet engine also, but typically in a ramjet engine what happens is the flow undergoes very fast change in its properties in a matter of 1 or 2 meters the temperature and the pressure across the ramjet engine may suddenly change very drastically.

The temperature may change by almost 1500 degrees over just one or one and half meters in a ramjet engine. Now, in a in a turbojet engine you remember the combustion chamber is separated from the intake by the compressor, which is a huge mechanical body that comes in the middle of the, in between the combustion chamber and the intake similarly, a huge mechanical body of the ramjet turbine comes in between the combustion chamber and the exhaust nozzle. So, these mechanical bodies of compressor and turbine effectively isolate the intake from the combustion chamber and they then again the combustion chamber from the nozzle.

In a ramjet there is no such buffer, the intake and the combustion chamber are essentially fluid mechanically very much connected to each other and the combustion chamber and the turbine are also fluid mechanically connected to each other very easily, because there is only a duct in between them. In this duct there is a very fast change in the fluid properties of pressure and temperature the pressure temperature in the intake, there is a very high ram compression and if the ram compression is very high the change in pressure is very high along with that there is change of temperature and then at the end of the duct you have the combustion.

There is a very high temperature rise there, so as a result the temperature rises by 1500 to 2000 degrees in a matter of one or two one and half meters and then the nozzle flow starts and there the pressure and the temperature again starts falling very fast in a matter of half a meter or one meter. So there is a very fast change in pressure, temperature and velocity through the ramjet engine and as a result of it the composition of the area of the of the air that, we are talking about the gas; that we are talking about and its properties the properties in terms of c p and gamma the specific ratio they are all as you remember dependent on the local temperature.

If the local temperature profile is constant, in a particular area then we can assume the assumption we made just a little while earlier that the pressure, temperature values are constant over a particular area if the pressure, temperatures are not constant at a particular area, the values of c p and gamma would be variable across a particular area they would not be constant in that area. As a result those variations would need to be factored into the estimation of the ramjet engine performance calculations and the property calculation that we are doing and those accuracy would then be would need to be factored into the design of the areas; final estimation of the areas and final shape of the ramjet engine components.

So some of these accuracies are what we will be talking about just a little while from now, because these are the accuracies which will finally, decide what the shape and the size of the jet engine would be.

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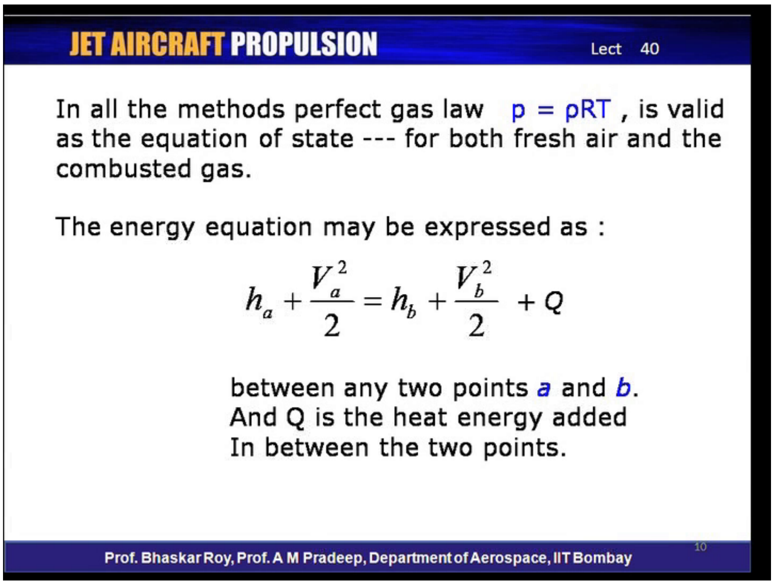

So let us look at how these accuracies can be brought into the estimation of ramjet engine parameters. One of the things that we would be using is the perfect gas flow, which is equal to p R T as all of you are aware of, and of course the energy equation which again you are aware of is the energy equation that holds from a say one at one station a to another station b. So, the energy equation is h a which is the static enthalpy plus the kinetic energy head that is V s square by 2 that would be equal to h b plus V b square at station b, where V b square by 2, and this is in consumption with the heat that is been released, and this heat release is to be brought into the focus when the energy equation is also being considered. So the heat release may be positive or negative depending on available the heat has been taken in or given out, so this is generalized equation.

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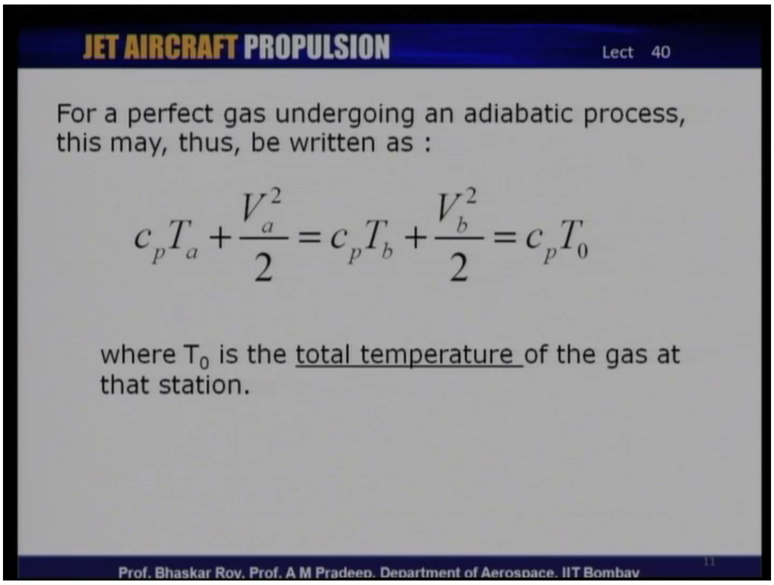

So, we have two equations: the perfect gas flow and the energy equation. Now, let us see: what else can be done, when you consider these equations and apply the perfect gas low undergoing an adiabatic process. It may be written in terms of the two energy levels at two different places, if they are in front of the a combustion chamber both a and b the energy would be constant the total energy would be constant from a to b. So, in front of the combustion chamber you may say that the total energy is c p into T 0 and this T 0 is the total temperature of the gas at that station. Now, after the combustion chamber again, if you have two stations a and b, Q would be part of that the heat release will be part of the energy, which is carried and that would again be constant from in area a to another station b and again T 0 would be total temperature would be held constant. So, there is one value of total temperature before the combustion and there would be another value of total temperature after the combustion.

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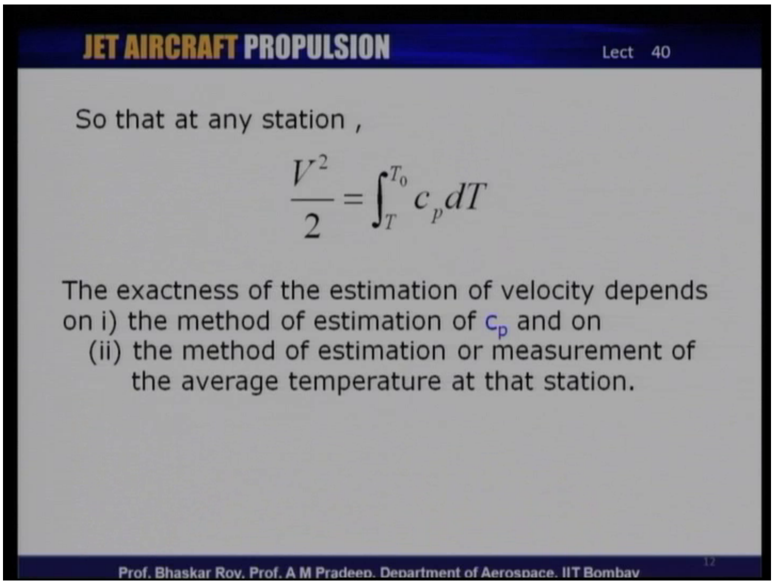

Hence, using this one can say that at any station the velocity V a, which we would like to have V square can be written in terms of the integral c p d T and the exactness of the estimation of velocity. Essentially, now depends on the method of estimation of c p and on the method of estimation or measurement of the average temperature at that station. Estimation of the temperature at the station before the combustion is quite often rather the easier thing to do but, after the combustion after the combustion process the kinetic reaction that is taken place estimation of the temperature is often a little more difficult and measurement of the temperature there is a far more difficult because of the extremely high temperature that exists over there.

So, quite often one needs to resort to certain estimation method through the process of reaction kinetics, which is not the focus of our lecture series here, but it is necessary that we have a reasonable method of estimation of a c p a local value of c p. As, we see now the c p would change from one station to another throughout the engine and quite often very fast and because it depends on the local temperature and we need to know what the local temperature is as we see now that this local temperature at any given station over the area at that particular station may also vary now that is something that will bring in far more complication.

We have a certain situation: in which we need to be very clear about what are the gas properties that we are calculating because we see now that the gas properties are very closely connected to the local temperature and the variation of the local temperature is very fast through the ramjet engine and at a particular station. It may vary along the area of the circumferential area of the local station depending on where it is and this variation brings in certain level of complication of estimation and we would like to have a look at: how this complication can be adjust in a somewhat simple manner to begin with without getting into more involved process of analytical process of CFD s.

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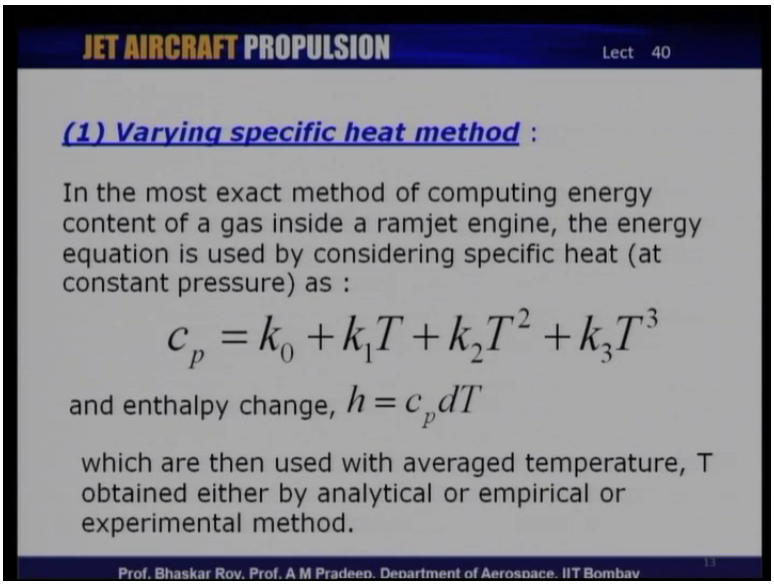

So let us take a look at: what all methods that can be adapted to estimate these parameters. The first method that is normally adapted is simply called the varying variable specific heat method or varying specific heat method, in which the specific heat of the gas and before the combustion it is simply air is to be calculated in a more rigorous manner, which means the c p can be now written down in terms of k naught plus k 1 T plus k 2 T square plus k 3 T cube. Now, this is the series that one can use or one normally rigorously is used in reaction kinetics or in reaction thermodynamics normally we know that c p is dependent on the local temperature.

This is how the dependence is rigorously expressed quite often for very simplistic reason we take only the first term k 0 and consider that as the value of c p for all simple practical purposes if one needs to be rigorous one needs to consider the more terms as many as your computational power allows you to so that you can compute the value of c p in more accurate manner. There is also question of the temperature what is the value of temperature that you are using and this temperature needs to be assessed very accurately, whether you measure it or find out through other thermodynamic or reaction kinetics that means whether the process is analytical or empirical or experimental needs to be decided because finding out the local temperature would impact on the value of local c p.

So, calculation of c p and calculation of local temperature is one of the things that may need to be done as rigorously as possible and if you can do that rigorously and then plug in those rigorous values into your c p calculation then you have a definitely a more exact knowledge of what is the variation of the properties of the gas going through the ramjet engine and then your area calculation there of the size calculation of the various locations would be more exact and when you have those exact values you have more final version of the ramjet configuration till such time as that your configuration would remain, somewhat in exact or approximate then this exact geometry of the ramjet can be now subject to rigorous CFD analysis which would finally, give you the certain more accurate estimation of what is happening inside the ramjet engine.

So this is the more rigorous method by which you can indeed calculate the various flow parameters through the ramjet engine let us look at some of the more approximate methods by which one can start off with.

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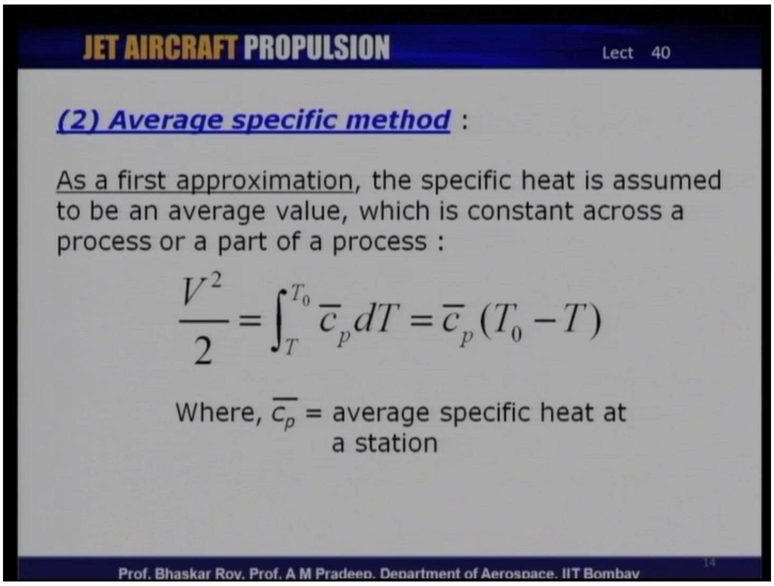

One can make an assumption that as a first approximation the specific heat is assumed to be an average value and which is constant across a process or a part of a process, in which case we say that this is c p bar and this is an average specific heat at a given station. If we use this to calculate the value of c p and use that value of c p for calculating the velocity the local velocity we get a reasonable first approximation of the local velocity and then that local velocity allows us to compute the local area at that particular station. If you calculate many of these local areas we have a first cut ramjet area variation through the ramjet the internal area variation through the ramjet and a first cut ramjet configuration. So this is the simpler method by which a c p bar an average specific heat at a given station can be quickly arrived at to calculate an area.

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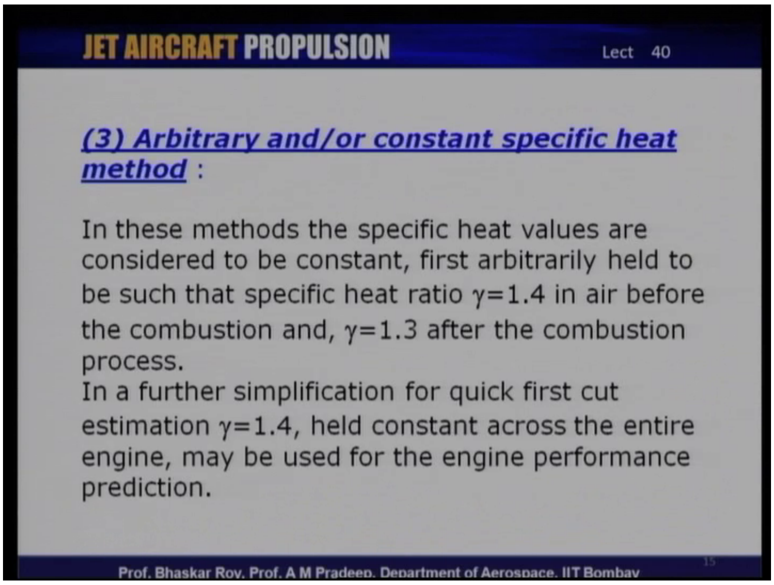

An even more approximate method which is can be used with the simple calculator is to use arbitrary or constant specific heat method which presumably you have used before in your other turbojet engine calculations in which it is held that the specific heat ratio is 1.4 for the air before the combustion and 1.3 after the combustion process. Now, this is something which is suppose you may have done in your turbojet and turbo fan calculations. If you use that over here you do get a first cut ramjet configuration this is gross simplification because as I mentioned to you earlier that in the ramjet engine the properties actually would indeed would be changing very fast in a matter of half a meter or one meter of the length of the ramjet engine. Hence, this is a very simplistic very quick method of estimating the various flow properties and hence the area of variation through the ramjet engine.

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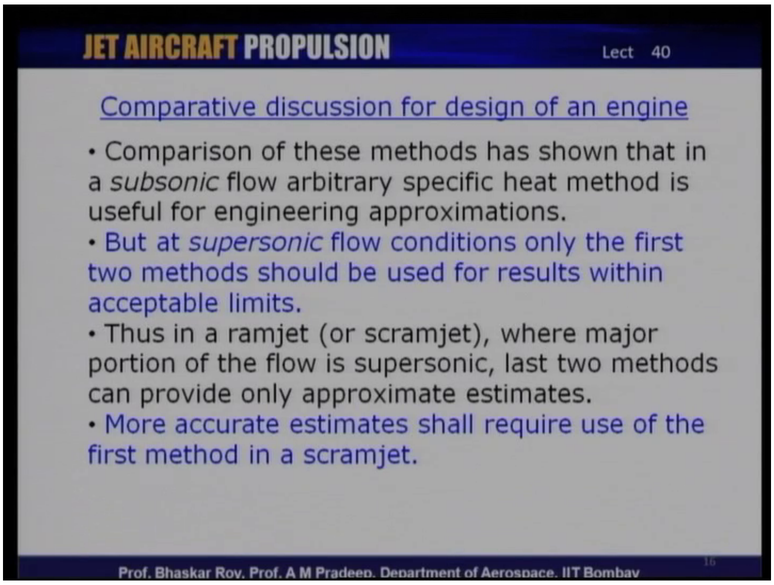

Now this three these three methods as we can see it: we can have a comparison of these methods and the comparison tells us that when you are having a subsonic flow, the first cut method the arbitrary specific heat method is and its useful for a good engineering approximation of what the ramjet engine configuration should be. However if the ramjet is actually flying or performing under supersonic flow entry flow conditions then the third method that we have talked about would be very gross simplification and a should not be really adapted one need the first cut method there should be the second method and a more rigorous method would need to be applied as quickly as possible as soon as a first cut geometry is available at hand.

In a modern ramjet and definitely in a scramjet the major part of the flow is indeed supersonic and in this supersonic flow one needs to really adapt the rigorous method, which was enumerated in the first method and as a result of which the third method should not be thought about at all one may use a very quick estimation through the second method and then quickly go on to the first method to estimate the flow properties to the ramjet. In a scramjet strictly speaking one should be using only the first method, because the flow is supersonic the change in flow properties both due to the supersonic flow due to the presence of the shocks and later on due to the combustion process the change of flow properties is extremely fast.

This fast change of flow properties can be captured only if you have more rigorous methods of estimation of c p and the local temperature unless the local c p and the local temperature are estimated very accurately, right from the beginning one would get somewhat ironies notion of what the ramjet engine sizes or shapes are. So instead of starting with such ironies notion it is much better and definitely recommended that one starts with more rigorous methods as far as the ram scramjets are concerned.

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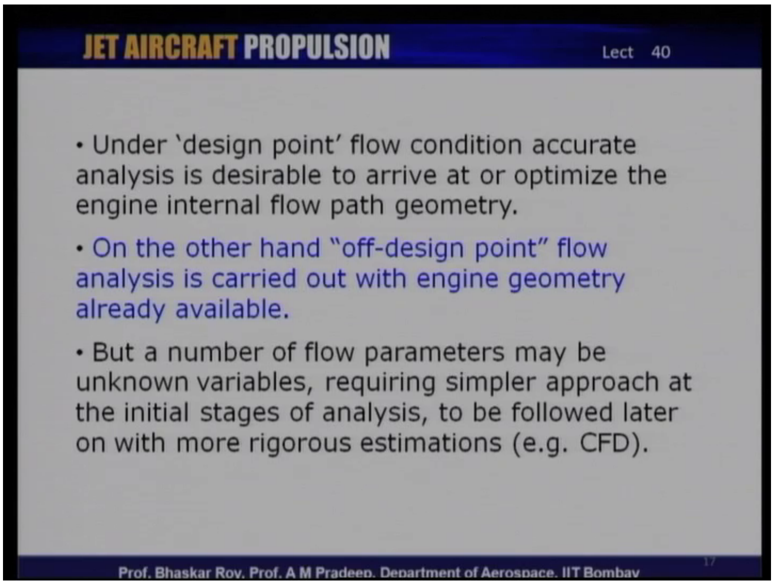

Now, as we talked about in most of the design of our discussion of turbojets and turbofans all engines have what is known as a design point and the cycle that you create is for this design point. So, you have a design point flow condition at which the engine geometry is to be design. So, the all the areas that we are talking about has to be designed in at a particular design point and this design point has to be fixed a priory under a particular flying condition and this is what the ramjet engine designer also needs to do first. He needs to figure out what the design point is and at this design point accurate analysis is desirable to arrive at or optimize the engine internal flow path. It is a flow path geometry that we are talking about what happens is under other off design flow conditions.

When the analysis is carried out it is possible that you may like to make small changes in the flow path geometry. This is a process of optimization between design and off design flow condition and this optimization process is normally done by most of the designers in the modern design process. As a result of, which once the design is over a more detailed off design analysis is often carried out and an optimization between the design point and the off design various points finally, we reach the internal flow path geometry which is the design of the geometry of the ramjet engine.

In the process here, we see that there are number of flow parameters which are unknown variables we do not know number of things to begin with we do not have to begin with we do not have the geometry we do not have the local temperatures available with accuracy and as a result quite often it is necessary that you may have to start with a simpler approach and then later on follow it with a more rigorous estimation and then follow it up with CFD. One needs to understand that under certain conditions the CFD is not necessarily the most accurate method because when the flow is in a separated flow or a flow is specially behind the flame holder of a combustion chamber and then you have reaction going on so combination of a separated flow and the reactive flow is often a challenging proposition.

So, the CFD needs to be used the best possible CFD needs to be used and needs to be used with knowledge and with certain amount of caution that you may have to still look at it in other methods so that and you may have to finally, do the rig testing to find out what is finally, been designed in. So the design process is often quite lengthy and often goes through various stages from design point estimation to off design analysis to more rigorous estimation through analytical methods and through CFD methods. So, that is the process by which finally, the design has to be taken through to arrive at a optimized ramjet configuration.

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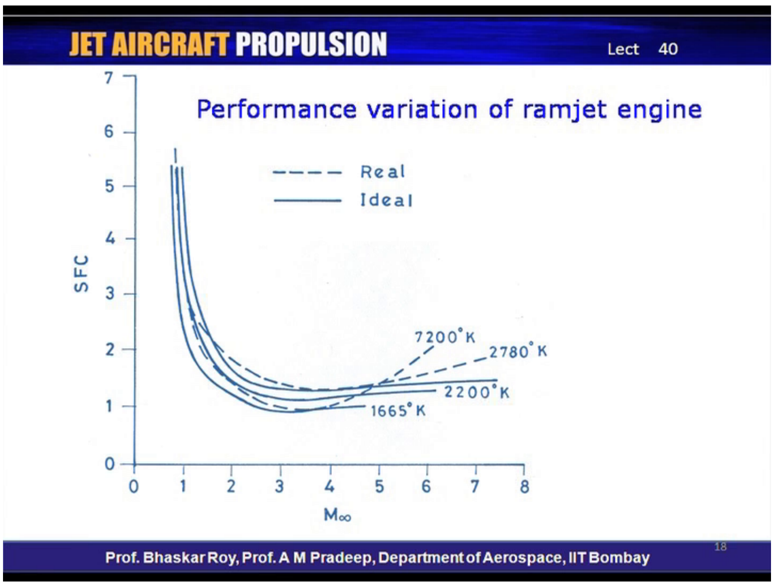

If we look at: what sort of performance typically a ramjet engine would be involved we can see that the S F C of a ramjet is typically varying with the Mach number and if the Mach number increases the S F C starts falling so typically a ramjet is actually a better engine at high Mach numbers above Mach 3 is specifically it is also me what dependent on the temperature that is being used after the combustion and if this temperature is kept high the specific fuel consumption is going to be higher, because you are asking for more performance. If you can hold the temperature little lower you get a better specific or lower specific fuel consumption, so these are some of the parameters that you may like to keep an eye on.

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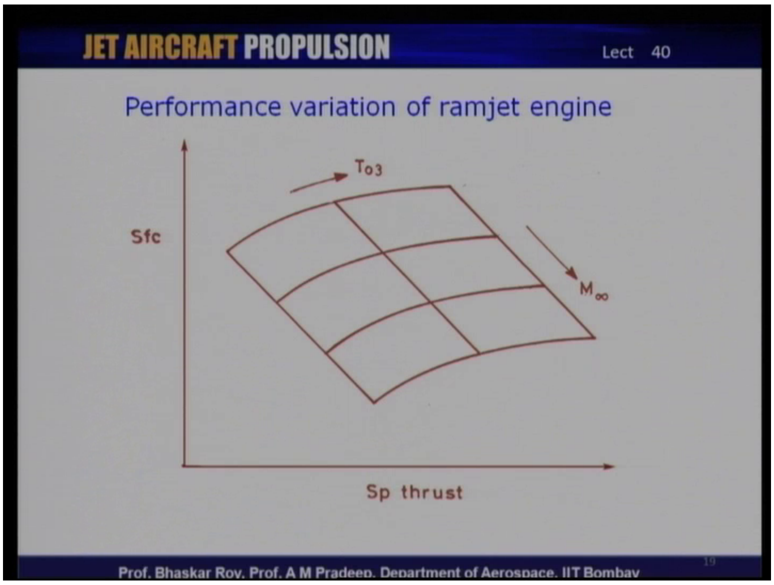

The other performance parameter is typically the performance map which involves the S F C and the specific thrust with the temperature variation and the Mach number variation and as you can see as the temperature the combustion temperature is increasing the specific thrust increases at the expense of specific fuel consumption. When the Mach number increases the specific thrust increases, but the specific fuel consumption also improves. So, the increase of specific thrust and decrease of specific fuel consumption needs that you increase the temperature to get more specific thrust and then you increase or operate at higher Mach number to get better specific fuel consumption.

So, if all of them are controlled in a proper manner right at the time of design you can get a ramjet engine would very good specific thrust at reasonable specific fuel consumption and this is what the designer would need to achieve through the design process.

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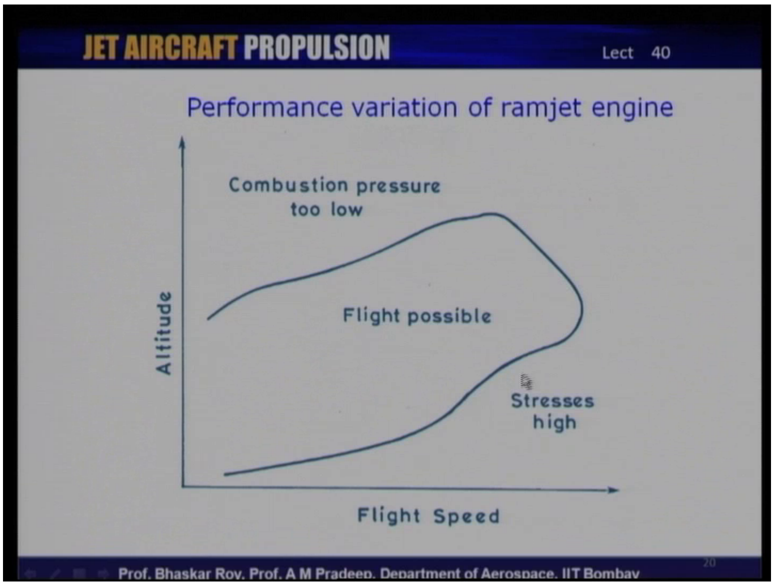

If you look at the performance variation of a ramjet engine with reference to the aircraft, you can see that the aircraft has a certain flight profile and in this flight profile the ramjet engine would indeed be useful within this loop and outside this loop one the combustion pressure would be too low and the other that means the combustion process would not be good. In the other case the stresses would be too high at very high fly speeds. It will almost behave like a pressure vessel and a hence flight would not be advocated.

So, flight is possible within a certain flight loop given the ramjet engine flight profile, so these are the limitations within which the ramjet engine would need to be configured. If we now look at a typical ramjet engine that may be design; we see that it has a number of parts it has an intake quite often it may have an isolator then it has a combustion chamber and then it has a nozzle. So, let us take a look at: a typical ramjet engine that has been design using the kind of theory that we have been talking about and also using some of the more rigorous analytical CFD method that we have also mentioned in our lecture today.

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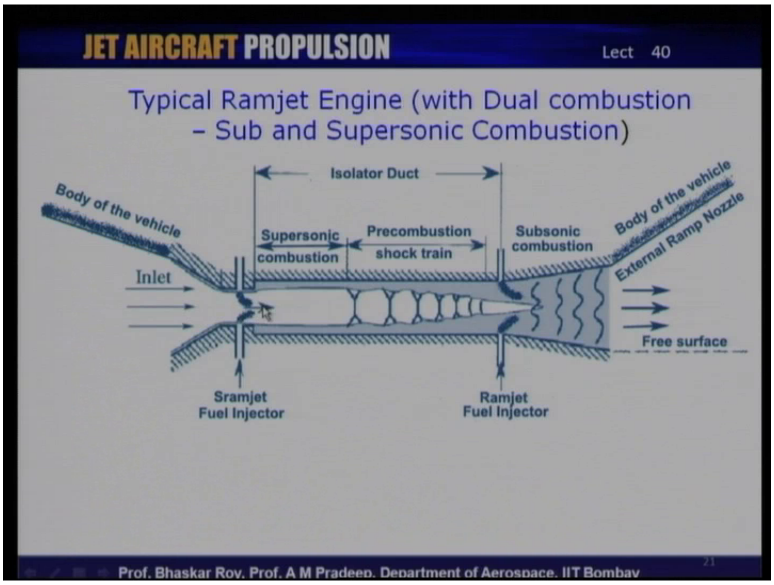

So let us take a look at a very typical ramjet engine as you can see here it has an inlet and then it goes through a process of supersonic diffusion and then the flow may be still supersonic in which case one of the methods is you go for a duel combustion, in which to begin with you have supersonic combustion and then the flow undergoes further shock related diffusion and it diffuses to subsonic value and then it goes through a subsonic combustion and then the flow is released through the nozzle into the exhaust jet ,which is likely to begin supersonic.

So, in this particular ramjet engine design what the designers have done is they have created two rounds of combustion: one in which the combustion is held supersonically at low supersonic Mach number and then later on the combustion is again held in a subsonic flow condition after the flow has been made subsonic through a series of shocks, which is called often shock train and after that the flow is exhausted through the nozzle. So, this is a typical kind of a ramjet which some of the modern designers are looking at it is also called the duel combustion a ramjet and this kind of ramjet provides more thrust and allows the flow to fly at a high Mach number like Mach 5 or Mach 6, where you can have a duel combustion.

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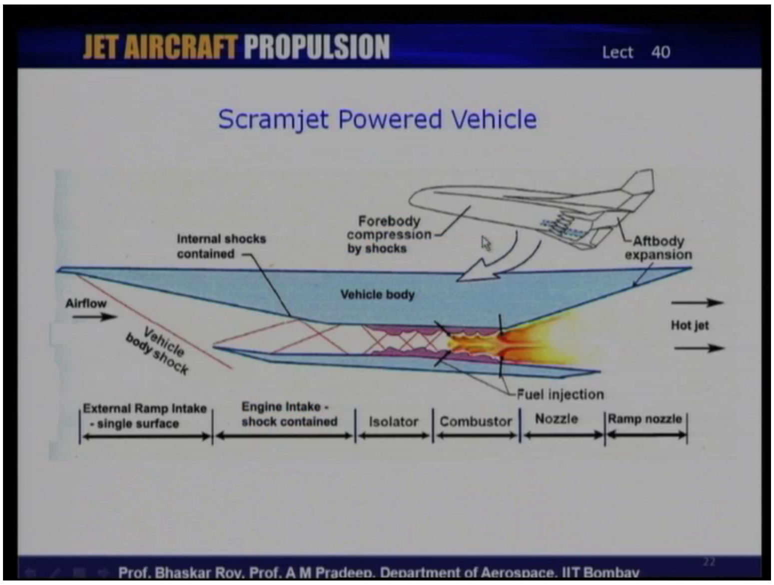

If you want to fly even higher than that it is necessary that you have scramjets, because the scramjets are the only ones that can take you to very high Mach numbers like Mach 8 or Mach 10 in the scramjet engine the flow comes in and then you have a intake shock configuration this shock configuration slows down the flow from very high supersonic values to somewhat lower supersonic Mach numbers and then through these lower supersonic Mach number it goes through an isolator where again you have shock trains. These shock trains then finally, allow the flow to go into the combustion chamber which is still supersonic. So, you have supersonic combustion over here and after the supersonic combustion.

The flow is finally, let out through the nozzle which is a fix geometry nozzle, so you have a fix geometry intake which includes the vehicle body so the first shock is indeed from the vehicle body and at the exhaust, the vehicle body provides one surface of the nozzle so it is also fix geometry. So it is a kind of scramjets which is often used in a vehicle like this which often would have multiple such ramjets four or five or six ramjets to provide sufficient thrust for this craft to finally fly at very high Mach number.

So you need to have a multiple engines quite often to achieve that fly Mach number because as you can see the process by which the thrust is created the thrust created by a single engine is unlikely to be of very high order. Something, we were talking about a little while earlier getting a positive net thrust is a little bit of a issue here for the designer or to begin with and hence quite often the aircraft designer would like to have multiple engines deployed in a one particular craft for creating sufficient net thrust for that craft to fly at very high Mach number.

So, this is how typically a ramjet or scramjet engine is designed into a particular craft, so that the craft can fly at very high Mach numbers all the way from 3 to 8 or 10. In the next class, we will take a look at how one can solve some very simple problems using the theories that we have done over the lectures, last three or four lectures using the cycle analysis that you have done, and the component analysis that you have done. And try to see whether you can use those theories to make some simple estimation of the ramjet, and scramjet, and pulsejet performances. So, in the next class we will solve some problems; so, that you get an idea about the numbers that are necessary for an engineer to be very familiar with while dealing with various kinds of engines.