Gas Dynamics and Propulsion
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Lecture – 38
Ramjets

In the previous class, we were talking about internal compression intakes.

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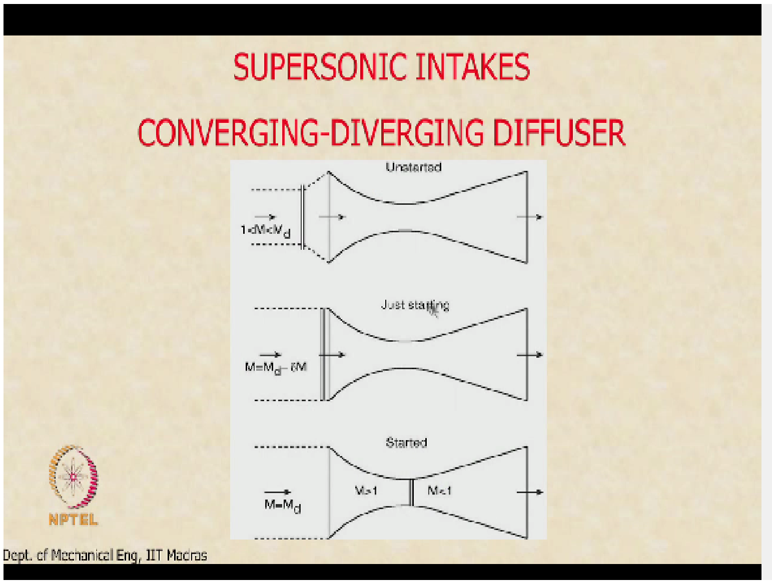

SUPERSONIC INTAKES

CONVERGING-DIVERGING DIFFUSER

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And in that too, we were discussing this converging-diverging diffuser. We pointed out the fact that even when the Mach number is supersonic, the intake is unstarted for values of Mach number less than the design Mach number, Md. There is a normal shock which stands in front and the flow that enters is usually subsonic and then as we increase the Mach numbers, as we approach the design Mach number, there is a normal shock which stands right at the lip of the lip intake.

And it is difficult to move this further down unless we overspeed the intakes. So under design conditions, this is what the flow field is supposed to look like. When M becomes equal to Md, the shock is supposed to move inside and stand at the throat as a very weak or infinitesimally weak shockwave but once you get into this type of a situation in real life, this shock will not move inside automatically.

So what needs to be done is to overspeed the intake, so that is what we talked about. We have to overspeed the intake and swallow the shock but the problem is even after that even the smallest disturbances in the inlet condition, will cause the shock that was swallowed to be disgorged. So it will come out again and stand outside like this. So which means that I need to speed-up the intake some more to pull the shock back inside.

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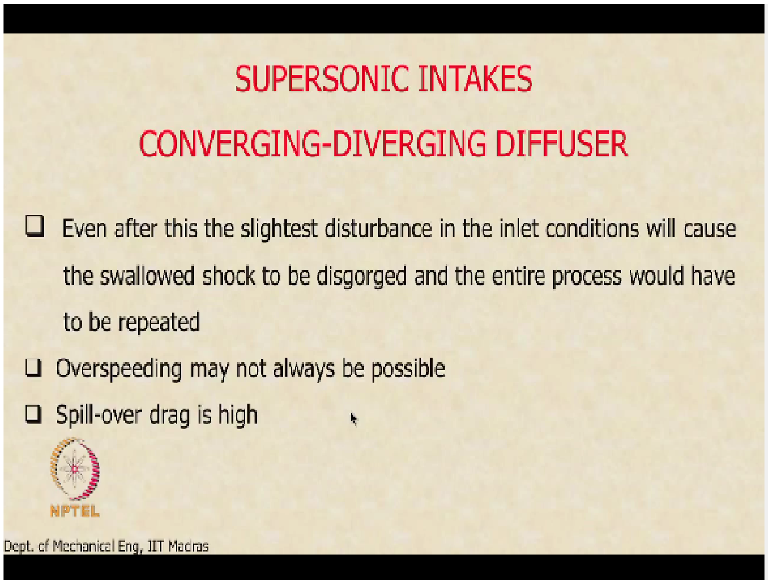

SUPERSONIC INTAKES

CONVERGING-DIVERGING DIFFUSER

- ☐ Even after this the slightest disturbance in the inlet conditions will cause the swallowed shock to be disgorged and the entire process would have to be repeated
- ☐ Overspeeding may not always be possible
- ☐ Spill-over drag is high

So this kind of cycle is very difficult to realise in practice because the intake has to be controlled constantly or the conditions have to be adjusted constantly which is not a good idea in practice. So this is a problem and spill-over drag is also high. Now there are 2 strategies which may be used for overcoming this problem and that is what we are going to look at next.

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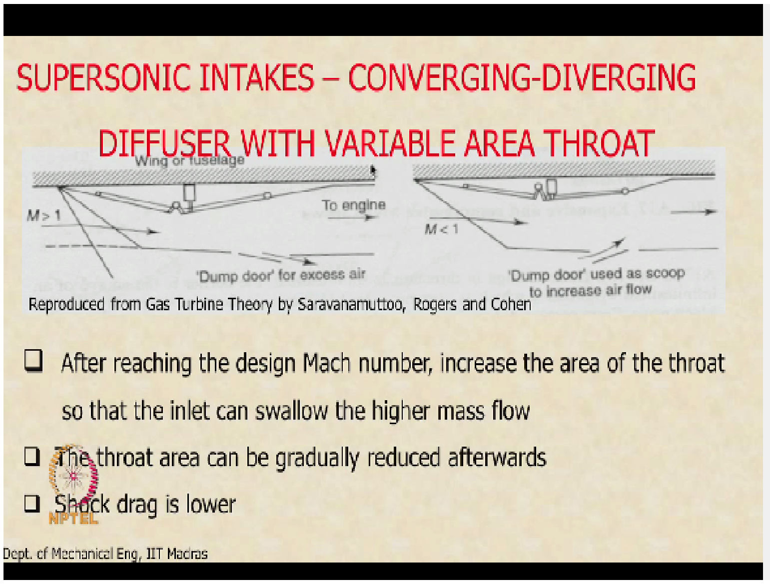

SUPERSONIC INTAKES – CONVERGING-DIVERGING DIFFUSER WITH VARIABLE AREA THROAT

Reproduced from Gas Turbine Theory by Saravanamuttoo, Rogers and Cohen

- ☐ After reaching the design Mach number, increase the area of the throat so that the inlet can swallow the higher mass flow
- ☐ The throat area can be gradually reduced afterwards
- ☐ Shock drag is lower

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One strategy is to have a diffuser with the variable area throughout. So the basic idea is that once you reach the design Mach number, for example, once we reach the designed Mach number, we still have a normal shock which is standing here and that was the problem, right. So to swallow the shock, we had to overspeed, okay. So the strategy is once we reach the design Mach number and there is still a normal shock here, you open this throat little bit wider.

When you do that, the shock begins to move inside, it is swallowed and then you bring the throat back to its original value so that you release the flow field like this. So if you open the throat a little bit, the shock goes inside and then will stand here and then you move it back so that the flow inside is completely shock free. Remember this was the strategy that we used in supersonic wind tunnels also to get the tunnel started.

We open the second throat to allow the shock to move through and then we brought it back. The same thing has to be done there also and this is something that is used for example here I am showing the intake of the Concorde which uses this kind of strategy. So the throat is actually widened or you allow some of the air to get out. So you dump some of the air. So the basic idea is to allow the air to come through.

If you do not do that, then the shock will always stand at the inlet, it will never move inside but if you allow the entire mass to come through to swallow the higher, then the shock will also move inside and that is what is done here, okay. So we can increase the area to allow the shock to move inside.

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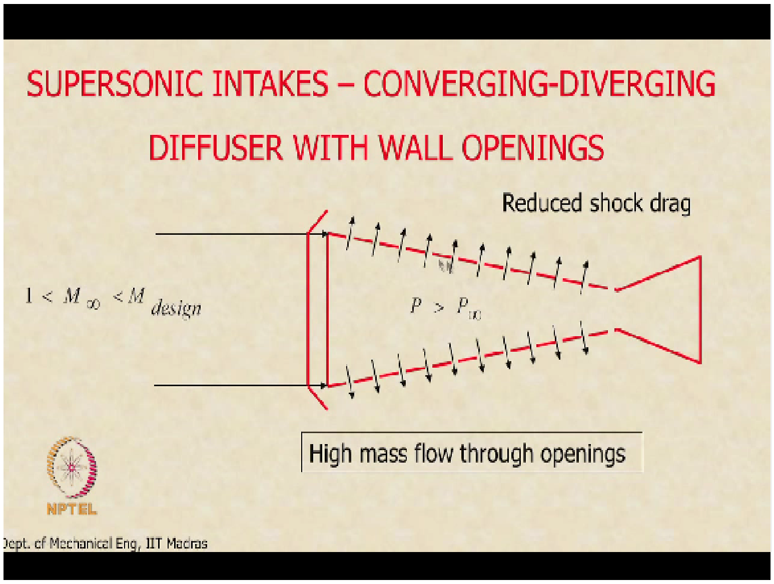

SUPERSONIC INTAKES – CONVERGING-DIVERGING DIFFUSER WITH WALL OPENINGS

Reduced shock drag

$1 < M_\infty < M_{design}$

$P > P_\infty$

High mass flow through openings

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Or we can also use this type of an arrangement where we spill the excess mass to force the shock to move inside. So here we are looking at the same converging-diverging diffuser but with openings on the side wall like what we saw in the previous slide. So the Mach number as it approaches the design Mach number, we have an oblique shock which stands like this and because we are dumping the excess mass, the shock will very rapidly move towards the intake, okay.

And in the initial stages, there will be lot of mass flow through this openings, the pressure here is more than the free stream pressure. So automatically there will be a lot of mass flow through these openings and the shock will keep moving towards the diffuser and you keep speeding up the intake and the shock keep moving towards the diffuser, then the mass flow also keeps increasing.

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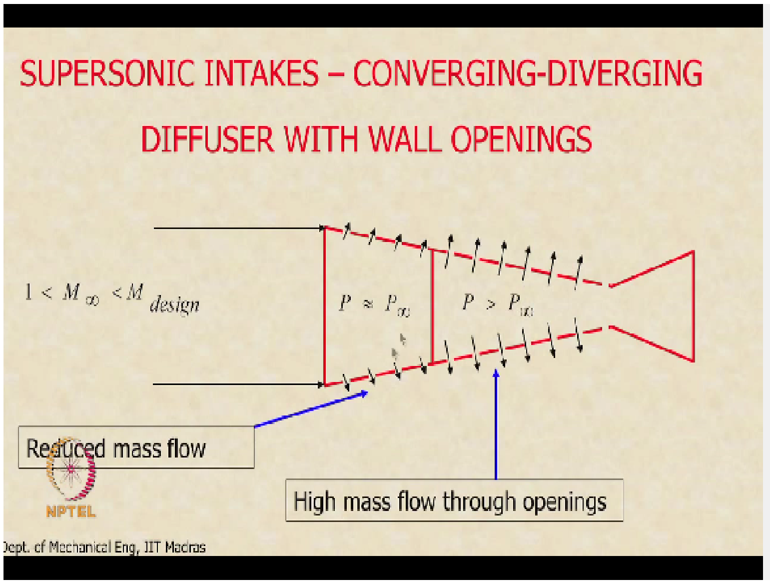

SUPERSONIC INTAKES – CONVERGING-DIVERGING DIFFUSER WITH WALL OPENINGS

Reduced mass flow

High mass flow through openings

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And we can see that as the shock moves inside, right, we can see that the mass flow rate through these openings will begin to go down because now there is no increase in static pressure if you see this, there is a considerable increase in static pressure across this normal portion, right, this part of the shockwave which is what causes the flow to be sent outside but as the shock moves in like this, then we can see that there is no high-pressure region here.

So the mass flow rate through these openings will reduce and there is a pressure rise across the shockwave, so that the pressure here is still high, so this mass flow rate will continue to be high and because you are allowing the intake to swallow the mass, the shock will keep moving towards the throat.

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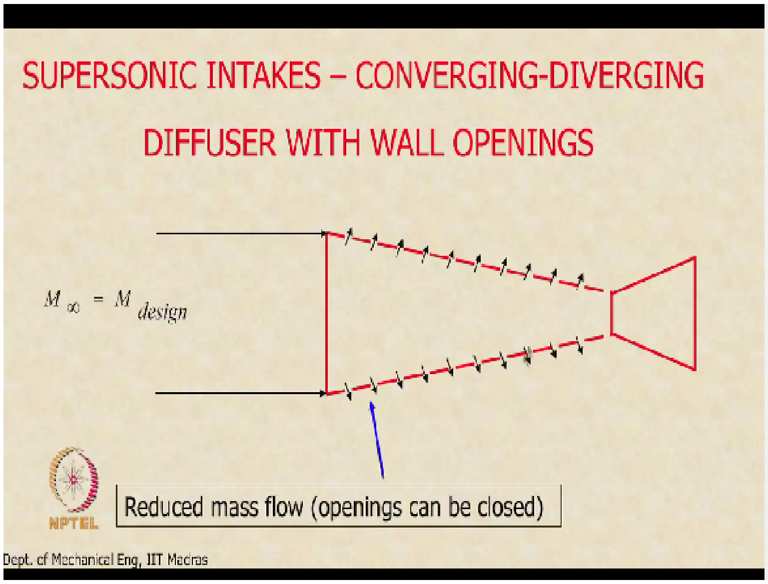

SUPERSONIC INTAKES – CONVERGING-DIVERGING DIFFUSER WITH WALL OPENINGS

Reduced mass flow (openings can be closed)

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And eventually it will go and sit at the throat where it becomes an infinitesimally weak shockwave and then the mass flow rate through these openings will become very small. So these openings can now be closed and if there is a disturbance in the conditions, let us say the inlet conditions, then the shock will jump out but once the shock jumps out and we open this ports, then the mass will begin to be spilled and automatically, the shock will come back and position itself.

So we do not have to actively do anything. Even if there is a disturbance, the intake will correct itself, dump the excess mass and then it will come back and the shock will be pulled back inside to this location. So the cycle that we mentioned earlier where we have to overspeed to swallow the shock and then come back to design speed and if there is a disturbance, then again we overspeed and then come back, so that kind of cycle is not necessary any more.

This is a self-correcting mechanism. If the shock stands here, the pressure here is automatically higher and there will be more mass flow rate through these openings. As the mass begin to flow out through these openings, the shock is pulled towards the intake. Now once it is pulled inside, it rapidly moves from the inlet to the throat where it positions itself. So this is a very stable operation and something that can be used, that has been used also in practical devices like the Concorde engine, okay.

So these are the 2 strategies that we can use to control the internal compression intakes. One is to upon the throat area, another one is to use spillage or dump doors, to dump the mass through the sidewalls of the diffuser, okay. Internal compression intakes always have this problem that during start-up, their normal shock has to be swallowed before the intake will start properly.

So later on when we look at mixed compression intakes, where part of the compression is external and part of the compression is interval, the internal part of the intake will still have the same problem, that you have to open the throat wide or dump some of the mass to pull the shock inside, okay. So all vehicles which use this type of intake have that problem.

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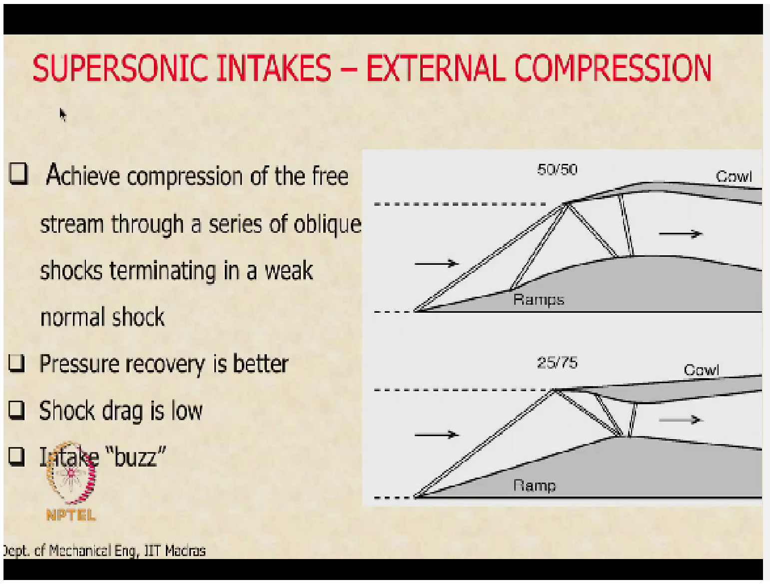

SUPERSONIC INTAKES – EXTERNAL COMPRESSION

- ☐ Achieve compression of the free stream through a series of oblique shocks terminating in a weak normal shock
- ☐ Pressure recovery is better
- ☐ Shock drag is low
- ☐ Intake "buzz"

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So here we are looking at external compression intakes, we saw internal compression intakes so far. Here we are looking at external compression intakes and the idea here is to achieve compression of the free stream through a series of oblique shocks terminating in a weak normal shock, we have seen examples of this before. So what you do is, you have well-adjusted ramps like this, right.

And each flow turning triggers an oblique shock and under ideal operating conditions, these oblique shocks are supposed to converge at the lip of the cowl. So you have a ramp and you have a cowl and these shocks are supposed to converge at the lip of the cowl. So part of the compression is done externally and part of the compression is internally. The internal compression could be due to reflected shocks or it could be due to a diverging area passage which is also okay, both are acceptable, okay.

The pressure recovery for these types of intakes is better because the external compression is done in the absence of any surfaces. So it is done in the external free streams, so that kind of compression is always better. Shock drag is also low for these types of mixed compression intakes, so they are used very widely but they do have a problem which is again a hysteresis kind of problem called the intake buzz, okay.

The buzzing of the intake happens because of the boundary layers on the surface of the ramp. So you have boundary layers growing on the surface of the ramp and when one of these shocks impinges on the boundary layer, there is a separation of the boundary layer. So the thickness increases. So when the thickness of the boundary layer increases, the blockage also increases. So when the blockage increases, the shock that was swallowed will again come out and stand in the front because now the area has become smaller.

Instead of opening the throat wider, you have actually closed the intake effectively, right. You have closed the throat and because of the closure of the throat, the shock that was swallowed will jump back outside. Once that happens, there is no more a reflected impingement shock on the boundary layer. Remember the reflected shock that was causing the boundary layer to separate and thicken, when the shock moves outside, there is no reflected shock, correct.

Since there is no reflected shock, separation of the boundary layer is also suppressed and the boundary layer is now attached and no longer thick. So once the boundary layer becomes thin, the passage area increases and the shock that stands outside is now pulled inside, okay. Once this happens, once it is pulled inside, once again we have separation of the boundary layer, thickening of the boundary layer and disgorging of the normal shock.

So this is hysteresis, low frequency hysteresis phenomena that is seen in these types of external compression intakes. It is called the buzzing of the intake. This happens when you are operating far away from the design operating condition, okay, very low values of mass flow rates, okay, far away from the design operating condition at the extreme end of your operating curve, the inlet will begin to buzz, so that is a region in which you should not operate the intake.

For higher mass flow rates, the intake will not buzz, the conditions are very stable and it is designed so that in a way it will not buzz but if you operate far away from the design point, we can encounter this kind of a difficulty in the external compression intake, okay and here you see, a judicious mix of internal and external compression, okay. This is actually a mixed compression intake because 50-50 here refers to the fact that 50% of the compression is achieved externally and 50% is achieved internally.

So that is a very good strategy. So the internal compression intake has advantages and the external compression intake has advantages because the pressure recovery is better and so on. So the idea is do not operate the internal compression intake at high Mach members. At high Mach numbers, the normal shock that stands in front of the internal compression intake can be very strong because the loss of stagnation pressure will be very high.

So decelerate the flow from the free stream Mach number to a reasonable value, may be 1.8 or so using oblique shocks and then use an internal compression intake to compressor the flow further. So this is the best way of utilising the advantages of the external compression intake and the advantages of the internal compression intake. So it is a judicious mix of both, okay and here you see a 25-75 intake where one-quarter, one-fourth of the compression is achieved externally and three-quarters of the compression is achieved internally.

“Professor - student conversation starts” Yes, go ahead. What is the frequency of oscillation of this intake buzz? It is usually very low. It will be of the order of, depending upon the device, it will be of the order of a few tens of hertz. It will be of the order of frequency of sonic velocity, means, frequency of sonic. Sonic, no, you mean… sonic frequency. No, it is not related to that. This is a fluid dynamic phenomenon not an acoustic phenomenon.

This is a fluid dynamic phenomenon, so the separation of the boundary layer due to the impingement of the shock is fluid dynamic phenomenon. The subsequent thickening is also a fluid dynamic phenomenon and then the shock jumps out, remember shock travels with the supersonic speed. So the shock will jump out immediately, then the boundary layer will begin to thin. So this is not related to any of the acoustic modes of the intake. If that is what you are referring to. It is not related to any of the acoustic modes. **"Professor - student conversation ends"**

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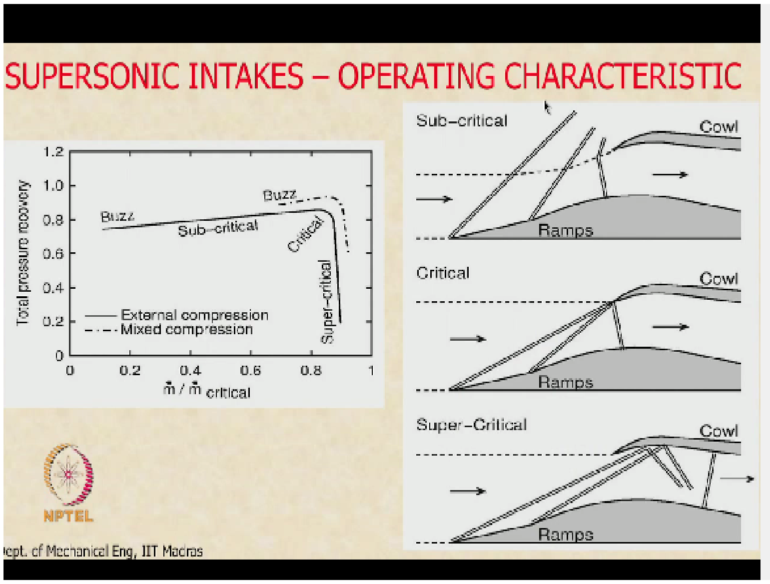

SUPERSONIC INTAKES – OPERATING CHARACTERISTIC

So if you look at a mixed compression intake. What we have here is the operating characteristic and what I have shown here are 3 different modes of operation of the mixed compression intake, okay. So this here, the so-called critical mode is a design mode of operation for the mixed compression intake, the one in the middle is the design mode of operation where we can see that the ramps are designed.

So therefore, the design Mach number, the oblique shocks will converge at the lip of the intake and the stream tube, free stream, capture stream tube looks like this. So the flow is deflected properly here and notice that this part of the free stream is deflected, is not at all deflected and enters the intake without any deflection, that is the top portion of the free stream tube. A streamline here is deflected upwards towards the shockwave and again it is deflected towards the shockwave and then it enters the intake.

So the capture area is equal to the, this is the capture area, okay, that is equal to the projected area of the intake, okay. So this is the critical mode of operation. So if you take a streamline here, we can see that it comes up to here without any deflection, then it is deflected a little bit here, little bit here and then it enters. Whereas a streamline that is shown here using a dash line is not at all deflected before it enters the intake, it just comes in as it is.

So this is the design mode of operation or the so-called critical mode of operation and mass flow rate that you get here is usually the maximum, almost the maximum mass flow rate that is possible. The maximum mass flow rate that is possible. So this is the design mode of operation, it is called the critical mode of operation and the pressure recovery is usually the highest possible for the design mode of operation.

Notice that, there is no wave drag for the design mode of operation because the pressure around the cowl surface is equal to the free stream pressure, there is no increase in pressure due to oblique shockwave or the cowl surface. So the free stream flows over the cowl surface, so the pressure here is also P infinity, there is no wave drag and the pressure recovery is also very good. So this is the design mode of operation where everything is the best, mass flow rate is the maximum possible, pressure recovery is the maximum possible.

And there is no shock drag or wave drag for this case. Now the subcritical mode of operation is when the pressure here is slightly higher or the mass flow rate requirement of the engine is less than what this provides, less than the design mass flow rate. So if the engine wants less than the design mass flow rate, then what happens is the pressure is increased slightly, okay and that has the effect of, remember that we have a terminal normal shock here and 2 oblique shocks.

So increasing the pressure here, pushes this terminal or normal shock out as well as the oblique shock. So all of them are pushed outside and you see now that if you look at the streamline that was here before, earlier in this condition, a streamline here will enter like this, right. Now the streamline here when it comes like this, it is deflected here like this, then it goes here, it is deflected further.

So instead of entering the engine, this streamline is now deflected around the engine, around the intake, right, that is called the spill-over flow. So the mass that the engine cannot swallow, is now spilled around the intake, okay. So it is spilled around the intake and unfortunately when spill-over happens, you see that the pressure here now is going to be higher than the free stream pressure which means that wave drag is going to be more now.

So previously in this case, the pressure here is the same as the free stream pressure. So there was no wave drag. Now the pressure here is higher because of this oblique shocks and it is going to wave drag in this case. So the mass flow rate reduces and the stagnation pressure loss may or may not be the same. It may decrease slightly but generally it will be about the same. There is less mass flow rate and there is increased wave drag now.

So you can see this plot here which shows the variation of the mass flow rate through the intake versus the total pressure recovery, this are the 2 critical parameters for the intake. So when the mass flow rate is a maximum, you see that that corresponds to the critical mode of operation here. So the knee, so you see a knee in the graph, so knee location is the critical mode of operation, where the mass flow rate is almost the maximum possible and the stagnation pressure recovery is also the maximum possible.

When you go into subcritical mode where the mass flow rate requirement is less, then you are in this branch of the intake characteristic curve, okay. So this is the intake characteristic curve, so the knee is the critical point of operation. This branch is the subcritical branch of the intake operating curve. So the mass flow rate decreases as you can see and the stagnation pressure recovery also deteriorates but only slightly. This is typical of most supersonic intakes, okay.

When you go to the extreme here, extreme subcritical operation, that is when the intake starts buzzing, the mass flow rate is very little, so the boundary layers are thick to begin with and any impingement of the shockwave separates and thickens the boundary layer further and reduces the passage area for the intake which then forces the shock to come out and then it keeps oscillating like that. So this refers to buzzing mode of operation.

Typically, intakes are operated near the critical point or slightly above the critical point, okay, that is what we are going to talk about next. So the so-called supercritical mode of operation is shown here, okay. So in the supercritical mode of operation, the mass flow rate, so if you look at this case, the mass flow rate requirement let us say is more than what the intake can provide. So you lower the pressure here and lowering the pressure here, has the effect of pulling these shocks inside the engine and that is what you see here.

The shocks are pulled inside the engine and now you get reflections from the surfaces, right. Unfortunately, when the shock is pulled inside, notice that these are all expansion surfaces, right. This is an expansion surface, that is also an expansion surface. So the Mach number actually increases. So this normal shock, terminal normal shock, now occurs at a much higher Mach number than before in addition to these reflections which were not present earlier.

So there is a loss of stagnation pressure across this shockwave 1, 2. Now we have 3, 4 and then 5 and 5 is occurring at a higher Mach number. Earlier, we had loss of stagnation pressure across 1, 2 and 3 and this was occurring at a lower Mach number. So now we have 5 as sketched in this one with this occurring at a higher Mach number. So the loss of stagnation pressure is very high in this case.

Whereas in this case, we said that the loss of stagnation pressure is likely going to be the same. It may even be less, right. In this case, the loss of stagnation pressure is going to be very high and the mass flow rate really does not increase that much because the capture area as you can see cannot be increased any further than this. So if there is lowering of the pressure here, that has a very devastating effect on the performance of the intake.

So the supercritical mode is very bad. We can see the steep loss of stagnation pressure. So from here, the mass flow rate increases only slightly but the stagnation pressure loss increases very very steeply. So this is the supercritical branch of the intake and that is to be avoided at all costs. So during operation, intakes are designed to operate at slightly supercritical mode and than during any changes in operating condition, we always try to keep it critical or subcritical, never go into supercritical, if at all it can be avoided and that is how they are usually designed, okay.

So these of the 3 modes in which they can operate and this characteristic curve, what we have shown here is for a purely external compression intake. The characteristic curve for a mixed compression intake is shown here. We can see that the mixed compression intake offers a narrow range of operating conditions but has a superior performance compared to the pure external compression intake.

We can see that the pressure recovery is better and the mass flow rates are also better for the mixed compression intake and we already talked about that, mixed compression actually enjoys the advantages of both the pure external compression intake and the pure internal compression intake. So it is always better and we can see that from the operating curve here. Only difficulty is that the range of conditions, operating conditions becomes narrower for the mixed compression intake but that can be managed during operation, that is not a major issue, okay. Any questions?

"Professor - student conversation starts" Yes. (()) (22:08) m./m. critical = (()) (22:11) depending upon what we will use here, it may be designed for a certain mass flow rate but it may not be possible to realise the same mass flow rate all the time, okay. M. critical for example may correspond to a case when fully isentropic flow exists or some situation like that or we can also use this critical mass flow rate and then non-dimensionalize that with respect to 1, okay.

Generally, this should be 1 but the characteristics curve always shifts to the right because what you design using isentropic theory, does not take into account boundary layer effects on the thickening of the boundary layers, reduction in the passage area due to boundary layers and so on. So when you actually determine the intake characteristic curve, the real curve will always have lesser mass flow rate than what the ideal critical case has. **"Professor - student conversation ends"**

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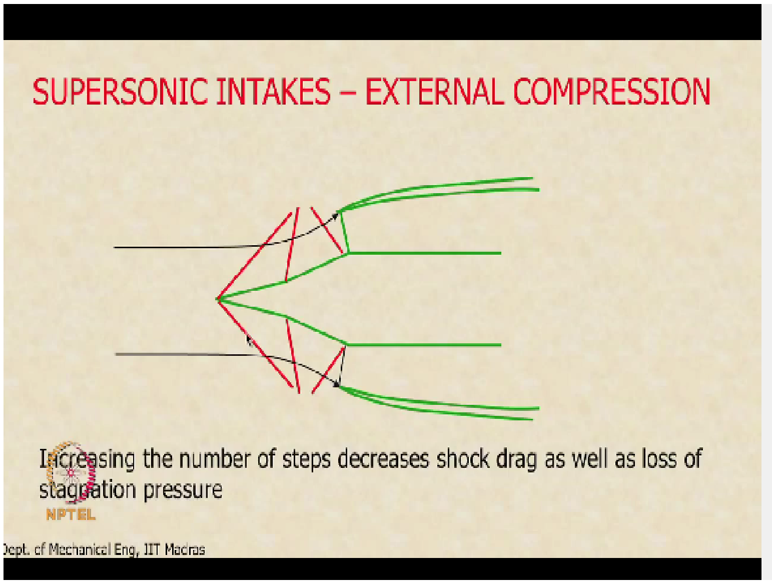

SUPERSONIC INTAKES – EXTERNAL COMPRESSION

Increasing the number of steps decreases shock drag as well as loss of stagnation pressure

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Now so far we have looked at 2-D compression intake. Notice that this is a 2-D compression intake. So you have a ramp and a cowl. We can also have axisymmetric intakes. So this is an axisymmetric intake that we saw earlier on the SR71. Now the center body of course again has ramps and each one on this surface or corner triggers an oblique shock, okay. So the more number of corners you have, the more number of oblique shocks you are going to have and the compression process will actually approach isentropic compression.

As you increase the number of steps, you are triggering more number of oblique shocks and so the compression process becomes more efficient. Unfortunately, there is also a downside to that. If you have more number of steps, then the length of the intake also increases. So in a real case because the length increases, the boundary layer will increase and the drag due to boundary layer effect will also increase.

Remember we are talking about supersonic flows here, Mach numbers 2-3. So the shear drag or the wall shear stress can be very high in this cases. So if you increase the length of the intake, there is going to be a commensurate increase in the friction drag and that will actually negate any benefit that you get from increasing the number of steps. So this has to be done very carefully.

For example, we can actually define the surface or you can actually design the surface using Prandtl–Meyer theory so that the entire compression process is isentropic, so there is no loss of stagnation pressure. But if you do that, this intake will be so long that the drag will be much higher than any thrust that we can thought to produce, okay. So most efficient, as we said earlier, is not always the most effective.

It may be very efficient but it may not be effective. So we are looking at practical designs where efficiency is a concern but effectiveness is a bigger concern. We want to realise working devices, not devices which are good on paper. So we try to optimise the number of steps with the increased drag, then try to come up with the configuration which will work very well, okay.

Now in this case also, the intake usually has 3 modes of operation, critical, subcritical and supercritical and in the practical design, what is normally done is, rather than allowing these shocks to open up, if you remember when you go to a subcritical mode of operation, this shock opens up. In the critical mode of operation, the shocks impinge on the cowling, I am sorry, the cowl leading edge, right.

In the critical mode, they impinge on the cowl leading edge and in the subcritical mode, the shock opens up and spills the mass. In order to minimise the spill-over drag or the shock drag that happens when the shocks open out, one strategy that can be adopted which is usually used is to actually move this intake. So when the shock tries to open out, if you pull the intake slightly inside the centre body, I am sorry, not the intake, if you pull the centre body slightly inside, then what was moved out can again be focused on the cowl leading edge.

So the shock drag can be eliminated completely. So in fact what I am saying is, if you have a mechanism by which for example in this case, where the shocks are open up and you are having spilling of mass around the cowl, what if you move this slightly back. By moving this slightly back, we can actually make this thing again converge on the cowl leading edge. So even for subcritical mode of operation, we can avoid the shock drag and adjust the and capture the amount of mass flow rate that you want.

It is still possible but it is very complicated to do this kind of movement in supersonic intakes. In fact, the SR71 actually has this type of a moving centre body and those were the days before computers took over navigation and flying the aircraft completely before the avionics was so good, those were the days when pilots flew planes, not computers. So the SR71 pilots actually had big shocks in front of them which used to give them for each operating condition where should the center body be.

So they would adjust the centre body position based on readings from the chart. So the entire operating space of the intake was mapped out and they would know exactly where to position the intake based on the actual operating conditions. So it was a very difficult thing to do. Nowadays of course computers do these things automatically, so there are no issues. So even unstable airframes can be flown without any difficulty because computers are flying the plane, right.

So if you ask a human being to walk across a tightrope, it will be very difficult to do. Whereas you are going to ask a computer to do the same thing, move a robot across a tightwire, that is not a problem, right. There are no other inputs, all the inputs are controlled. The same thing happens with most of the modern military aircraft. They are all actually unstable aerodynamically but they are able to fly and stay aloft because computers are able to control the movement of the control surface is so finely and so fast that even though they are unstable, they are perpetually unstable that means they are also stable.

There are unstable in a stable manner, okay. So similar kind of thing can happen here also. So we can keep this on its toes all the time so that becomes a stable point of operation, it is not an issue, right. So that is what happens with these types of intakes. So many strategies are possible to offset some of these difficulties associated with these intakes. The drag or wave drag, reduced mass flow rate, starting problem is a problem which is still there for all these intakes and we can again overcome that either by spilling the mass or by opening the throat little bit wider.

As a result of which, these types of intakes are now extensively used in many of the ballistic missiles. Many of the ballistic missiles use either solid fuel ramjet engines or even liquid fuel ramjet engines are also being used today. The Brahmos missile for example is a liquid fuel supersonic ramjet missile. Any questions so far?

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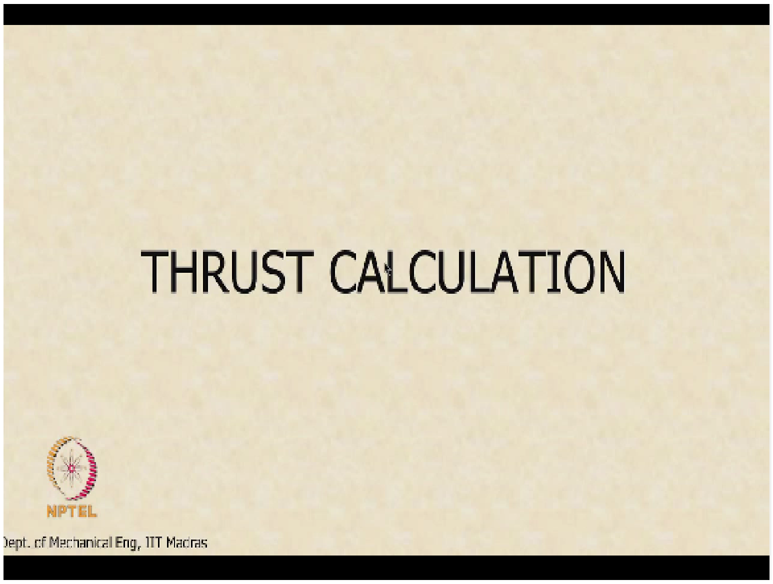

THRUST CALCULATION

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So what we are going to do next is look at thrust calculations for a ramjet engine.

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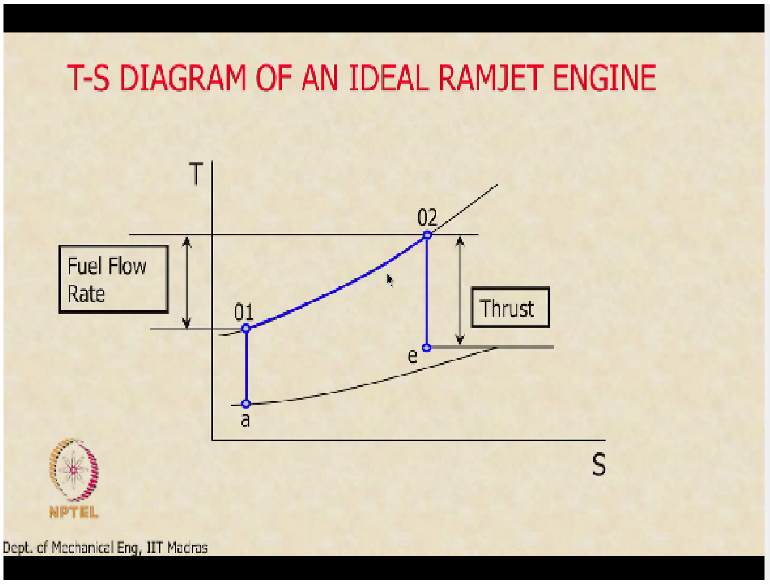

T-S DIAGRAM OF AN IDEAL RAMJET ENGINE

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The thrust calculations for this case is much simpler because the thermodynamics cycle as you can see is also much simpler. So this is an ideal ramjet engine. So a is as usual is the free stream state. So a-01 is the intake. So with the properly designed intake, we are decelerating from a supersonic Mach number typically to a subsonic Mach number. The flow is actually subsonic when it enters the combustion chamber in a ramjet engine, then we add head.

There is no compressor here. So we are able to achieve the entire pressure ratio for the cycle in the intake itself. Then we add heat from 01-02, this is the combustor and as we discussed earlier, the combustor is very simple in construction. It is just like an afterburner duct. There are fuel injectors, there are flame holders and combustion takes place. So it is not as complicated as a aviation gas turbine engine combustion, right.

Remember we saw aviation gas turbine engine combustors which are much more complicated than this. This is a very simple duct in which you inject fuel and burn it, right and then you go into the nozzle, the flow expands and produces thrust. If the exit pressure matches the ambient pressure, of course there is no pressure thrust; otherwise, you get both momentum as well as pressure thrust.

This is an ideal ramjet engine and actual ramjet engine as you know, there will be a loss of stagnation pressure in a-01 due to irreversibilities and other effects and there will be a loss of stagnation pressure here in the combustor because once again due to irreversibilities and the fact that we are adding heat now to a compressible flow. The Mach numbers at entry to the combustor now will be quite high, 0.5 maybe, 0.4-0.5 depending upon the operating condition, it can be substantial.

Substantial in the sense when compared to an aviation gas turbine combustor where we were pretty much operating in the incompressible regime. So here there is going to be loss of stagnation pressure due to, number 1, heat addition to a compressible flow and number 2, irreversibilities and then we come to the nozzle and again due to irreversibilities in the nozzle, we can actually have an increase in the entropy and this point e will shift to the right due to irreversibilities, loss of stagnation pressure due to irreversibilities.

We will take this into account in the same manner as we did for the turbofan engine, okay. So we do the same thing, starting from, so if you look at these strategy, we start from the free stream static state, we go through the cycle, we determine this stagnation condition, this stagnation condition and then here we need to determine the exit pressure and the exit velocity. Once we have that, I can calculate the thrust, yes.

“Professor - student conversation starts” In this, we are using CD nozzle. It does not matter, we can use the CD nozzle or a conversion nozzle, both are okay. If you use a conversion nozzle, then you may get some pressure thrust plus momentum thrust. If you use the CD nozzle and expand it to the correct ambient pressure, then you will have only momentum thrust.

We are going to do one example next where we will demonstrate the use of both. We will do the calculations with the conversion nozzle and a conversion-diversion nozzle. As I said earlier, it depends upon the stagnation pressure that you have here. If the stagnation pressure ratio P02/Pe is > 4 or 5, then it may be a good idea to use a conversion-diversion nozzle. **"Professor - student conversation ends"**

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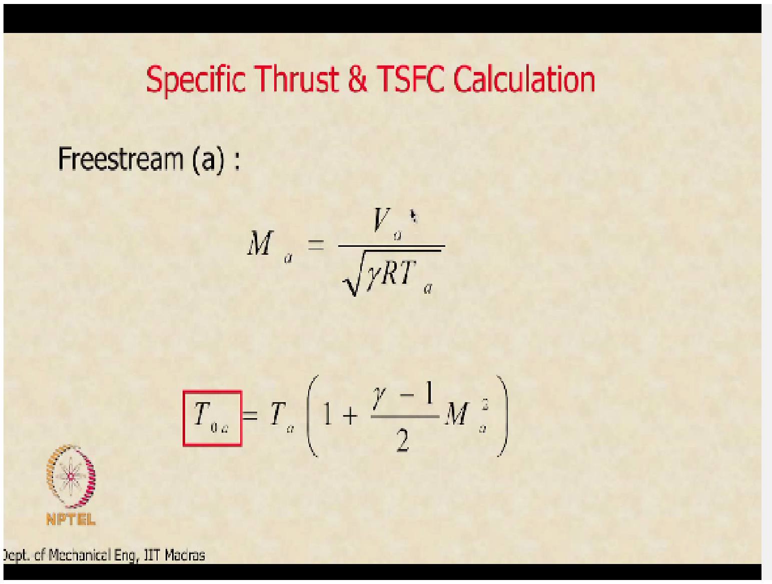

Specific Thrust & TSFC Calculation

Freestream (a) :

$$M_a = \frac{V_a}{\sqrt{\gamma R T_a}}$$

$$\boxed{T_{0a}} = T_a\left(1 + \frac{\gamma - 1}{2} M_a^2\right)$$

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So assuming that the free stream velocity and static temperature and static pressure are given, I can calculate the free stream Mach number in the usual way, right and then I can calculate the stagnation temperature, free stream stagnation temperature using this Mach number and I know the free stream static temperature, now I know the Mach number, I can calculate the free stream stagnation temperature, okay. So once I do this, I can then go to the combustor inlet.

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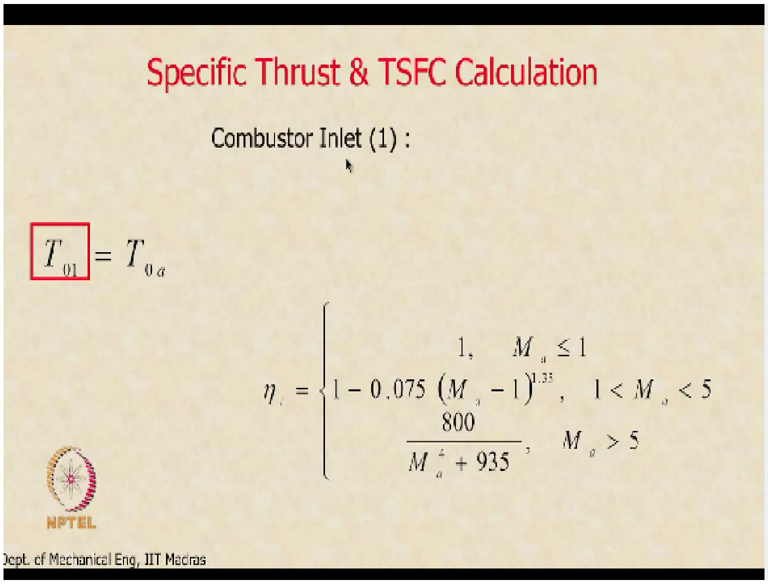

Specific Thrust & TSFC Calculation

Combustor Inlet (1) :

$$\boxed{T_{01}} = T_{0a}$$

$$\eta_r = \begin{cases} 1, & M_a \le 1 \\ 1 - 0.075\left(M_a - 1\right)^{1.35}, & 1 < M_a < 5 \\ \dfrac{800}{M_a^4 + 935}, & M_a > 5 \end{cases}$$

So this is the intake portion that we are talking about. So there is no heat additional or work addition in the intake. So stagnation temperature remains the same, right and for supersonic intakes, we use this relationship to calculate the efficiency of the intake, okay. This is called military specification or mil spec.

It is called mil spec and depending upon the free stream flight Mach number, we can calculate the pressure recovery using this formula. Notice that this is not an isentropic efficiency, this is a stagnation pressure recovery. So this simply gives me the ratio of the stagnation pressures, okay. For Mach numbers even > 5, we can use this relationship. This is actually an extremely good relationship.

This is a (()) (34:52) but works extremely well, easy-to-use, okay and this is what, we will be using for our ramjet calculations, not the isentropic efficiency. Notice that when the Mach number becomes 1 or < 1, the pressure recovery automatically, this relationship automatically switches to 1. So for subsonic inlets, we will use our isentropic efficiency

And for supersonic inlets, we use the mil spec, okay. So using the mil spec in the definition of eta R, I can calculate P01. P01 is basically stagnation pressure recovery. I am sorry, eta R is basically stagnation pressure recovery. So P01/P0a gives me eta R that is the definition of eta R. So now I have T01 and P01. Combustor outlet, normally the peak temperature is given, okay.

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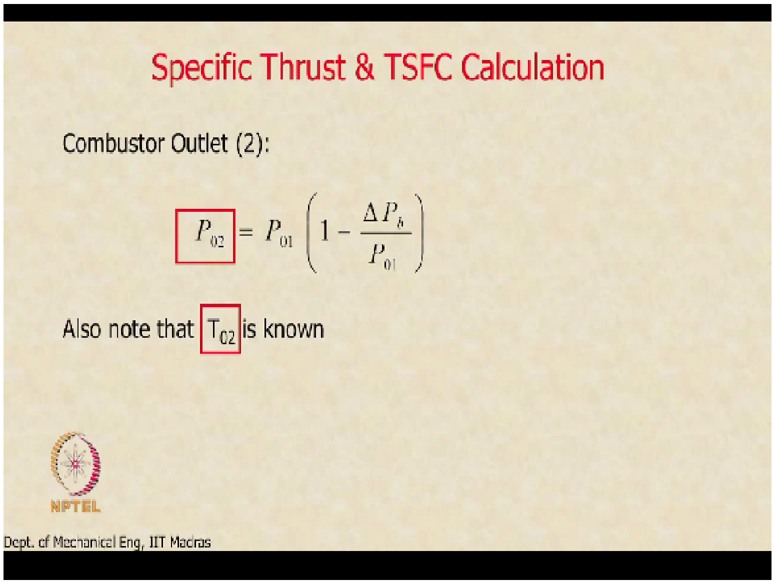

Specific Thrust & TSFC Calculation

Combustor Outlet (2):

$$\boxed{P_{02}} = P_{01}\left(1 - \frac{\Delta P_b}{P_{01}}\right)$$

Also note that $\boxed{T_{02}}$ is known

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And the stagnation pressure loss is also usually given just like what we did earlier or if required, we can calculate the stagnation pressure also. At least stagnation pressure loss due to heat addition can be calculated using our Rayleigh flow concept. If required, we can do that. Or if it is given, we can use this number and calculate P02, just like what we did before. So now P02 and T02 are both known.

Notice that in the case of the ramjet engine, since there are no moving parts, the stress is only thermal stress, exposure to high temperature. So the operating temperature for ramjet engines will be much higher than the operating temperature for gas turbine engines because the first stage or the first few stages of the high pressure turbine is exposed to or they are exposed to high pressure, high temperature and high rotational speeds.

We need to make sure that they can withstand the stress which is why the peak operating temperature for gas turbine engines today is around 1700 Kelvin. Ramjet engine, there are no protruding parts, so there is no rotational stress which means that I can elevate the temperature, operating temperature or the peak temperature inside the engine. So typically these may see temperatures as high as 2000 Kelvin or even beyond that, okay.

Only thing is we need to make sure that the materials that we use can withstand such high temperatures and the other advantage is these materials do not also undergo the kind of fatigue and creek that we saw earlier. Remember fatigue comes due to cyclical loading and the cyclical loading came because of, you know, takeoff, climb, cruise and then descent and again reverse thrust and so on. So that cycle is not present for dismissal. They are usually taken up to the flight Mach number and then released.

So there are some advantages in this which is why T02 in these cases is usually much higher than what you have seen with turbofan engines or with gas turbine engines. Now after the combustor, we come to the nozzle outlet and the strategies are seen as before. We determine the critical pressure once I know P02 and then given the efficiency of the nozzle, I can calculate the critical pressure and I compare my critical pressure with the ambient pressure, okay.

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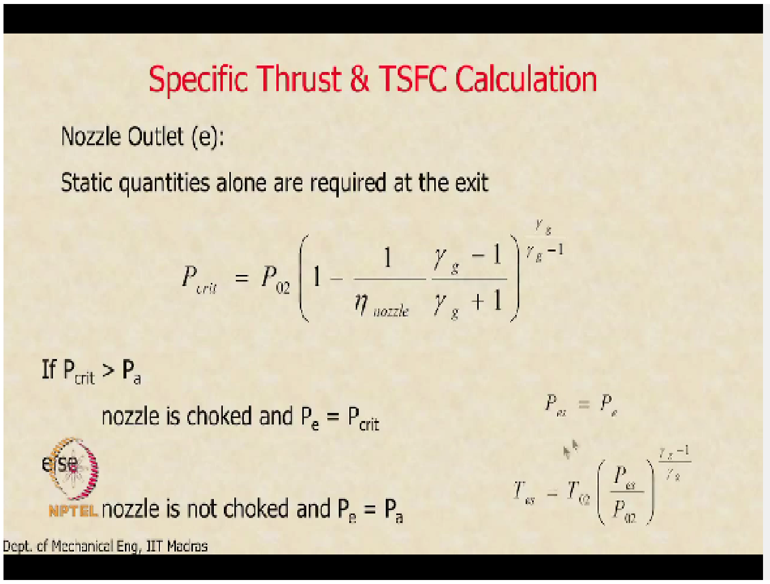

Specific Thrust & TSFC Calculation

Nozzle Outlet (e):

Static quantities alone are required at the exit

$$P_{crit} = P_{02}\left(1 - \frac{1}{\eta_{nozzle}}\frac{\gamma_g - 1}{\gamma_g + 1}\right)^{\frac{\gamma_g}{\gamma_g - 1}}$$

If $P_{crit} > P_a$

nozzle is choked and $P_e = P_{crit}$

else

nozzle is not choked and $P_e = P_a$

$$P_{es} = P_e$$

$$T_{es} = T_{02}\left(\frac{P_{es}}{P_{02}}\right)^{\frac{\gamma_g - 1}{\gamma_g}}$$

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So if the critical pressure is more than the ambient pressure, then the nozzle is choked and Pe=P critical just like before. If the critical pressure is less than the ambient pressure, then the nozzle is not choked and we say that Pe=Pa. Now in the case of ramjet engines, there is another possibility also. Remember this is true only for a conversion nozzle. In the case of ramjet engine, it is possible to have a conversion-diversion nozzle where Pe=Pa.

And the flow is supersonic at the exit of the nozzle, that is also possible. So we need to take that also into account, okay. So what happens is once I have the exit pressure, I know Pes because from our TS diagram, you know that Pes=Pe and once I know Pes, I can evaluate Tes using the isentropic relationship in both cases. Once I know my Pe, I know my Pes. Once I know Pes, I know my Tes. Once I know Tes, I can use the definition of the nozzle efficiency to calculate my exit static temperature or a velocity, both can be calculated, right. So that is going to be our strategy.

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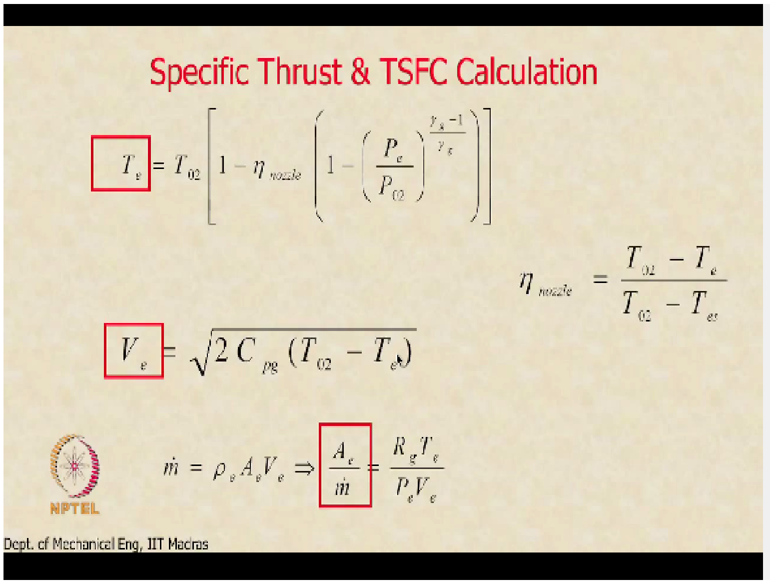

Specific Thrust & TSFC Calculation

$$\boxed{T_e} = T_{02}\left[1-\eta_{nozzle}\left(1-\left(\frac{P_e}{P_{02}}\right)^{\frac{\gamma_g-1}{\gamma_g}}\right)\right]$$

$$\eta_{nozzle} = \frac{T_{02}-T_e}{T_{02}-T_{es}}$$

$$\boxed{V_e} = \sqrt{2C_{pg}(T_{02}-T_e)}$$

$$\dot{m} = \rho_e A_e V_e \Rightarrow \boxed{\frac{A_e}{\dot{m}}} = \frac{R_g T_e}{P_e V_e}$$

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So you can see once I have my Tes, I can calculate Te because T02 is known, now Tes is known, eta nozzle is known, I can calculate my Te, right. So if you calculate Te, this is what it looks like, okay. Notice that the quantity inside here is nothing but Te/T02 or Tes/T02, right. So once I have this, I can calculate my Te and I can calculate my Ve. Alternatively, I can also calculate Ve by recognising the fact that the numerator here is nothing but Ve square over 2Cpg and the denominator here is nothing but Ves square over 2Cpg.

I can calculate Ve square from here also, you will get the same answer. So that is what we have done here. So I know Te, I know Ve and Pe is also known. In case the specific thrust is desired, I need to evaluate this quantity Ae/m. which I do in the same manner as before. The mass flow rate at the exit of the nozzle is rho*A*V and I can then calculate Ae/m. using this formula, all the quantities on the right-hand side are known. If the thrust is as far, then usually m. is given.

If there is a specific thrust that is as far, then m. may not be given and we need to evaluate this ratio which I can evaluate using this expression here. So this is going to be our strategy, okay. Then of course you have to calculate the fuel flow rate. Fuel flow rate we can calculate in the same manner as before by using energy balance for the combustor. So we can see that Ae/m. comes out to be like this to all the 3 quantities that we need, can be evaluated now, okay.

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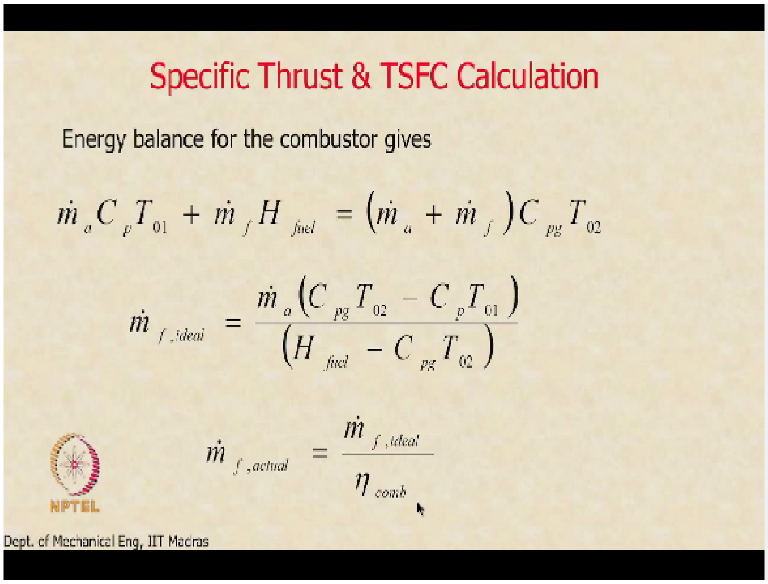

Specific Thrust & TSFC Calculation

Energy balance for the combustor gives

$$\dot{m}_a C_p T_{01} + \dot{m}_f H_{fuel} = (\dot{m}_a + \dot{m}_f) C_{pg} T_{02}$$

$$\dot{m}_{f,ideal} = \frac{\dot{m}_a (C_{pg} T_{02} - C_p T_{01})}{(H_{fuel} - C_{pg} T_{02})}$$

$$\dot{m}_{f,actual} = \frac{\dot{m}_{f,ideal}}{\eta_{comb}}$$

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Now fuel flow rate can be evaluated by doing energy balance for the combustor. Here H fuel is the calorific value of the fuel, m.f is the fuel mass flow rate. Notice that m.f is usually much smaller than m.a. So in this term within the bracket, we can actually ignore m.f and keep only m.a. If you do that, this expression will simplify like this and this is the ideal case when there is no loss of heat.

So all the calorific value of the fuel is realised as increase in stagnation temperature but in reality, when you burn the fuel, lot of the heat will go towards heating the components and some of it may be lost you know and then lots of things can happen. So we allow for that by defining something called a combustion efficiency. So how much fuel should I actually burn to realise a certain increase in stagnation temperature. So that is when compared to the ideal amount of fuel.

So that is the combustion efficiency. Just like before, we can use this to account for losses of heat in the combustor and elsewhere, okay. So this can be accounted for in our analysis. So this gives me m/f from which I can calculate TSFC, okay. So what we will do next is to do worked example involving ramjet engines. Let us lay out the problem in this lecture then we will start doing the detailed calculations in their following lecture, okay. Let me just write down the problem now.

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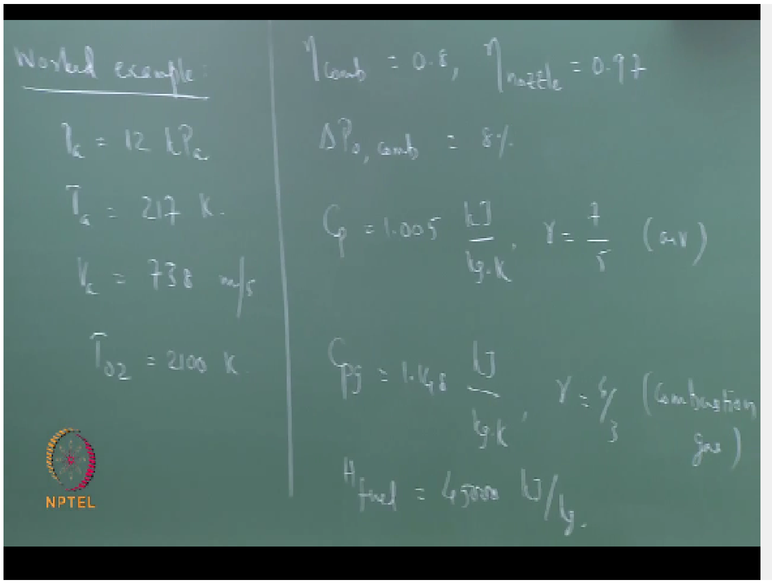

Worked example:

$P_a = 12\ kPa$

$T_a = 217\ K$.

$V_a = 738\ m/s$

$T_{02} = 2100\ K$.

$\eta_{comb} = 0.8,\ \eta_{nozzle} = 0.97$

$\Delta P_{o,comb} = 8\%$.

$C_p = 1.005\ \frac{kJ}{kg.K},\ \gamma = \frac{7}{5}$ (air)

$C_{pg} = 1.48\ \frac{kJ}{kg.K},\ \gamma = 4/3$ (combustion gas)

$H_{fuel} = 45000\ kJ/kg$.

So we are looking at a ramjet which is designed to fly at an altitude where the ambient pressure is 12 kilo Pascal. The ambient temperature Ta is 217 Kelvin and it flies at a velocity of 738 meter per second. The maximum temperature in the combustor is given to be, so that is T02 that is given to be 2100 Kelvin. The combustor efficiency is given to be 0.8 and the nozzle efficiency is given to be 0.97.

Stagnation pressure loss in the combustor is given to be 8% and property values for air, Cp is 1.005 kilojoule per kg Kelvin and gamma is given to be 7/5 for air and for combustion gases, Cp is given as 1.148 and gamma is given to be 4/3. The calorific value of the fuel, H fuel is given to be 45,000 kilojoule per kg. The calorific value is given to be 45,000 kilojoule per kg.

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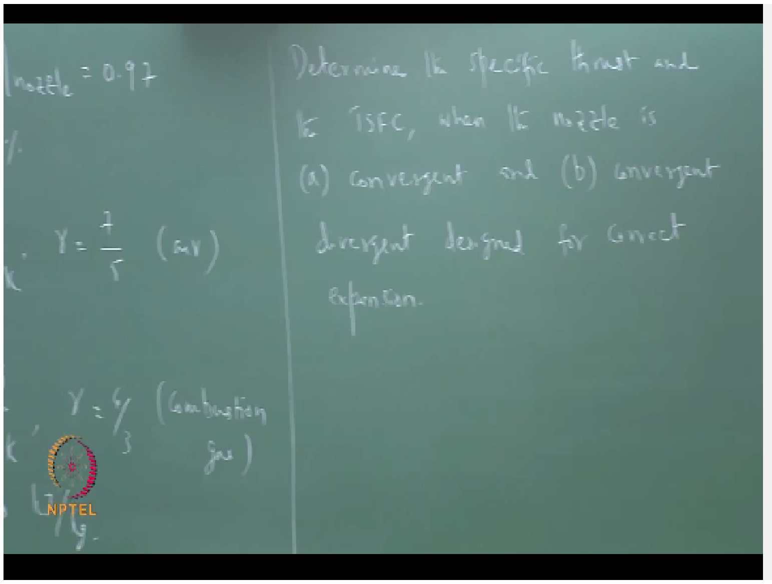

and we were asked to determine the specific thrust and the TSFC and the nozzle is A) convergent and B) convergent-divergent designed for correct expansion. So you look at both these cases and that will answer one of the questions that was asked earlier, okay. So this is worked example. What we will do in the next class is starting from free stream, we will go through and calculate T0a, P0a, T01, P01, T02 is given, P02 we can calculate and then exit conditions of the nozzle and the thrust and fuel consumption, okay. We will do that in the next class.