Gas Dynamics and Propulsion
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Lecture - 31
Components of the Gas Turbine Engine / Thermodynamic Analysis of the Engine

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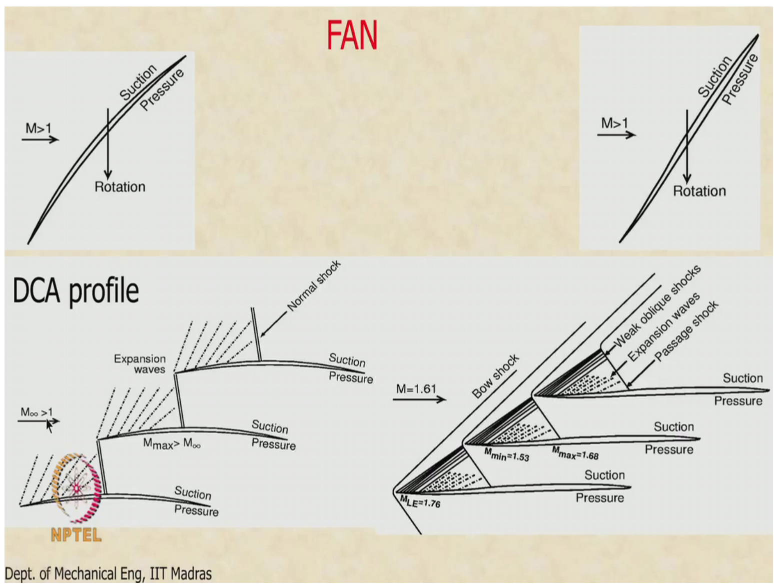

So in the last class, we saw that double circular arc profile cannot be used for diffusing a supersonic flow, and we showed that because it has the contact surface here by the time the flow reaches the entrance of the blade passage which is over here, you can see that the maximum Mach number is going to be more than the free stream Mach number probably much more than the free stream Mach number.

So this normal shock will be quite strong and as you saw from our normal shock diffuser calculation the loss of stagnation pressure will also be quite high, which is very undesirable in the case of the fan in a turbofan engine. So the custom diffusion airfoil tries to minimize or less than this difficulty by using concave and then convex portion, so the flow is decelerated in the concave portion from a Mach number of 1.61 to about 1.53 or so.

And then this is followed by a convex portion where the flow inevitable accelerates again to a Mach number of 1.68, so you can see that the Mach number just at the entrance of the passage now is compatible to the field free stream Mach number but not more than that, which is the best that we can possibly do because increasing this concave portion is not practical from a manufacturing stand point of view okay.

Remember these blades are very, very slender, but at the same time they have to be able to stand very high amounts of loads which is what we are going to discuss next. So here we are worried only about the gas dynamic aspects of the diffusion process, so the air that comes through here then goes through bow shock and the Mach number probably will be <1 here, and then you have a passage it may not even be <1, we can design the passage for both.

If it is still >1 then we have a converging diverging passage here which will decelerate the air without difficulty to subsonic value and then we have the pressure rise that we are looking for. Typically, the pressure ratio here will be 1.7 or so, so design of the fan blade section and the fan blade passage requires the concepts the gas dynamic concepts that we learnt earlier okay, and as you can see from here it is very, very critical in an application like this okay.

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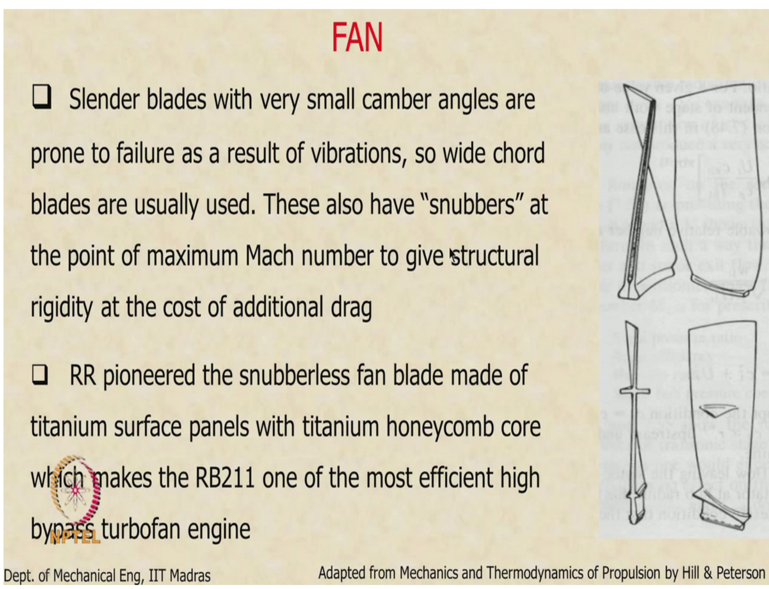

Now we look at the gas dynamic aspects of the fan blade so far. Let us now look at structural aspect because that is also important, remember many times a design may be good on paper but it may not be possible to actually realize that in concept or in real life, and that is what we are looking at next, what are the structural issues associated with fan. And we saw that there was a problem with the fan blade speed so we overcame that with a multi-spool technology.

Then we had a challenge in that we had to handle a transonic flow across the fan blade, which we overcame by gas dynamic means by designing the blade passages properly using double circular arc as well as control diffusion airfoil we overcame that challenge. The next challenge is the structural challenge how do we make sure that these blades can operate with the kind of loads that we are looking at okay.

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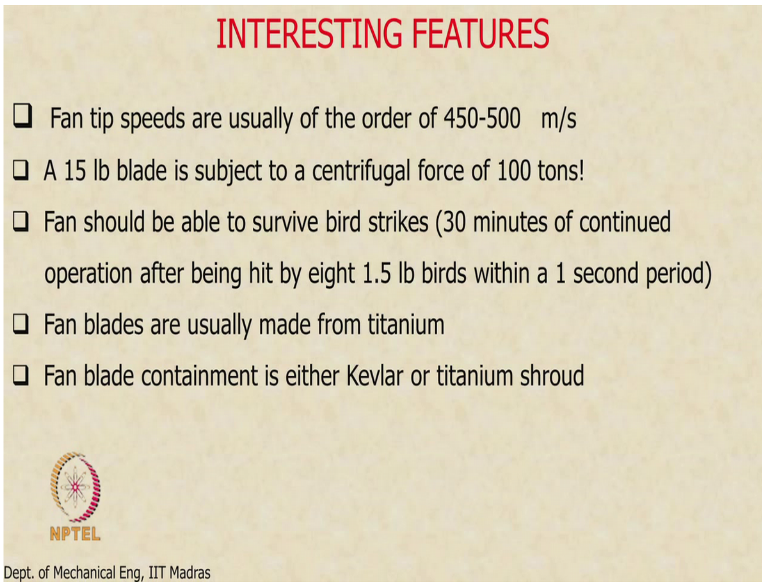

Now probably let us go to the next one, before we come to this some of the requirements of the blades as you can see from here are very challenging. The tip speeds are typically the order of about 450 to 500 meter per second, and so the relative Mach number approaching the fan blade will be in the range of 1.6 to 1.7 okay. What is probably the most challenging aspect from a structural perspective is that the fan blade itself which incidentally looks like this okay.

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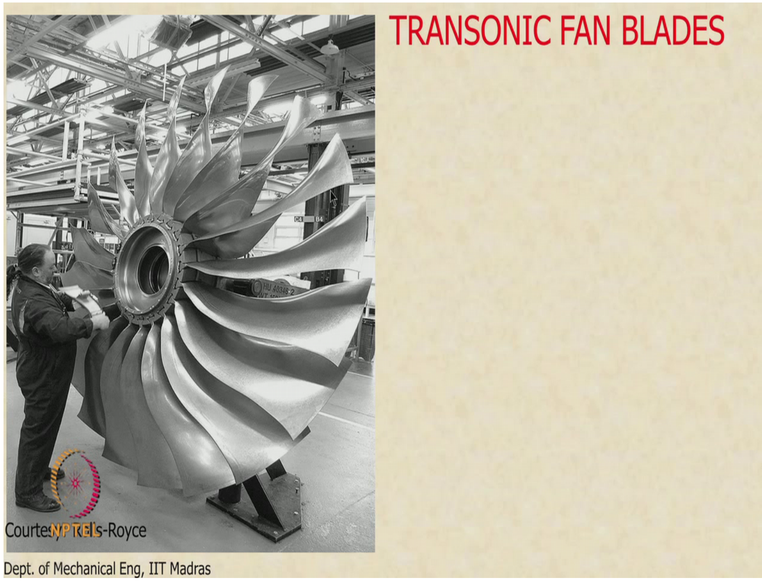

Each turbofan engine will probably have about 20 to 25 such blades okay, you can see how thin they are, and you can also get an idea about the size of the fan blades, how big they are and also how incredibly thin they are. They appear to be made of paper right, so the fan blades each blade that you see here a single blade weighs only 15 pounds, but it has to bear a load of 100 tons okay, to give this in perspective Rolls-Royce puts this in perspective very nicely in their website.

They say that you can take a train locomotive and hang it from one blade and the blade will still be able to bear the load, a 15-pound blade you can take a single blade like this and hang any train locomotive from it, it will not budge that is how strong it has to be, but it has to be slender because the flow here is relative Mach number is supersonic, we cannot put as you know we cannot put thick bluff bodies in supersonic flows, we saw that also earlier.

What happens when you put a bluff body in a supersonic flow? They get very strong bow stocks which is something we want to avoid, so it has to be slender from a gas dynamics perspective but it also has to be strong from a structural perspective, because it has to with stand this kind of load. So if you think about fan blade each blade has to bear a load which is the same as the weight of a train locomotive and it transmits power of the order of 30000 horsepower, which is about 5 times that are the most powerful engine that locomotive engine that is in service today.

The most powerful electric locomotive engine service in India produces about 6000 horsepower, so the power transmitted through a fan is of the order of about 30000 HP or so, so those are the design requirements for this. Now on top of that there are also very stringent safety restrictions because the cross-sectional area of fan is very large, it is also more prone to bird strikes, as the area increases the probability of birds hitting the engine also increases naturally right.

So it should be able to survive bird strikes that it should be able to operate for 30 minutes after being hit by 8 birds within a 1 second interval, so it is tested for such stringent conditions okay that is why we have the fan blade containment also, even if a fan blade comes lose the fan blades must still be contained within the engine must not come out and the engine should spend too stop without any harm to the fuselage or the passengers inside.

Those are some very, very strange and requirements the blades are usually made of titanium, so that is something that we will discuss here. So other challenges with the fan blade in addition to the load, the other challenges with the fan blade it has to do with vibration, so if you look at a fan blade like this, this is a tall slender structure okay. And all of you would have studied in your strength of materials course or design courses that tall slender structures are very prone to failure due to vibration tall slender columns are very prone to they can vibrate themselves to distraction.

And this fan blade is also a tall slender column, so vibration is another serious challenge with these fan blades okay, so the blades have to be strong and the blades have to be stiff, they have to be strong to bear the load, and they have to be stiff to withstand the vibrations okay. So the white card blade, this is called a white card blade, you can see the blade twisting upon itself, you can see the blade twisting upon itself from root to tip that is called a white card blade that gives it the flexural rigidity that you are looking for okay.

So this gives it the rigidity that is required to withstand the vibrations, in early designs these kinds of fixtures called snubbers were also used in this fan blade, so they are placed at a strategic locations and they used to provide additional stiffness but as you know adding any component to this stream is going to cause drag and loss of stagnation pressure. So over a period of time the technology has evolved where we can dispense with these snubbers and actually you can see that the white card fan blade is not only strong but also very stiff.

It can withstand the vibrations without the snubbers, the strength comes from the fact that the blades are made out of titanium, but they are not made out of solid titanium, it is actually made out of a titanium skin with a hollow core inside which is filled with a titanium honeycomb matrix. So the titanium honeycomb matrix while being laid gives it the structural rigidity that you are looking for, the titanium skin gives it the strength that you are looking for.

So this blades are light, they are strong and they are stiff and they can handle supersonic flows, so those are the design challenges that had to be overcome before the high bypass ratio turbofan engine technology could be realized and these are major challenges. Remember the important lesson that engineers must learn from this is a design that looks very good on paper will many times prove impossible to realize okay, which is why engineers should be flexible.

So if something 1.7 Mach number proves too much then we must be prepared to redesign from a gas dynamics perspective using our knowledge of gas dynamics to make the engine viable to make the design viable. So whatever we decide we said it has to be slender because that is what is the requirement from a gas dynamics perspective, but from the structural perspective if it cannot be met then we must go back to the drawing board and redesigned based on the knowledge of gas dynamics that we have learnt okay.

So all the decisions that we make that has tremendous consequences down the line, so usually fan blades are made from titanium the containment is usually made of Kevlar which is what the bullet proof vest are made of, it can withstand such high impact loads or some companies also use the titanium shroud around the blades to contain the blades in case of a blade off event.

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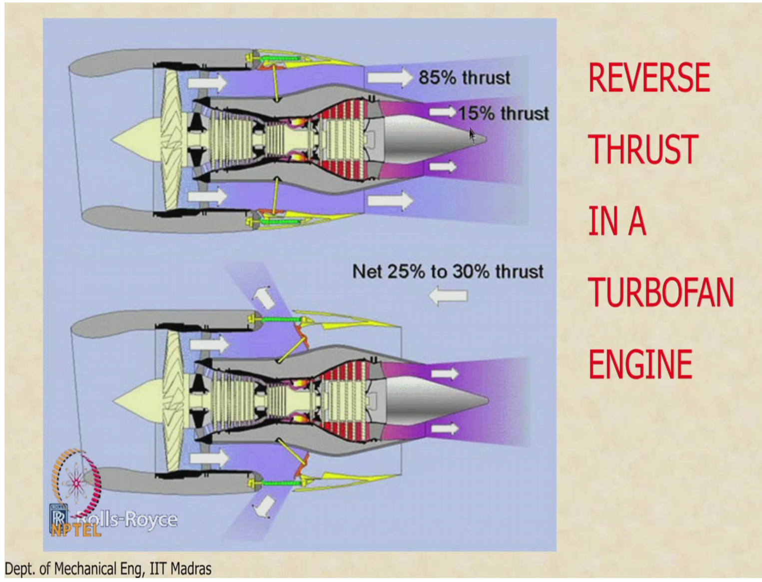

Thrust reversal maybe we saw thrust reversal in a turbojet engine, which had only one nozzle and we had these clamshell thread thrusters which were deployed when the thrust has to be reversed, but in a turbofan engine it does not make sense to provide thrust reverser here because this generates only 20 to 25% of thrust. Thrust reversal must be deployed in the stream which produces bulk of the thrust and that is fan stream okay.

So what is the normally done is, so here is the fan stream and you can see a unit here this is actually something like a cascade of blades, and when the thrust reversal this is the normal operation and when the thrust reversal is deployed we can see this cascade, and the air is deflected through the cascade. So the cascade is like a set of stator blades which deflect the flow like this right, so it deflects the flow.

So it is actually a set of stator vanes which deflects the flow this way right, and then it gives you about 25 to 30% thrust in the forward direction, okay. This is what is used to bring the aircraft to a halt, so you can actually see if you manage to fly next time and if you manage to get a seat right above the wing and you can see this opening when the aircraft lands and you can see the air coming out okay, and this is deployed in the fan stream, any questions?

So we have looked that all the design features of turbojet and turbofan engine different components, and we have also looked at the challenges and how they are overcome that should give you a big picture idea of the technology that is involved in this okay. What we are going to do next is to do a thermodynamic analysis and a gas dynamic using gas dynamic principles we are going to do analysis of an engine to calculate the 2 quantities that we always said we want to calculate.

One is thrust, the other one is fuel consumption or thrust specific fuel consumption, and that is what we are going to do next. So we are going to take a closer look at the thermodynamics of the engine and the processes, efficiencies and so on.

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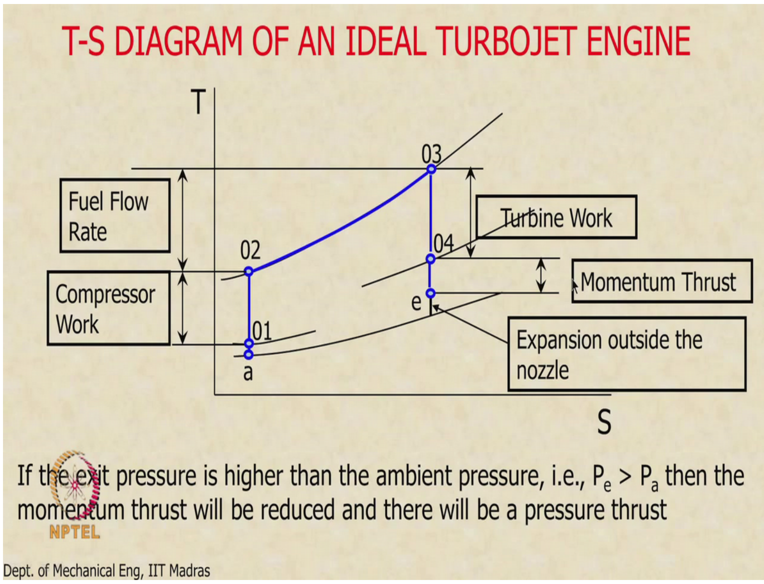

So let us start with the basic turbojet cycle, so we are going to start with the TS diagram of an ideal turbojet engine, what I mean by ideal is the losses or neglected. We will take losses into account later on, when we do a component by component analysis, we will come up with a metric for the losses or we will define and efficiency and take losses into account that way. For now we will look at an ideal engine, because the principles and the important ideas are easier to understand from an ideal cycle.

So we are going to look at turbojet engine, there are 2 isobars the engine operates between these 2 pressures, remember the pressure ratio is one of the parameters of a turbojet engine, so it operates between these 2 pressure this is the freestream denoted by letter A, this is the state at which the fluid enters the engine. And because in subsonic aircraft the inlet does not play too much of a role, so we go from free stream air to stagnation state 01 at the entry to the compressor 01 is an entry to the compressor okay.

So 01 to 02 is compression process in the compressor right, so the stagnation pressure increases as you can see due to addition of work, and this is proportional to the compressor work right. Then we add heat in the combustor, and so we go from here to stagnation stage 03 at the end of the combustor and the vertical distance is proportional to the fuel flow rate, the higher the fuel flow rate the higher the stagnation temperature here right so this is proportional to fuel flow rate.

This is the turbine and again we go from state 3 to state 4, we extract work from the fluid here so that we can use it for running the compressor okay, because isobars diverge from each other these 2 are equal numerically but not in this figure okay because isobars diverge from each other right, the turbine work is = the compressor work. But in this diagram 3 and 4, T03-T04 will not exactly be = T02-T01.

However, the work will be the same okay, so you must keep that in mind okay. So the reminder of the remaining enthalpy is then extracted as thrust in the nozzle and this is converted to thrust in the nozzle, if the exit pressure is about the ambient pressure meaning flow is under expanded, then we also get this is the momentum thrust that we get from the engine, and we also get a pressure thrust from the nozzle right.

So if the pressure is higher and then we also get an additional pressure thrust, if the exit pressure is equal to the ambient pressure then we get only momentum thrust from the engine okay, so the momentum thrust is proportional to this we cannot really show the pressure thrust here but the pressure thrust is also available in case Pe>Pa, it is a convergent nozzle so Pe cannot be <Pa right.

So you see the different terms here and what we are going to try to see next is how is the thrust affected when we adjust different parameters in the cycle. What are the parameters in an ideal turbojet cycle there are only 2 parameters, one is the pressure ratio right this is the pressure ratio, and the other one is the turbine inlet temperature. These are the only 2 adjustable parameters in the cycle.

So what is the effect of adjusting these parameters on the performance or on the thrust and the fuel consumption? These are the 2 things that we are looking for thrust and fuel consumption right. So we let us take a look at that next.

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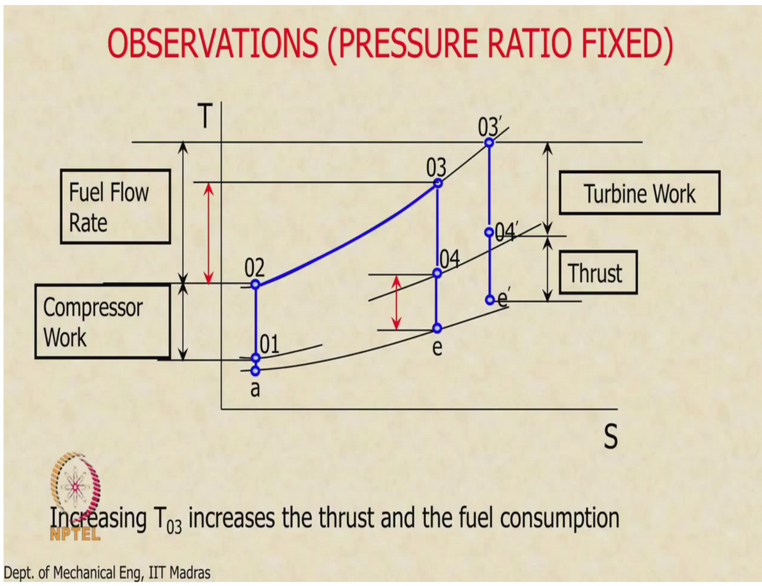

So we will first look at the effect of increasing the turbine inlet temperature keeping pressure ratio fixed, so this was the basic cycle that we saw earlier right, I have just redrawn the same cycle here, I have not change anything this is the basic cycle. What we are going to do now is what happens to the thrust that is produced and the feel that is consumed if I increase the turbine inlet temperature, which means I keep sliding along this and then I want to see the effect on the overall performance okay.

So you can see that this is the fuel consumption, this is the thrust that is produced assuming that let us assume that it is correctly expanded that is easier to deal with, really there is no loss of generality for the sake of simplicity we will assume it to be like this okay. The compressor work does not change right because the pressure ratio is fixed, so the compressor work does not change the only thing that is going to change is the turbine entry temperature, which means this state point is going to slide up along this isobar right.

So we go from 03 to 03 prime if I increase the turbine entry temperature, and remember the turbine has to produce enough work okay to run the compressor and the compressor work has not change, which means that this point will be located such that the work from this is equal to this work or equal to this work actually, it must produce the same amount of work. So that means this is what I am going to realize as thrust okay.

Notice that had the previous case been correctly expanded this case would be under expanded, e prime will be more than e, Pe prime will be more than e, because now I am up here at a higher temperature right, and I am extracting the same amount of work which means that 04 is going to move up, which means that e prime will also move up from e okay. So now we can see that the fuel flow rate has increased from this value to this value now because this has gone from here to there okay.

Turbine work has remained the same, but the thrust has changed from here to there and that is also a pressure thrust which we are going to realize now which was not there before okay. So we can summarize these observations this way, when I increase the turbine entry temperature clearly the fuel flow rate increases and the thrust will also increase that we can see from this diagram very clearly, both the thrust as well as the fuel flow rate increase when I increase the turbine entry temperature or turbine inlet temperature.

Of course remember this is only a theoretical exercise, we saw that the turbine entry temperatures cannot exit about 1700 Kelvin today, so what we are trying to see is the effect of turbine entry temperature on the performance of a cycle, so this is a theoretical exercise that we are going through to see how these parameters affect the cycle. This is also important because what we can get from these types of parametric studies is which one will give us more benefit.

Do I benefit more by attempting to increase the turbine entry temperature or do I benefit more by attempting to increase the pressure ratio in the cycle right that is the kind of insight that this theoretical exercise will provide okay. So we have looked at effect of one parameter, what we are going to do next is keeping turbine entry temperature fixed we were look at the effect of changing the pressure ratio increases the pressure ratio.

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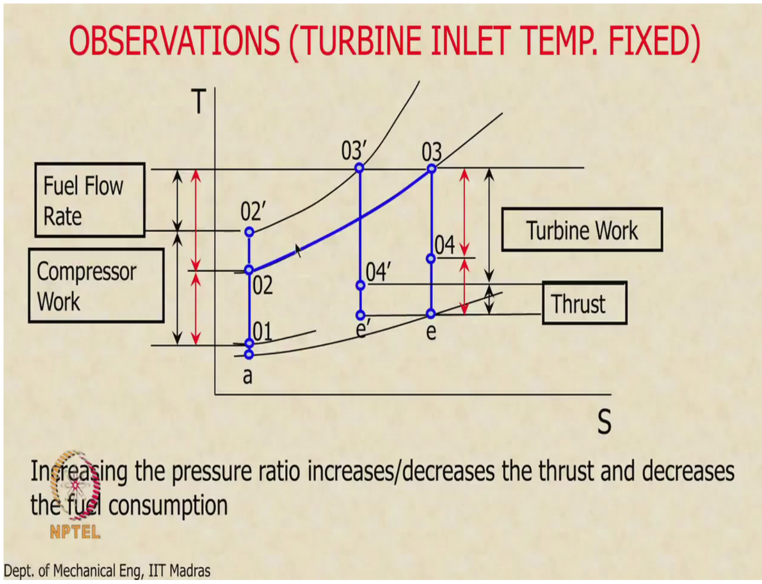

So we will keep the turbine inlet temperature fixed, this is the basic cycle that we saw earlier, so what we are going to do now is we are going to keep T03 same, we will keep T03 the same and we will increase the pressure ratio okay. So let us see what happens, this is compressor work now the compressor work will also change because we are increasing the pressure ratio right, so this is the earlier value for the compressor work and turbine work.

And this is the fuel flow rate and this was the thrust that we had earlier, and this is the thrust and we have all these other quantities, so the base line quantities are indicated in red here. What happens or what will happen when I increase the pressure ratio, so I go to 2 to 2 prime right because I am keeping this fixed I can go only up to 03 prime here, because T03 is fixed the peak temperature is fixed right, so then I extract some work right.

Notice that because 3 prime is to the left of 3 this actually will probably move down from 04, because 3 prime is to the left of 3 okay, remember the isobars diverge, so when I am moving to the left to get the same work out of my turbine I have to drop down a little bit more than what I do here, so that means this is going down okay, and then I expand from 04 prime to e prime okay. So what are the implications on fuel flow rate and thrust?

So you can see that the compressor work has increased now understandably, turbine work has also increased okay, what has happened to the fluid flow rate? So compared to the earlier one the fuel flow rate has decreased understandably right, because the pressure ratio is more the air is actually hotter when it comes out of the compressor now than before. Previously, it was coming out at a temperature which is corresponding to this now there is hotter because the pressure ratio is also higher.

So that means if I keep my peak temperature fixed, the air entering the combustor is hotter that means I can add only less amount of heat in the combustor that means the fuel flow rate will also be less and that is what this one is showing me. Turbine work is more which means the thrust has actually will most probably go down, but that depends upon this pressure ratio related to this, for example if this pressure is such that 3 prime maybe is over here then the thrust may not decrease so much okay.

But if it is too far to the left then the thrust will likely decrease, but we can say clearly that will flow rate decreases and the thrust may or may not decrease that depends upon the exact value that we are looking at okay, we will quantify this in the next view graph when we actually show some numbers, but for now from this figure we can qualitatively infer that fuel flow rate will decrease and the thrust may increase or decrease.

In fact, in under some circumstances when we are located over here, these isobars are such that remember I am also getting a pressure thrust now okay, I am getting a momentum thrust and also a pressure thrust, so it is quite possible for some values that we may actually get the slight increase in thrust, so that depends upon their relative position of 3 and 3 prime okay. So now we need to work with numbers to see how it will come out and that is what I am going to show next.

But for now we can summarize our findings this way, inferences from this graph or like this. increasing the pressure ratio can increase thrust maybe or decrease the thrust depending upon the actual value or the baseline case that we are looking at, but it definitely decreases the fuel consumption that is unambiguous okay. Now so what we will do now is we will have combined these 2 findings and try to look at them in with some numbers thrown in so that we have good idea.

So we get quantitative idea all the influences now are qualitative we will try to get a quantitative idea on how this happens.

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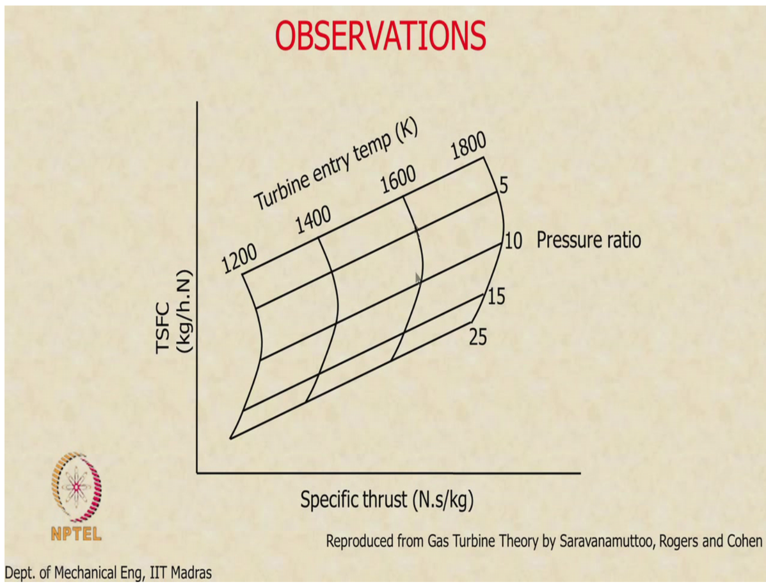

So here is how the numbers look like, so I have plotted thrust specific fuel consumption okay, so this is real flow rate and this is specific thrust. So the influences that we gave earlier seem to be okay, so with increasing turban temperature for irrespective of the pressure ratio, an increase in the turbine entry temperature increases fuel flow rate on the y-axis right and thrust also that was what we saw from our earlier view graph right.

For any pressure ratio increase in turbine entry temperature increases the fuel consumption and also the thrust. However, for a given turbine entry temperature if you take any one of the turbine entry temperature here and if you look at the effect of pressure ratio, you see that the specific thrust actually increases slightly up to about a value of 10, and then it begins to decrease and that was what we had also said thrust can increase or decrease depending upon the actual value of the pressure ratio and that is what this one also tells you.

Now this tells you quantitatively that thrust actually increases up to a pressure ratio of 10, and then begins to decrease specific thrust. But what happens to the fuel consumption as we inferred from a earlier view graph fuel consumption continuously decreases as I increase the pressure ratio right that was something that we said that was unambiguous and you can see that from this curve also.

So for a given turbine entry temperature any value here, the fuel consumption decreases like this. Notice that what we have plotted here is actually thrust specific fuel consumption and not exactly fuel consumption okay, so we have plotted fuel consumption per unit thrust, so you can see from here that the thrust increases and decreases, but these values these increase and decrease are actually much less than the changes in the fuel consumption which is why you are able to infer this trend from this graph also.

We did not have specific quantities in the previous TS diagram right, we had only other quantities but the trends that we are seeing here are consistent with what we saw earlier, so this is the effect of these parameters on the cycle performance. And you can see now from this graph why there is a continuous push to increase the turbine entry temperature and a continuous push to increase the pressure ratio, so now we are operating at pressure ratios around 40 or so.

So there is a continuous push to increase this, and the continuous push to increase this also right, **“Professor - student conversation starts”** any questions? Yes, why is the specific thrust increase? This is thrust per unit mass and that has to do with the way this curves are, the way they diverge okay, what happens is when these are closed here we are getting momentum thrust, but we are also getting some pressure thrust from here.

So the sum of the 2 because we are now operating at the different conditions can actually exceed what we had previously okay, as we go from smaller see the graph also if you look at the graph, the graph starts from low pressure ratio and keeps increasing, which means that for the baseline case this 3 will be over here, and the next one will be over here. So the 2 curves will be quite far apart we are starting from very low values of pressure ratio and then increasing it.

So which is why initially because of the way the isobars are there can actually be a slight increase in thrust, but then it will begin to decrease as you go to reasonable values of pressure ratio, there is just the way the diagram is and the isobars are. In this exit pressure T04 and T04 dash is the same?

No they need not be same that is what I am saying, we cannot say because what the state point 04 prime and state point 04 are such that the amount of work produced by the turbine is equal to the amount of work required by the compressor that is what determines the exit state okay. When we do numerical example later on you will see that, so we get the exit state by equating the work from the turbine to the compressor okay, the exit state of the compressor is known because I know the pressure ratio.

I know the cycle pressure ratio but the exit state of the turbine is determined based on the amount of work that we extract from the turbine. Remember the pressure ratio is only for the compressor not for the turbine right. Any other questions? Okay. **"Professor - student conversation ends."**

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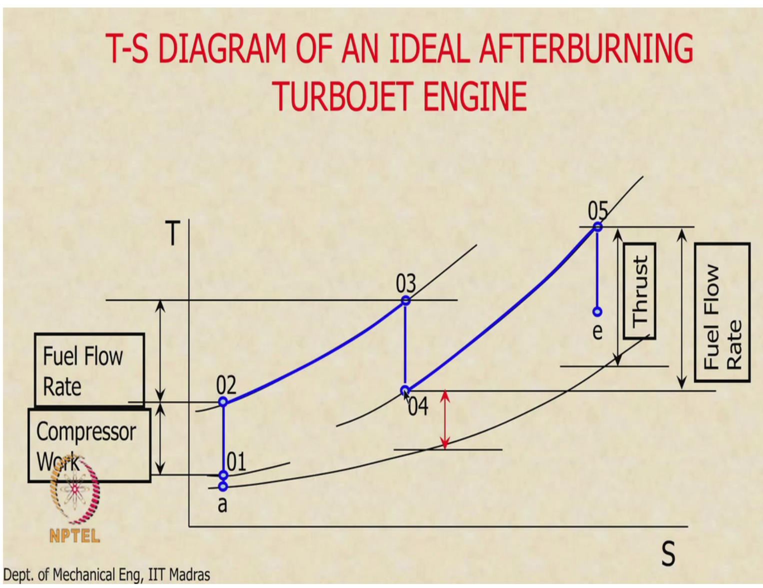

So now let us take a look at the ideal cycle for an after burning turbojet engine, and you can see here that this is the basic cycle right, this was the basic turbojet cycle, this is proportional to the compressor work, this is proportional to the fuel flow rate, and then turbine work and this was the thrust that we had produced earlier. Now when you add an after burner, so we take the fluid from the turbine exhaust and before we send it to the nozzle we actually send it into then after burner, where we burn fuel and increase the stagnation temperature.

So we go along this isobar up to state point 05, where the stagnation temperature will be more than what it was here most cases or it may be comparable to this that does not matter okay, so goes up to there and then we expand this in the nozzle okay. Notice that because we are now burning fuel in this case also in addition to this fuel flow rate, there is also an additional fuel flow rate here between 4 and 5 correct.

Because we are adding fuel and burning the fuel here in the after burner duct, in addition to this fuel flow rate there is one more fuel flow rate here which is what is indicated here, but you can see that there is a considerable increase in the thrust as a result of this okay, and that was something that we saw earlier also addition of the after burners can give us 30, 40 or maybe even higher values of thrust augmentation, so which is a good thing.

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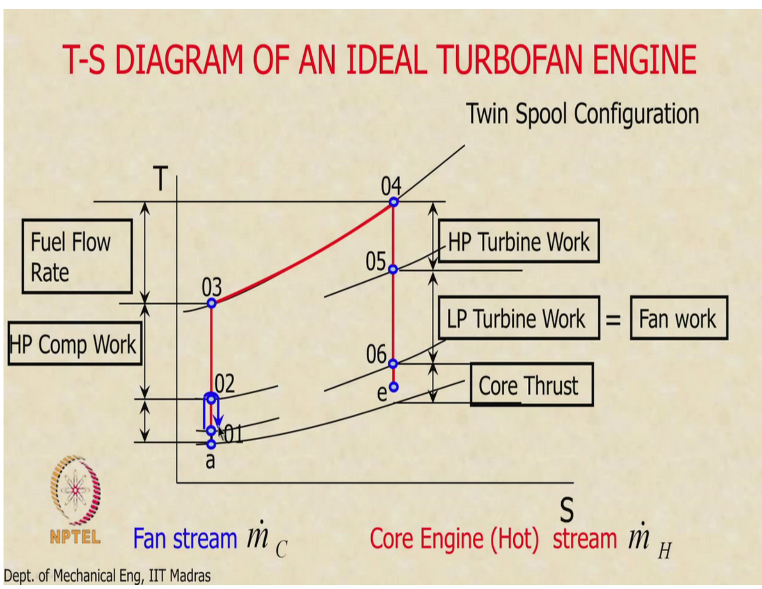

So if it is 30, 40 augmentations that means the actual value is as we are seeing here 150% of this right, is we will follow this up with a look at the TS diagram of an ideal turbofan engine okay. And the turbofan engine as I said earlier has multiple spools because of the differential speed requirements of the fan and the compressor blades, so the fan has to spin at much lower RPM whereas they are the last stages of the compressors have to run that much higher RPM.

So it will have multiple spools and what we will discuss in the course is a twin-spool configuration, so it has 2 shafts fan is mounted on a separate shaft and the rest of the compressor is mounted on a separate shaft, so that is why it is called twin-spool configuration, and let us see what this look like. So as you can see from here this TS diagram corresponds to the basic turbojet part of the turbofan engine that is why I am calling this the core engine or hot stream okay.

If you remember the core engine or hot stream is the engine in the innermost part of the entire engine, so the turbofan or the fan bypasses the air around this core engine. So what we are seeing here which is indicated in red is the thermodynamic process that an amount of air mass flow rate of m dot H will go through okay. There is a new difficulty here in depicting states on thermodynamic depicting processes on this TS diagram.

Because the mass flow rate is different between the core engine stream and the fan stream, and mass flow rate is not something that we can indicate on this diagram okay, so you have to be extremely careful in interpreting enthalpy changes on this diagram right. So m dot H is the mass flow rate of air that goes through the core engine. So you can see that, so if you follow a streamline that goes through the core engine we start from the free stream.

And then we go through the intake at the end of the thermodynamic state is 01, and then this part of the air the m dot H part of the air goes through the inner portion of the fan right, where it achieves a certain pressure rise usually as we said 1.15 or 1.17, so that is this. So this is the m dot H the amount of air m dot H that goes through the inner part of the fan right, so there is the pressure rise there.

And then the air goes through the rest of the compressor m dot H goes through the rest of the compressor combustor turbine with this is the high pressure turbine, remember this is a twin-spool configuration that means there are going to be 2 turbines 04 to 05 is the high pressure turbine 05 to 06 is the low pressure turbine, and then it goes through the engine nozzle okay, so this is indicated in red, red indicates the air that goes through the core engine okay.

So now if you can see this is the HP compressor work, and remember the HP turbine produces enough work to run the HP compressor, so HP turbine work is = HP compressor work for the core engine, and this of course is proportional to the fuel flow rate, this is where we are adding heat in the combustor in the core engine. The fan stream is cool throughout, so there is no heat addition there, and the thrust produced by the core engine is indicated here.

So I can see that this is the core thrust and if it is under expanded that is going to be additional pressure thrust also that is available from the core engine okay. What I am going to do next is overlay the thermodynamic processes undergone by the air that goes through the fan alone or the bypassed air alone okay. We denote that mass flow rate as m dot C, so this is the fan stream okay, m dot C is the amount of air that is bypassed around the core engine okay.

So the total mass flow rate through the entire engine is going to be = m dot C+m dot H okay, writing it this way is more convenient because the bypass ratio is equal to what is it equal to? m dot C/m dot H okay. So writing it this way is easy, C denotes the air which is cold air that means heat does not add at all, so if you look at the fan some part of the fan an amount of air=m dot H, which goes through the entire core engine.

The rest of the fan handles amount of air=m dot C, which goes only through the fan and the fan nozzle okay. So that is what we are going to indicate next, so you can see that I have indicated that using a curved arrow to differentiate between these 2 okay, so the m dot C of the air goes through the intake from a to 01, and then from here it goes through the fan and then 02 to 02 to the exit will be the fan nozzle.

I have not indicated the fan of the here but the expansion process from 02 to this pressure is the fan nozzle part of it okay. Remember the fan has nozzle, the thrust is produced by nozzle unlike a propeller okay, this is blue the most important thing that you must remember is the amount of air that goes through this fan stream is much higher than the amount of air that goes through the rest of the engine okay.

So the change in stagnation state in the fan maybe it may appear small because 01 and 02 appear to be small, but the amount of work is very large because this is going to be multiplied by the amount of air that the fan handles, which is going to be m dot C+m dot H. Whereas the LP turbine handles only m dot H, but it has to produce an amount of work which is equal to the fan work, which is why you see 05 and 06 being quiet for apart.

Whereas 01 and 02 although the work is the same 01 and 02 being very close to each other that is because of the difference in the mass flow rates. This enthalpy change is multiplied by m dot C+m dot H, whereas this enthalpy change is multiplied by m dot H alone that is why they appear this way okay. Once again the expansion in the fan nozzle from will be from 02 to some exit state which we will denote as e sub C, C denotes cold and H will denote hot okay.

So again the exit pressure from the fan nozzle may be equal to the ambient pressure, it may not be equal to the ambient pressure also that is also possible, it is difficult to illustrated here you know the figure will become too crowded I am not indicated that, we will look at it later on when we focus on the fan nozzle on the nozzle part alone okay.

“Professor - student conversation starts” Is that clear are there any questions? (()) (38:58) we do not go beyond that we stop with the exit of the nozzle, the mixing process normally takes place outside in the ambient, in some cases it may take place in the duct also, but for our cases we are trying to predict only the thrust which means all I need to know is the exit velocity and the exit pressure from the core nozzle and the fan nozzle right.

The mixing process is only from a noise perspective and that is not of interest to us we are not interested in that right. Are the central portion and the tip of the pipe will it be same? That is why I said that the portion of the air which goes to the core part of the engine we will also have the same pressure rise, and the one in the tip will also have the same pressure rise, the blade speed may be different from here to there, but the overall pressure rise across the fan will be constant that is usually 1.17 or so.

This is subsonic that is supersonic or it is the transonic fan, which gives the pressure rise of 1.17 across it right, that is why I have indicated 02 for the core stream also and for the fan stream, so that pressure rise is the same across the 2. “Professor - student conversation ends.”

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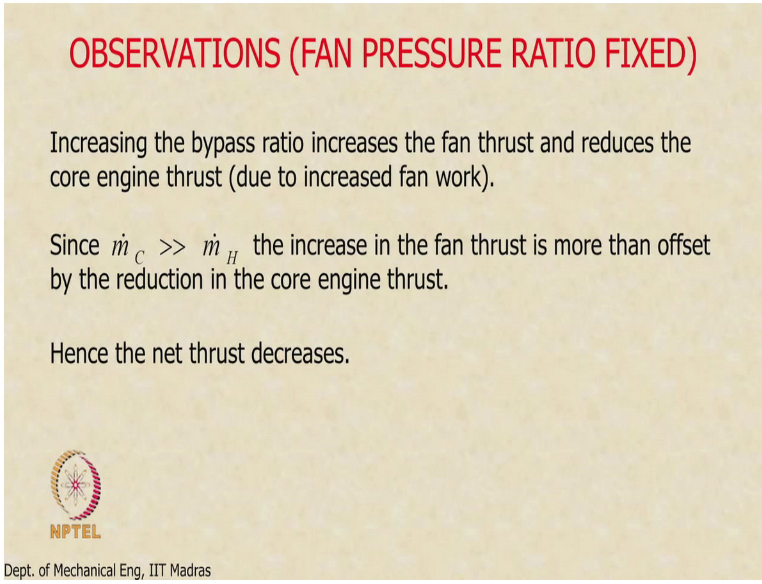

Now if you think about this in the earlier turbojet cycle we identified 2 parameters in the cycle, one was the pressure ratio, other one was the turbine entry temperature. Now with a turbofan cycle and we looked at the effect of increasing the turbine entry temperature on the performance of the cycle, and the performance was assessed based on fuel flow rate and specific thrust or thrust itself that was so we looked at the effect of increasing turbine entry temperature on these 2 matrix.

And we also look at the effect of rising the pressure ratio on these 2 matrix, so there were 2 parameters in the turbojet cycle right pressure ratio and the turbine entry temperature, and the performance metric was thrust and mass flow I mean fuel mass flow rate. Similarly, with the turbofan cycle in addition to the pressure ratio which will be P03/P01, and the turbine entry temperature which will be T04.

There are 2 more parameters now, one is the fan pressure ratio P02/P01, the other one is the bypass ratio m dot C/m dot H, so we have 2 additional parameters. So we want to see how these parameters affect the performance metrics namely total thrust and fuel consumption right. So that is what we are going to look at next, so first we look at the effect of bypass ratio alone with fan pressure fixed, remember this is only a thermodynamic analysis.

For example, if we increase the bypass ratio the engine size will increase the nacelle drag will increase, so there are other effects, so we are not taking those effects into account here there is only a thermodynamic perspective of what happens when you do this okay, so keep that in mind. So if you increase the bypass ratio understandably m dot C increases that means for the same pressure ratio, if I increase m dot C then I am going to get more the velocity change may be the same because the pressure ratio is the same.

But the m dot is multiplying the change now, which means I get more fan thrust, so the fan thrust definitely increases. But the core engine thrust has to decrease now, because the fan is now consuming more work, since if I increase m dot C right what happens is the work consumed by the fan increases because that is multiplied m dot C that means the low pressure turbine now has to do more work.

So if you see here everything here will remain the same up to 06, remember this is the LP turbine work which is equal to fan work, 02 will remain the same because the fan pressure ratio is fixed right, we are only looking at increasing m dot C, so that means the effect of m dot C will not show up anywhere here except here, if I increase the fan work that means this state point 6 will keep moving further and further down as I extract more and more work right.

As it keeps moving further and further down what happens to the core engine thrust, the core engine thrust will decrease right, for example here the way we have drawn the core engine nozzle appears to be under expanded right. So there is momentum thrust+ pressure thrust and as I keep moving this down right, if it is under expanded that means the core engine nozzle is choked right as I keep moving this further and further down e will also keep sliding down.

So eventually what happens to the core engine nozzle it may actually become unchoked correct, so the thrust produced by the core engine nozzle decreases continuously as I increase the bypass ratio right that is what we have written here, so as I have increase the bypass ratio the fan thrust goes up, but the core engine thrust is reduced okay. Now the core engine thrust is reduced much more because m dot C is so much higher than m dot H that means for producing the increased amount of work the state point 06 will slide down much more because m dot C is much more okay.

So the loss of C engine thrust is usually more than the gain that you get from the fan thrust increase in fan thrust, remember the fan thrust increases because m dot C increases okay, but increase in m dot C is a certain amount right, for the same increase in work the LP turbine exit will have to move further down okay. So that means the reduction in the core engine thrust is more than the increase in the fan thrust, which means the overall thrust will decrease when you increase the bypass ratio.

Even without taking into account the increased nacelle drag okay, so generally when you increase the bypass ratio, the overall thrust will reduced, because V eH is usually much higher than V eC, where V eH is the velocity from the exhaust or the hot nozzle, and the nozzle becomes unchoked then the overall thrust will actually decrease in this case increasing in the bypass ratio okay that is one affect.

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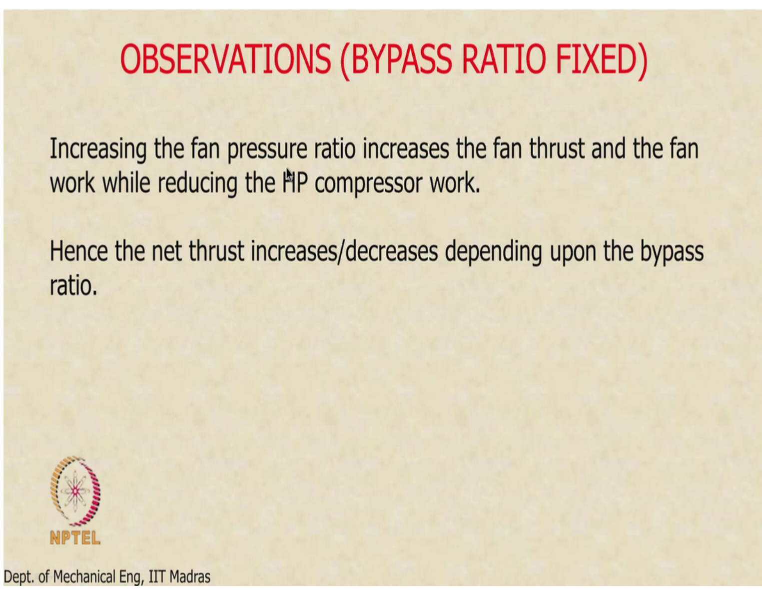

The next effect is keeping bypass ratio fixed what happens if I increase the pressure right, now that also we can see from here, now increasing the fan pressure ratio increases the fan thrust and the fan work right, so if you see here in the cycle if I increase the fan pressure ratio that means I am moving to upwards right this work will increase, this work is going to increase because I am moving this up and this must produce enough work to do this.

But keep in mind that this work has will decrease now, because this is moving up, so the HP compressor work is also moving up, so the advantage now is in the previous case 5 was fixed, 6 kept moving down. In this case now 6 is moving down but 5 is also moving up, do you understand the point? Because increasing this pressure ratio reduces the amount of work that the HP compressor has do, which means this will go up that is fixed we have fixed the turbine entry temperature that means this will go up.

So the increased fan work is being accommodated by this moving up and this we do not know how much this will move perhaps it may not move at all or if this increases too much then this may begin to move downwards that is possible right. So in this case whether the total thrust we cannot say whether it is going to increase or decrease all the time, so increasing the pressure ratio will definitely increase the fan thrust, but it may not adversely affect core engine thrust.

The core engine thrust may remain the same, in fact if this goes up too much the core engine thrust may actually increase slightly also that is also possible correct, this goes up right and if this also goes up right then the core engine thrust may actually increase slightly because this goes up what happens to the pressure thrust? Pressure thrust will increase right, because the flow will be more under expanded now okay that is the difference between increasing the bypass ratio alone or increasing the fan pressure ratio.

This point begins to slide up on this vertical line, so the overall thrust may increase or not okay, so that is what we are saying here, increasing the fan pressure ratio increases the fan thrust and the fan work while reducing the HP compressor work. So consequently the net effect is that the net thrust can increase possibly but depending upon the actual pressure ratio and the bypass ratio it may also decrease.

If the bypass ratio is already too high okay already very high then increasing the fan pressure ratio may actually reduce the fan thrust, because the amount of work that the fan is taking up is so high that it is going to heat up all the work that the turbine produces. So that depends upon the exact value of the bypass ratio, so it is a complex interplay between these components.

And remember this is only the thermodynamic analysis increasing the bypass ratio as lot of downsides for the down the line as I said you know the frontal drag increases, the mechanical inertia of engine also increases, engine become less responsive to changes, so the overall drag increases+ mounting the engine on an existing aircraft is also a problem, because the wing height may not be sufficient to accommodate the increased bypass ratio.

So the fuselage and the wings will have to be redesigned, so from a thermodynamic perspective increasing the bypass ratio maybe you know maybe desirable, in fact many engine manufacturers are going that way, but to go to really high bypass ratios you need to look at where the engine has to be mounted, and that is something that we will see as we go down the line okay alright. So what we are going to do next in the next class is look at this individual processes and account for realistic effects.

So we have assumed this process as to be isentropic, what we will do is assume that there are irreversibilities in the process in the compression process in the expansion process in the turbine, expansion process in the nozzle, core engine nozzle, fan nozzle and also pressure losses in the combustor, these are all realistic you know that when we add heat to a flow, there is going to be loss of stagnation pressure.

So there will be a lot of stagnation pressure in the combustor also probably 10 to 15%, we need to account for all this in our thermodynamic analysis before we go on to do thrust calculation, and that is what we are going to look at in the next class. How do we account for irreversibilities in each one of these processes here okay, and we will come up with the efficiency metric for these devices and account for irreversibilities that way that is what we will do in the next class.