Jet Aircraft Propulsion

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Lecture No. # 36

Tutorial – 6

We have been talking about off design performance of aircraft engines, and we have talked about various methods, and various kinds of engines on which off design performance can be performed a calculation that need to be done, and certain way that the off design performance can be estimated. Today I will try to give you a demonstration of how off design performance on an aircraft engine. A very simple turbojet engine can be carried out using some of the theories that we have done, and in the process of this demonstration of the numerical example, I will try to also bring in one or two methods, which are kind of semi empirical methods which help estimate the off design performances because, some of these methods are semi empirical simply because they need lot more support system to carry out the off design performance estimation and hence, sometimes in absence of very elaborate support system you may have to make use of some of the semi empirical methods.

So I will indicate, where those things are brought into the estimation a procedure and I will also mention what are the various elaborate methods that you should or you may like to have to have more accurate off design estimation. The off design estimation can be performed to begin with when the aircraft is engine is first designed or first configured in terms of the cycle configuration, in terms of the first cut engine design; however it needs to be done again later on when the engine design has been finally, made and sized and the geometry of various components are readymade; and in those situations 1 can do elaborate off design estimation again at that stage of time one may have the component performance maps available the intake map, the compressor map, the turbine map those things would be available also certain amount of integration between the intake and the compressor, might have already been done again integration between the turbine and the nozzle may have been done.

The overall engine may have already been integrated into one unit, so many of those things are done at the end of the engine design. At that point of time, if you are doing off design analysis, you would get a lot of support in terms of the compressor map, the turbine map so on and so forth. However if you are doing an off design analysis a priory when the engine is first being designed or the first cut design a cycle design or a first cut design is just available to you, you would probably be looking for a more quick analysis of the off design possibility and as to where the engine may be fulfilling its need and where it may be falling short of the needs of certain requirements.

So at that stage of time you may have to employ certain semi empirical relations, which are often a very quick method to find out whether the off design performance of the engine is indeed suitable for requirement of particular aircraft application. So in today's demonstration we will take up a simple turbojet engine; and demonstrate step by step how off design performances are made in the process, we will also look at what its design performance indeed was or what it was designed for, and the design values of various performance parameters the figures of merit would also be shown alongside, so that one has a good idea about what the off design performance, actual numerical values are with reference to the design performance values.

So those comparisons would be made alongside, and some of the design parameters would be set forth right in the beginning, so that you get a good notion of what is happening with reference to an off design performance with reference to the design performance.

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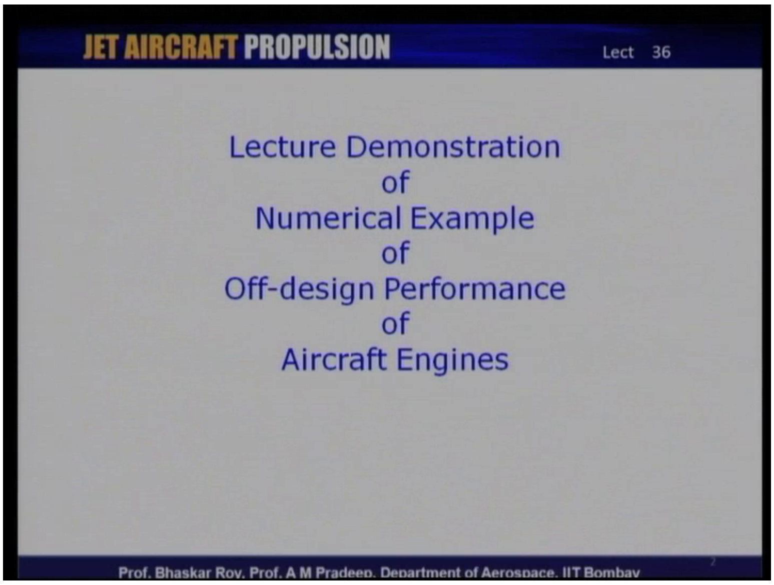

So in today's lecture we will take up a simple turbojet engine in which the off design performance would be demonstrated through a numerical example, so that that step by step performance estimation can be understood and followed by you.

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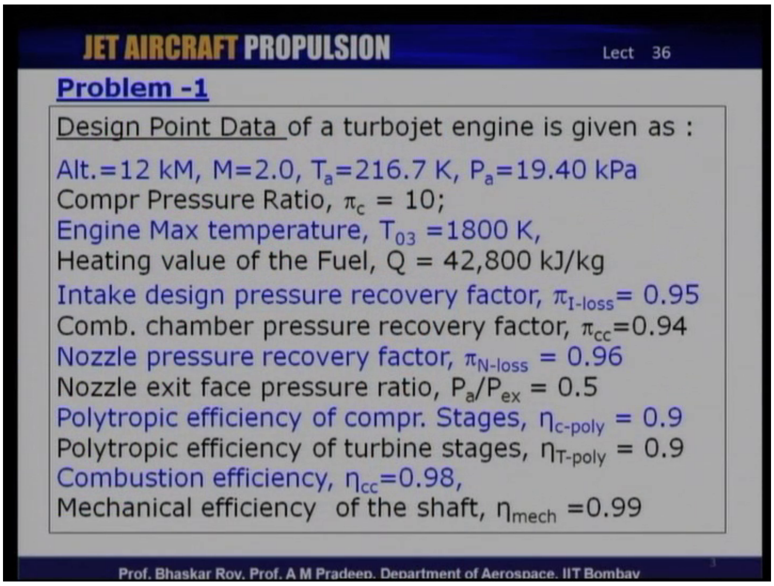

So let us take up a simple example which is useful for off design performance estimation. If we look at design data of a typical turbojet engine, it is mach here, it has been designed for a 12 kilometer altitude at mach two, so it's flying at supersonic speed, where the ambient temperature is 216.7 k and ambient pressure is 19.4 kilopascals. Now at that design point it is configured that the compression compressor pressure ratio or compression ratio would be 10, the engine maximum temperature which is the turbine inlet temperature would be 1800 k. The heating value of the fuel normally given as q would be 42800 kilojoules per kg, and intake design pressure recovery factor which we are putting as pi i loss would be equal to 0.95. The combustion chamber pressure recovery or pressure loss factor pi c c would be 0.94 and the nozzle pressure recovery factor that is pi n loss would be 0.96.

Nozzle exit face pressure ratio that means at the exit of the nozzle P a by P x e x would be 0.5, and the polytrophic efficiency of the compressor stages for each of the stages is 0.9; polytrophic efficiency of the turbine stages is given as also 0.9. The combustion efficiency is given as 0.98 and the mechanical efficiency of the shaft eta mechanical is 0.99. Now as you can see here the design is being done for the turbojet engine at supersonic flight condition at 12 kilometer altitude, where the aircraft is flying supersonic at mach 2 and at that condition the design is being configured. So all the values at prescribed here are essentially valid for the design condition and we shall be using a some of these essentially for our off design configuration.

So let us see where all the off design values would differ from the design values and where all we may continue to use some of the design values to estimate off design performance.

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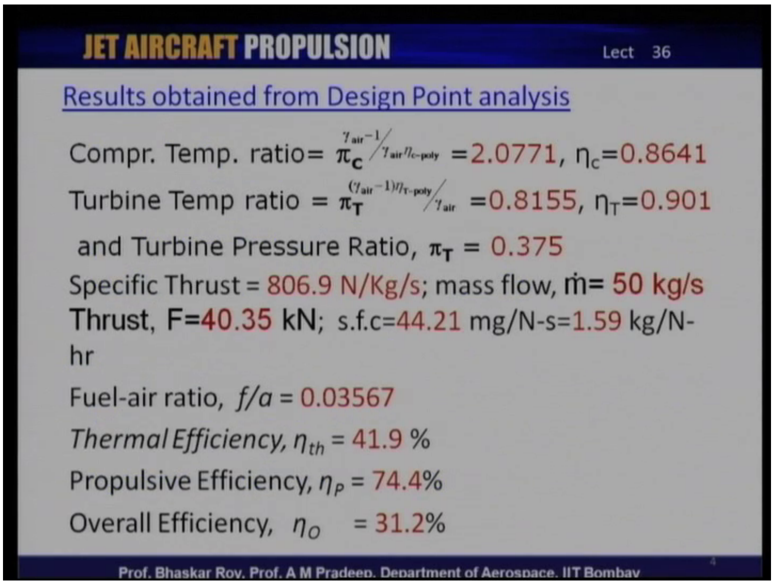

Now this design point data that has been given yields certain design point performance estimation which we can put down here and we may use this for comparison purposes as we go along with our off design performance. For example, the compression temperature ratio can now we written down in terms of the polytrophic efficiency that has been given, and the pressure ratio that has been given and given the pressure ratio on a polytrophic efficiency and given the value of gamma air that is 1.4, a normal value of gamma we get a temperature ratio across the compressor as 2.0771 and the corresponding isentropic efficiency of the compressor given the polytrophic efficiency which is 0.9 and considered to be equal for all the stages the overall isentropic efficiency of the entire team pressure ratio compressors would be 0.8641 which is 86.41 percent.

The turbine temperature ratio across the turbine you have a temperature pressure drop normally so there would be temperature drop and hence, again using the polytrophic efficiency of the turbine that is been prescribed in the design we get a turbine temperature ratio of 0.8155 and the corresponding turbine isentropic efficiency is 0.901 which is 90.1 percent. So those are the values we get for the compressor and the turbine, the turbine pressure ratio then comes out to be 0.375 across the turbine that drives the compressor.

If we use all these values and if you follow the overall cycle analysis that we have done in the cycle analysis chapter, in this lecture series and if you follow the procedure, you would probably get specific thrust of the order of 806.9 Newton's per kilogram per second. The mass flow through the engine is 50 kg per second. The thrust would correspondingly then be 40.35 kilo Newton's the corresponding SFC would be 44.21 milligrams per Newton's per second or which can also be expressed in terms of kilograms per Newton hour.

The corresponding fuel air ratio ratio f by a or f would be 0.03567 and that is the fuel air ratio that we would be looking at thermal efficiency of this engine at the design point would be 41.9 percent, the propulsive efficiency eta P would be 74.4 percent and the corresponding overall efficiency of the engine would be 31.2 percent. Now these are the design values we get out of the design point that has been prescribed to us following the design point cycle calculation, the the methodology that you have done in some great detail in your cycle analysis chapter, and if you follow that methodology you would get these values out of the design point that has been prescribed to us.

Now we can see what all prescription is given for off design point, and then we will proceed on to do the off design performance estimation, so let's look at the off design performance prescription.

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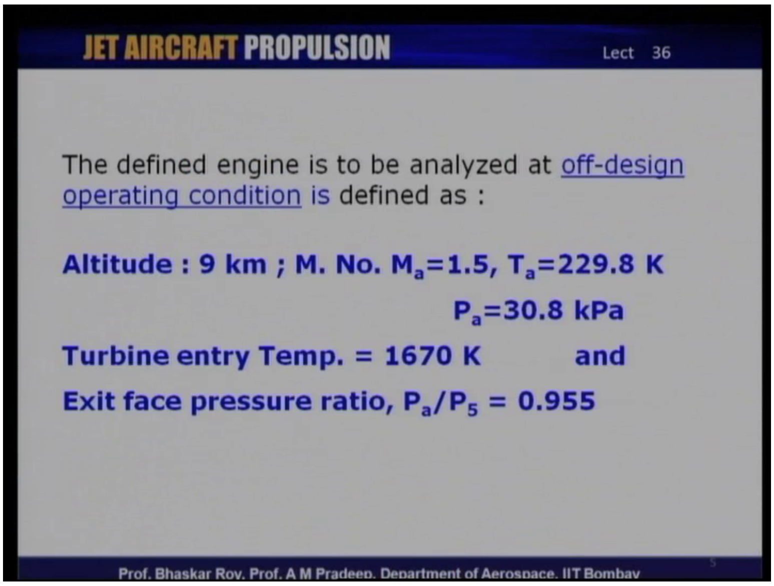

The prescription that is given is that off design engine is performance need to be estimated at an altitude of 9 kilometers at which the aircraft engine is now flying at a mach number of 1.5, where the temperature is 22 229.8 k and the pressure is atmospheric pressure is 30.8 kilopascals prescribed is that the turbine entry temperature would be 1600 and 70 k, and the exit phase pressure ratio at the exit of the nozzle the engine nozzle would be P a by P 5 would be 0.955 that means it will completely close to be equal to the ambient pressure, so the exit pressure could be very close to be equal to the ambient pressure.

Those are the prescriptions aircraft flying at 9 kilometer altitude at a mach of 1.5 and turbine entry temperature 1670 k as prescribed for off design calculations, now let us see how we can proceed to do off design performance estimation.

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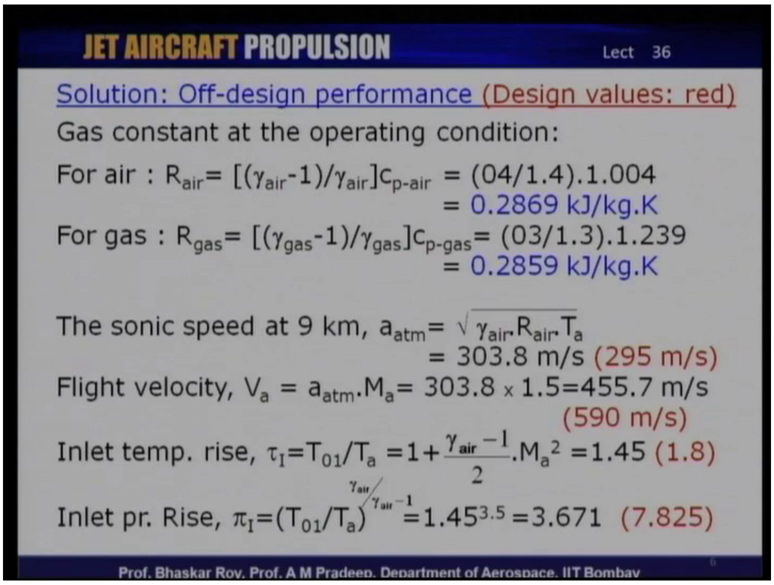

As I have mentioned before we will probably be showing all the design point calculations that has been done a priory and we will try to show them alongside here, so that you get a notion of the different between the design point and the off design performance that we are calculating now. To begin with we can calculate the gas constants at the operating condition, which is we can do it both for air ambient air as well as for the gas the combustion gas mixture of air and burnt fuel, and the combination gives us the gas constant or value, for the air we can calculate at and it comes out to be 0.2869 kilojoules per kilogram per Kelvin.

The corresponding value for the gas that is the combination mixture of air and burnt fuel the value of R comes out to be 0.2859 kilojoules per kilogram Kelvin. Now if you remember normally for ambient condition at sea level the universal value that normally used for air is 0.287, so as we can see here if the operating condition of the engine is different you would probably need to calculate the values of R afresh to get more accurate estimation of your engine performance.

Now off design performance has been pegged at 9 kilometer altitude at which we can now find out what the sonic speed would be and using the normal isentropic relation that is root over gamma R T for the sonic speed we get a sonic speed of 303.8 meters per second at 9 kilometer altitude, and as you can see that sonic speed is higher than the design value which at 12 kilometer was 295 meters per second. Correspondingly at 9 kilometer the flight velocity is now with reference to mach 1.5 would be 455.7 meters per second, now contrast this to the design flight velocity which was 590 meters per second at mach 2.

So it's flying at a lower altitude but, it also flying at a lower mach number and as a result the flight velocity is now less by a substantial amount from the design flight velocity correspondingly the inlet temperature pressure rise which is conversion of the kinetic energy to pressure that is ramp pressurization as we may call it as we have called it in this lecture series. Now this inlet temperature rise comes out to be 1.45 using the normal isentropic relation of conversion of kinetic head to static head, corresponding the design value was 1.8 so at 12 kilometer at design point the temperature rise was compared to the ambient pressure temperature it was much more, the corresponding inlet pressurization or pressure rise using again the isentropic relation from the temperature ratio that we have just found and we can find pi I and the temperature ratio to the power gamma by gamma minus 1 gives us essentially the pressure rise or the pressure ratio across the inlet which essentially is the ramp pressurization and this ramp pressurization is now 3.671 for the off design operating condition which at design point was much higher at 7.825.

So as we can see now there is a big different between the design point and the off design ramp pressurization or the ramp effect that is happening across the intake of the engine, so with these values we can move forward to calculate some of the other values the of the engine.

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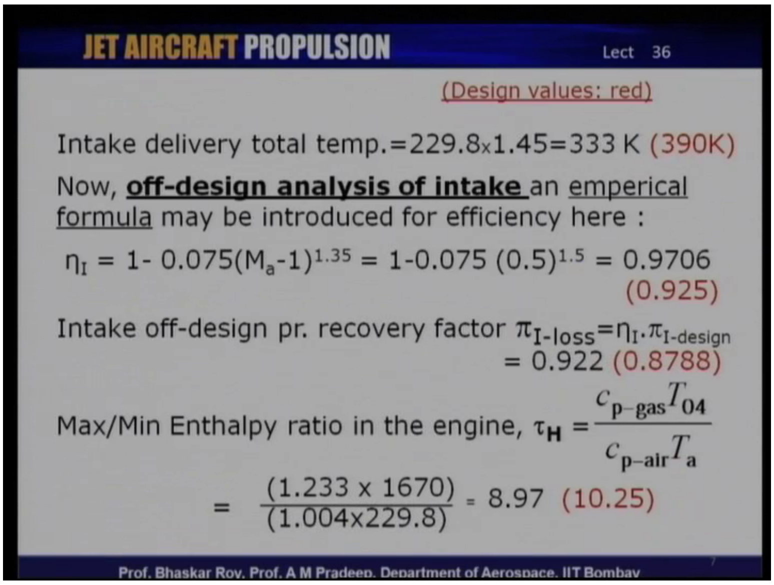

From this calculations so we can say that the intake delivery total temperature would be 333 k which is again far less than the design point value which was 390 k. So the flow was going into the compressor earlier at a somewhat higher temperature. The off design analysis of the intake uses certain empirical formula here or semi empirical formula I would say to calculate the intake efficiency. Now it stands to aerodynamic sense that the intake which is once it has been designed. You would probably need to analyze it for under various off design operating conditions now these off design operating conditions operating at different ambient condition different mach number entry mach number would promote completely different kind of aerodynamics inside the intake and in this case we are looking at a supersonic intake which means the shock structure in front of the intake would be quite different from the design shock structure and as a result the flow through the intake would be quite different from the design shock flows and hence, the intake aerodynamics would be quite different.

Now that requires more elaborate aerodynamic analysis may be using c f d and that elaborate analysis is possible only when the intake is completely designed in an integrated manner with the whole engine, and only when the intake is designed you have a complete picture of what may be happening and you can do a full c f d analysis of the intake or may be a test rig analysis of the intake geometry in full. At that point of time you would have a more accurate idea of what what is happening inside the intake under various off design operating condition. Now till that is done you do not know extremely accurately very accurately what are the intake performance schedules under various off design operating conditions, so till that is available made available to you, you may use certain semi empirical relationships to move along in your off design performance estimation.

So in this analysis we are doing that because, the full intake performance accurate performance schedule is not available to us, and we have to move a long and get a first cut reasonable performance estimation under off design condition. So if we look at the empirical formula, where may be used it says that the intake efficiency eta I can be 1 minus 0.075 into a a minus 1 to the power 1.3, now this essentially tells us that it gives us first cut notion of what the intake efficiency could be and that comes out to be 0.976 contrast this to the design point intake efficiency which is indeed 0.925.

And as a result of it we can see that the intake efficiency at off design condition is indeed actually higher than the design point intake efficiency which should not be a big surprise in view of the fact that now it is operating at mach 1.5 which is a lower mach number, and the shock losses would be far lower than the design point which was at mach 2. So this higher intake efficiency should be quite acceptable in view of the fact that the shock losses would be higher the corresponding intake pressure recovery factor which means how much of the ideal total pressure is recovered by this intake can now be found out and that would be intake efficiency eta I into the pi design which was given earlier, and this tells us that the value could be 0.922 which is again higher than the design value which was .8788.

So the pressure recovery also at mach 1.5 is better than that mach 2 which is again what is expected in view of the fact that it's flying at a lower mach number. Now we figure out what the maximum to minimum enthalpy ratio in the engine could be you are probably familiar with the engine cycle temperature ratio which is normally given in terms of the maximum temperature to the minimum temperature with which the flow is going in and this temperature ratio can here also be converted to enthalpy ratio by also using the values of C p of gas and C p of air, and if we do that we get maximum to minimum enthalpy ratio of these engine in terms of their prescribed parameters as 8.97.

Now as you can see here this is less than the design value which was given as 10.25 now which means it's operating firstly with a lower turbine entry temperature and as a result of which the enthalpy ratio available now would be somewhat lower than the design enthalpy ratio.

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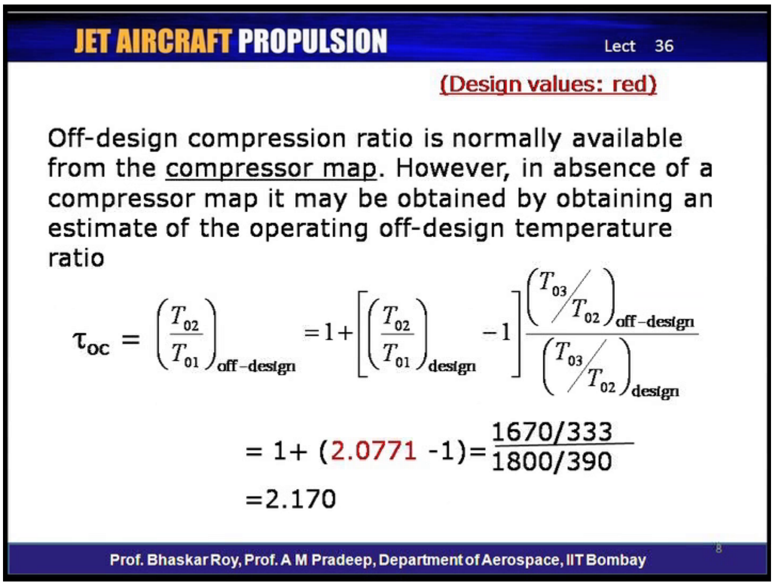

If we move forward and try to find out what the compression ratio would be at this off design condition we need to make use of whatever is available at hand now ideally, if the compressor has been fully designed you may like to have the compressor may map made available to you and then you can find out what the compression ratio would be under the off design condition. We have discussed the compressor map in quite a great detail in the earlier lectures, and if you look at them you will find somewhere we had clearly shown there was a design point and all the other operating conditions of the compressor are off design point.

So we have to find this design off design operating condition on that compressor map and then figure out what the compression ratio would be at that particular operating condition and use that to do our off design estimation. However, what happens is when the engine is first being designed the compressor may not be fully design as yet and if the compressor is not fully designed it’s simply means that the compressor map is not yet available to you, and if the compressor map is not available you would probably need to find out some good first cut method of finding out what the off design performance schedule would be at the given off design operating condition.

So we shall use that methodology assuming that the compressor is not yet fully designed and hence, the compressor map is not yet available to us. So let's look at what methodology one can use to estimate the off design compression ratio of the compressor. What we can do is we can find out what the off design performance would be firstly we find out what the temperature ratio under off design condition and this temperature ratio can be related to the design temperature ratio, which was prescribed earlier and as as result of it we get if we use this simple thermodynamic relationships simply finding out what the design to off design ratios are of the maximum to minimum temperature and then factoring that has a possible off design temperature ratio across the compressor what we get is a compression ratio of the order of 2. 17.

Now contrast that to the off design condition design point temperature ratio which was 2.077 and we can see that the temperature ratio at off design condition is indeed more than the design point temperature ratio.

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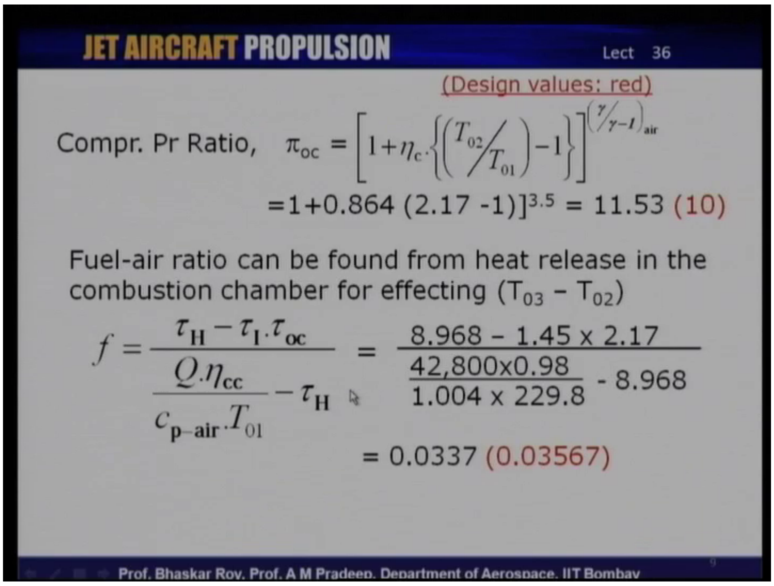

This means that the compression ratio the pressure ratio across the compressor would indeed also be more than the design point pressure ratio which was prescribed as 10 and we see here that the off design point we have a pressure ratio which is 11.53 using the simple thermodynamic relations that we have done before probably more than once. Now this means that in terms of the compression ratio we are now getting more compression at off design condition compared to the design point compression ratio that was prescribed for the engine.

Now this is something which is not totally unexpected because, what happens is if you if you remember the compressor map your map it has a design point but, the compressor map compression ratio is not maximum at the design point there is a certain compressor map in which the compression ratio is indeed higher than the design point and of course, it moves towards the stall, so this particular operating point is now somewhere between the design point and the stall point and as a result of which it is actually working at a higher compression ratio than the design point and hence, some of its performances would be accordingly altered from the design point quite substantially.

So we can we they have got off design operating point now at which the compression ratio is indeed higher than the design point to some extent it also has some meaning that we saw that the inlet temperature to the compressor from the intake is indeed actually lower than the design point design point because, of the very high mach number the inlet temperature was a little on the higher side and of course, the compression ratio was lower. Here the inlet temperature is on the lower side and we are in the process getting a higher compression ratio across the compressor, so we have an off design point where pressure ratio is higher than the design point pressure ratio.

Now let’s look at what happens to the other parameters. The fuel air ratio can also be found from the heat release in the combustion chamber we know what the heat release would be across the combustion chamber, and if we do that we find that and we use the enthalpy ratio that we have found we can find the intake temperature ratio we can use the compressor temperature ratio, and then we use the heating value of the fuel that is being given to us the efficiency of the combustion chamber and factor that with the inlet condition, if we put it altogether in this simple formula which essentially uses the heat release that has been effected through the heat release process in the combustion chamber in thermodynamic manner we get a fuel air ratio which is a 0.0337.

Now we can see here that the fuel air ratio is now less than the fuel air ratio of the design point which was 0.03567, so the fuel air ratio now at off design point is indeed lower than the design point fuel air ratio to some extent this corresponds to the fact that it is operating at a higher compression ratio. So typically a cycle which operates at a higher compression ratio can do with a lower fuel air ratio, so the two values we see here to some extent corresponds to each other from thermodynamic cycle point of view that we have done before.

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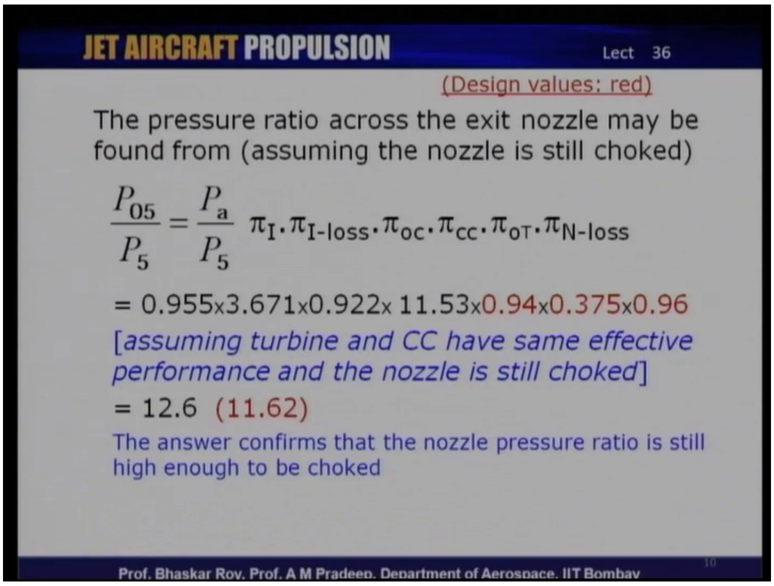

If we now continue we can find out what the pressure ratio across the exit nozzle may be from all the pressure ratios that we have put together. We have the intake pressure ratio we have the intake pressure recovery factor which we have called pi I loss then we have the pressure ratio across the compressor we have the pressure ratio across the combustion chamber which is nothing but, pressure loss across the combustion chamber we have also got the temperature re pressure ratio across the turbine and the nozzle pressure recovery factor.

Now the last two that is the turbine pressure ratio and the nozzle pressure recovery factor we assume these two remain same as the design point because, we are assuming that the turbine in the combustion chamber has same effective performance and that the nozzle is still choked in fact we can we probably would also be assuming that the turbine is also working under still under choked flow condition. So once we assume that the turbine some of the turbine related parameters can be again used for off design performance estimation and it allows us to move forward and which is a fair assumption really under various off design operating condition many of the turbine and combustion chamber and nozzle related parameters do actually hold constant whereas, some of the intake and compressor related performance parameters change quite significantly.

If we now put together all the parameters that we have put here, and we put there numerical numbers holding on to their design values related to the turbine and nozzle, we see that and the combustion chamber we see that the pressure ratio across the nozzle is now 12.6 and contrast this to the pressure ratio available at design point which is 11.62 and then it also tells us that the nozzle pressure ratio still very high for it to remain choked.

We have discussed this in your intake nozzle chapter and we have shown that unless if the nozzle pressure ratio is very high you have to use a convergent divergent nozzle and this convergent divergent nozzle is what has been indeed used in this particular engine, for the design pressure ratio which was 11.62 which means this convergent divergent nozzle would continue to be useful at the off design operating condition that we are looking at because, the pressure ratio is still very high.

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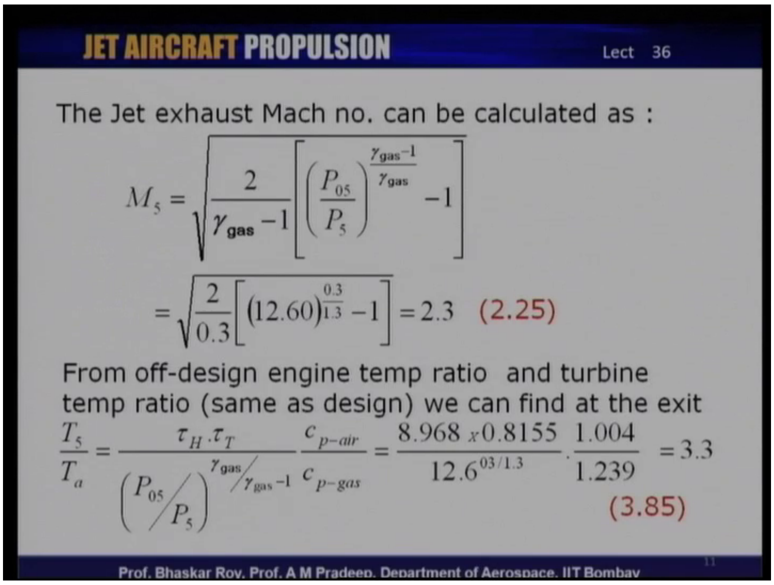

Now if you look at the jet exhaust mach number which promotes the thrust making this can be calculated from the thermodynamic relations that we have done in detail through the course of this lecture series, and we use the performance the pressure ratio that is we have just found across the nozzle, and if you use that we find that the mach number at the exit phase of the engine is 2.3 which is marginally more than 2. 25 which was the design exit mach number of the jet.

Now we still see that its creating a supersonic jet at the exit and at the off design operating point it is marginally more than the design point exit jet mach number what we can do now is we can find the off design engine temperature ratio and the turbine temperature ratio, now we are saying that the turbine temperature ratio holds which is same as the design because, it is still undo working under choking condition.

And hence, its temperature ratio and pressure ratio would hold, and if we do that and we use those values the temperature ratio of the engine across the engine exhaust phase with reference to the ambient condition that is T 5 by T a can be related to again to the enthalpy ratio which if you remember was essentially more related to the turbine engine temperature ratio and then of course, the turbine temperature ratio and we use the pressure ratio across the nozzle and then of course, the values of C p of air and C p of gas assuming they are two different values and we have those values available with us.

And if we use those values we get a temperature ratio across the turbine phase exit to exhaust phase nozzle exhaust phase as 3.3 which if you contrast to the design value which was 3.85 so the turbine the nozzle exhaust temperature now is less than the nozzle exhaust temperature which was happening under design operating condition. So which is essentially means that it’s going out with a lower temperature under off design operating condition.

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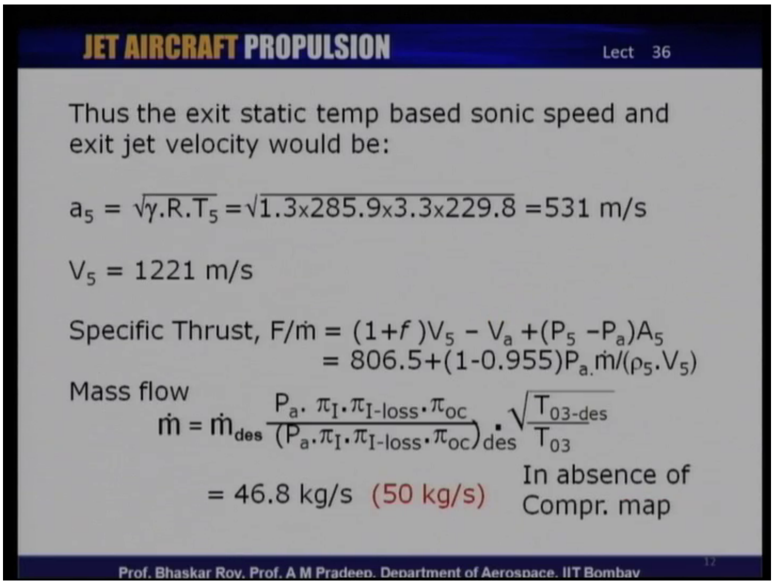

If we now try to find out what is happening at the exhaust condition first we find out what the sonic speed is based on the exhaust temperature that we have already found and the sonic speed if you put together root over gamma R T at sonic at the exhaust phase using the values of gamma gas on R of the gas and if you put those values we get sonic speed of 531 meters per second at the exhaust condition of the jet engine correspondingly from the mach number that we have got of the jet exhaust we get a a exhaust velocity V 5 or V exhaust as 1221 meters per second.

So this is the jet velocity with which the flow is being ejected from the main engine, and this is the jet which is effectively helping us create the thrust the with which the aircraft would be flying. Corresponding to this calculations we can now say that the specific thrust may be calculated now using the normal relationship or specific thrust which is 1 plus f which is a fuel air ratio into the V 5 minus V a V of course, is the flight velocity and the pressure thrust P 5 minus P P a as we now know certain amount of residual pressure exists at the exhaust phase and that would give us a little bit of pressure thrust.

Now this the first part that is the momentum thrust comes out to 806.5 however, the pressure thrust calculation requires the values of mass flow and also the density which of course, we can calculate from P 5 and T 5 which we have already completed and V 5 which is available with us. So rho 5 can the density can indeed be very quickly calculated but, we need to quickly find the mass flow which is passing through the engine now calculation of the mass flow requires again a little more discussion.

If we look at the mass flow that needs to be calculated again if we had the compressor map or if we had the turbine map or we had the maps of intake compressor, turbine, nozzle all of them available with us. We can have a coordinated configuration of the engine from which we can get this off design mass flow. The easiest way or the more adapted method is the one where we use the compressor mass flow you have the compression ratio available with you and from which from the compressor map you can find out what the mass flow would be which is normally the x axis.

That mass flow can be used for the engine calculations however, as I have stated before the compressor map is not really available with us at this stage of our estimation, the turbine map is not available with us and as a result of which we have to use certain simple method using the basic thermodynamics that we are doing to calculate what the off design mass flow could possibly be. So without the aid of the turbine or the compressor map which nowadays of course, would be available in digital form or digitized maps in absence of those maps we have to adapt a very simple straight cut method of finding out what the off design mass flow could possibly be, so let’s look at what the off design mass flow could be through a very simple straight forward method.

The mass flow at off design can be related to the design mass flow now by using first of the design mass flow and then if we use the parameters that we have of the engine the ambient condition, the intake pressure ratio, the intake pressure recovery, the compression ratio the product of all of them a compare to the product of all of them at the design point.

And then a root over of T 03 which is the turbine entry temperature at the design point and the same thing at the off design points, so if we just compare all the values of the important engine parameters at the design point and then at the off design point and take a simple ratio of them we can arrive at a first cut mass flow estimation which gives us the mass flow to be 46.8 kilograms per second. Now as you can see here the mass flow now is less than the design mass flow which was given for given as 50 kilograms per second, so our off design mass flow is now less than the design mass flow.

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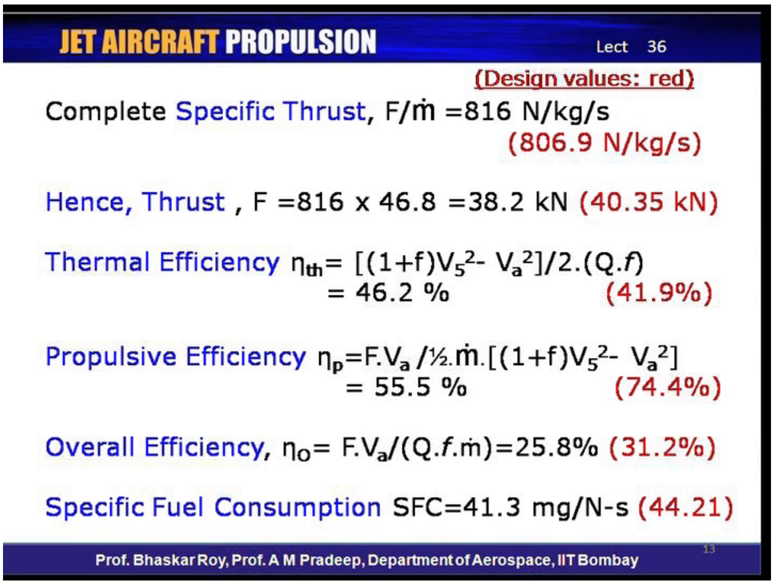

If we use this mass flow now we get a certain estimation of the specific thrust which then comes out to be using this mass flow we can go back to the specific thrust that we were estimating and we can come back to the second term which is the calculation of the pressure thrust, where we can now plug in the mass flow and also we can plug in the value of density of the gas at the exhaust phase. And if we plug in those values and we get the second term also calculated which is the pressure thrust we get a complete specific thrust of 816 Newton's per kilogram per second which as you see now is slightly higher than the design specific thrust of 806.9 kilograms per second.

So your off design specific thrust is coming out to be a little more than the design specific thrust because of the various operating condition that has been prescribed, and the fact that the compression ratio is higher than the design point its operating at a higher compression ratio and we end up getting is specific thrust that is marginally higher than the design specific thrust. It is one of the reasons is that at this condition we have a certain amount of pressure thrust that is also contributing to the specific thrust. Hence, now if you multiply this with the mass flow that we have just calculated at this off design condition the thrust of the engine comes out to be 38.2 kilo Newton's which is now less than the design thrust which was 40.35 kilo Newton's.

So now you can see here that even if the specific thrust is higher than the design value the actual value of the thrust would be lower because, the mass flow was quite a lot lower than almost 3 to 4, 5 to 8 percent lower than the design value and as a result of which the actual value of the thrust is also lower at 38.2 kilo Newton's.

We can now estimate the thermal efficiency which is normally done using the energy that is imparted to the gas in terms of a normally estimated in terms of the kinetic energy, now the kinetic energy of the gas of the specific kinetic energy of the gas is 1 plus f into V 5 square and minus V a square that is the kinetic energy with which the air had gone inside the engine it entered the engine with that kinetic energy and it is coming out with this kinetic energy and the different between the 2 is of course, the energy that is been imparted to the air in the process of operation through the engine its travel through the engine.

Now that compare that to the amount of energy that has been burnt in the fuel, so the burnt fuel energy that is Q into f gives us the energy that is being burnt available through the brunt gas of the fuel air mixture and that again u per unit mass flow so both numerator and denominator of the unit mass flow in the sense the mass flow cancel them out and as a result of which we get a thermal efficiency of 46.2 percent.

Now again mach here that this thermal efficiency is indeed a little more than the thermal efficiency of the engine at design point now this higher thermal efficiency that we have found also stands to reason by the fact that at off design it is operating at higher pressure ratio, this higher pressure ratio indeed yields the higher thermal efficiency and we had seen that it also gives higher specific thrust. So we have a off design operating condition now, where certain parameters are indeed higher than the design point parameter in terms of compression ratio, in terms of specific thrust however, the mass flow is lower the thrust produced is lower indeed it is supposed to be flying at a lower mach number.

Next we can find the propulsive efficiency which again we use the definition that we have introduced earlier in this lecture series and that is the actual thrust work that is done by the engine F into V a that compared to the energy that is available with the gas which is the exhaust energy minus the entry energy which we used in the earlier definition in the numerator that now comes in the denominator multiply by the mass flow is the energy that is available to this mass of air that is passing through the engine but, the engine thrust that is being created is F and with the velocity with which it is flying that tells us what the thrust work that is being done.

So when we compare the thrust work to the energy available to the gas we find that only 55.5 percent of the energy that is available to the gas is indeed being used for thrust creation and rest of it is probably likely to be wasted in exhaust energy. Now contrast that to the design point the propulsive efficiency which as you can see now here was much higher, so the propulsive efficiency of the engine at the design point is expected to be at the best and it is indeed higher than the off design point at which we are now trying to find out what the propulsive efficiency is.

Now this tells us that even if you have a thermal efficiency that is higher than the design point you can have a propulsive efficiency that is lower in fact it is substantially lower than the design point now these two efficiencies together essentially yield the overall efficiency actually the overall efficiency could essentially be the multiplication of the earlier two efficiencies however we can use the original efficiency definition which is the thrust divided by the energy that is being put in by the burning of the fuel and the this yields as overall efficiency of 25.8 percent which as you can see here is lower than the overall efficiency of the engine at the design point which tells us that the engine is now working at a lower efficiency than compared to the design point. The design point efficiency as expected is supposed to be one of the highest efficiency operating points of the engine and this particular off design operating point the overall efficiency is indeed lower than the design point operating efficiency.

This contrast to the fact that even if it is operating at a better compression ratio even if it is producing higher specific thrust and may be one or two other parameters which are better than the design point its overall efficiency is still less than the design point. Correspondingly the fuel air consumption that we get is calculated using the fuel fuel air ratio that you have got the SFC is nothing but, the fuel air ratio divided by specific thrust and if you do that you get a value of 41.3 milligrams per Newton second and this can also be of course, expressed in terms of kilograms per Newton hour.

And contrast that to the design point of value where we get 44.21 which means that the specific fuel consumption at this operating point is actually slightly less than the specific fuel consumption of the design point which was a flight mach number at altitude of 12 kilometers at mach 2. So we have calculated the engine parameters at an off design operating point which is defined at altitude of 9 kilometers and at mach 1.5 and compared all the parameters with the design point parameters.

So we have estimated the off design estimated performance of the entire engine and it tells us that overall efficiency is lower than the design point efficiency the thrust is lower than the design point thrust and but, some of its other figures of merit the specific thrust is good it is actually marginally higher than the design point and the specific fuel consumption is indeed actually lower than the design point specific fuel consumption. So this off design point is a good off design point, where the aircraft can operate very successfully without using a lot of fuel of the engine and the engine has a good operating efficiency good operating performance at this off design operating condition.

So this is what our off design estimation at the prescribed off design point tells us in comparison to the design point estimation that we have done before and that means prescribed to us earlier. We have done this without the aid of the compressor map or the turbine map without the aid of detailed intake estimation with the help of c f d or rig test and without the detailed nozzle estimation again with the help of c f d rig test, so without the help of any of those things we have used simple thermodynamic based relations and I have introduced some of the semi empirical relations to a move along in the off design calculation and that gives us a reasonable off design estimation of this particular engine which has been prescribed to us and we see that it is a good off design operating condition.

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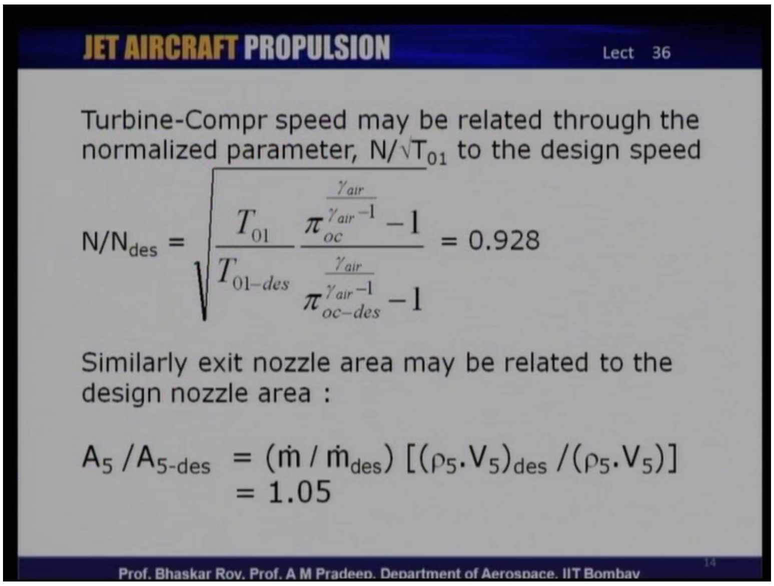

What I will do is I will just give the same engine to you under various different off design condition, if the given off design condition you can also find the specific speed of the turbine compressor and that comes out to be 0.928 we related that to the temperature operating temperature with reference to the design, and the pressure ratio of the compressor with reference to the design pressure ratio and it tells us that the off design engine speed can be 92.8 percent of the design operating speed.

Similarly the exit nozzle area may be related to the design nozzle area and again using the simple ratio with reference to the design values of the mass flow of the exit flow conditions and we see that the off design area of the nozzle at the exit should be 5 percent more than the design point nozzle area at the exit at the exhaust phase. So these two things can also be found very quickly by very simple off design estimation using the simple thermodynamics.

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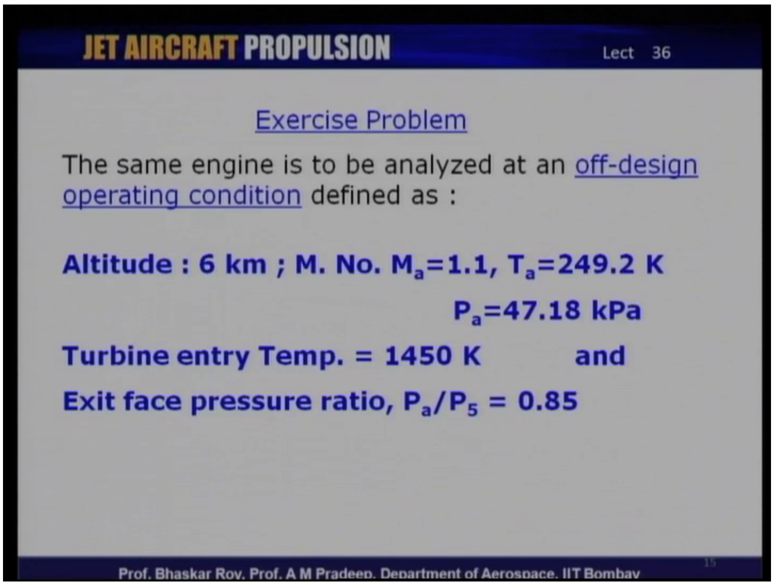

We will now leave you with an exercise problem which is configured at an off design condition under altitude of 6 kilometers and its flying at a mach number of 1.1 at that altitude the prescribed temperature is 249.2 Kelvin and the pressure is 47.18 kilopascals the turbine entry temperature has been prescribed as 1450 k and the engine exit phase pressure ratio is again prescribed as .85 you can try to do the off design calculation on your own using the same procedure that we have just enumerated through this off design calculation and see what kind of answers you get and whether you get a good off design operating condition we got a good off design condition just see whether you are also getting a good off design condition.

So that brings us to the end of this off design numerical example, I hope you would be able to look at the off design procedure and make use of it yourself and see whether you yourself get a good off design condition or whether you get off design condition which is indeed probably not so good I leave that to you to do it by yourself.