Aircraft Propulsion
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Module No # 04
Lecture No # 18
Aircraft Engine Intake, Intake Efficiency

Welcome to the class. This class is dedicated towards intake and nozzle of an aircraft engine we know that the aircraft engines are either of turbo prop, turbo jet or may be ramjet and turbo phantom but in either this turbo or ramjet aircrafts we will have an intake and then there is a nozzle. So this nozzle we are interested to study along with intake in this class how to quantify the performance and how to understand the flow and how to associate it with the corresponding performance parameter.

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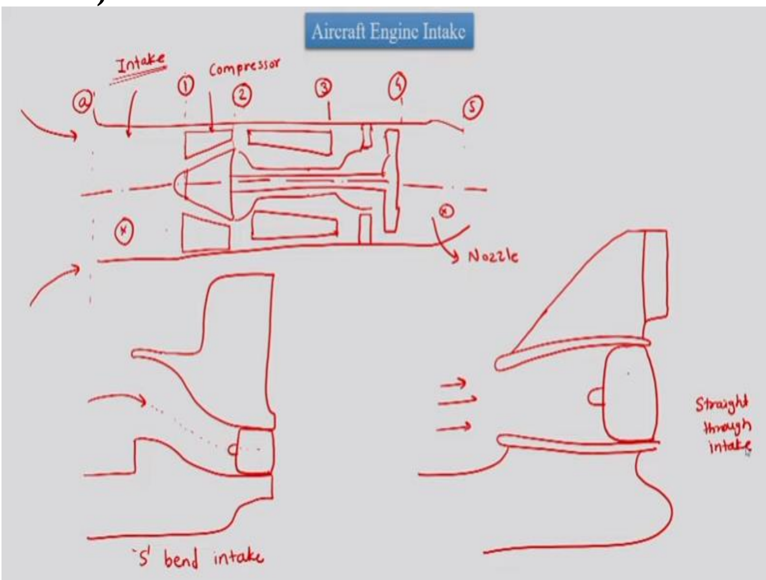

So this is what that objective of today's class so here first we know that there is suppose engine and that engine has the components which includes aircraft intake for the engine and then after the intake there will be compressor and then after the compressor there will be combustion chamber and then after the combustion chamber there is turbine and then there is nozzle. So these are the component of an aircraft engine.

So if I feel that this is the compressor if this is the compressor of the engine then what will happen air will try to come towards the compressor of the engine where we will see that this is the section in which atmospheric conditions are there and then after passing through this passage which we are calling it as intake it would reach condition which is 1 after the end of compressor it would reach conditions which are 2 and then after having compressor we have a turbine.

In case of turbine it will enter before turbine we have combustion chamber in the combustion fluid would enter at state 3 and leave at state 3 for the combustion entry state is state 2 and the state at the exit which state 3 and then we have turbine we have entry state is 3 and then exit state is state 4. Having said this after this turbine fluid enters into the nozzle and then at the exit it as state 5. So these are different component of the aircraft engine which are known to us.

Now our focus at this moment is on intake and nozzle so our focus is on this component and is on this component. So practically we will see about intake to start with as I said intake is practically diffuser and the job of intake is to increase the pressure while flowing through the duct and then it will supply that high pressure air to the entry to the compressor. So this is the primary job of an intake but we have to reduce the losses which are related to loss of pressure loss of total pressure in the intake and then intake should be properly aligned such that it should be having highest performance at different angles of attack and it should have a high performance at various operating conditions like maximum thrust, low speed and high speed.

So for that the intake should always supply given mass flow rate of air with designed pressure or a required pressure to the compressor. Then there are different types of intakes we can have an intake which is like S bend so this is an S bend intake this is also termed as a buried intake and in this intake we will have engine buried inside the intake passage and then this is the engine. So flow will come like this so center line of the intake has change in geometry so this is a *S* bend intake.

And then there is straight through intake in case of straight through intake we have engine at the end of the intake passage and then this engine is placed somewhere the control surfaces of the aircraft. So this is a straight through intake so there are different ways by which we can design an intake passage.

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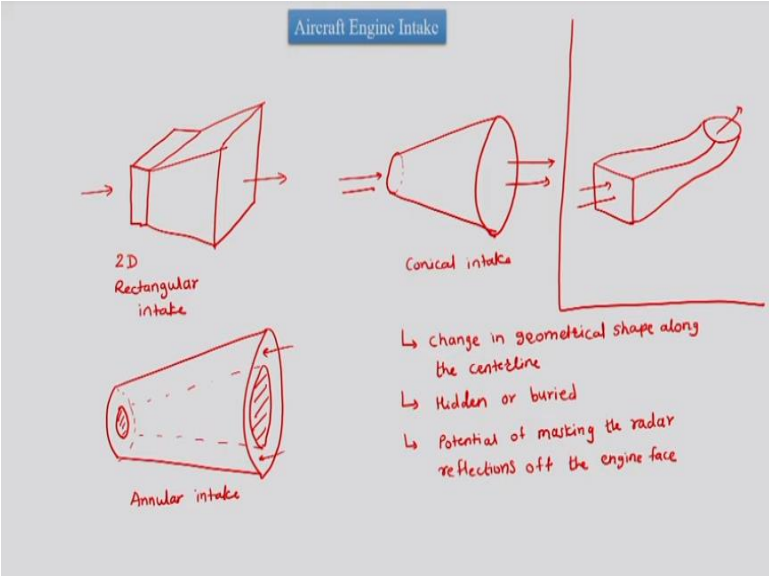

So intake passage can in general be a rectangular duct where we have a two dimensional duct which is rectangular duct like this where this duct would act as a diffuser. So this inlet this is outlet this 2D rectangular intake or intake can be conical where it will have a cone shape where this will be the entry then this is outlet or there can be intake which is annular intake. So this cone would have a passage which is an annular passage and flow is going through the annular passage and then doing the necessary pressure raise.

So this is annular intake so intake in general might have different shapes so some times in all sometimes there might be change in geometrical shape along the center line or there might be change of the slope of the center line itself. So there are some intakes which are hidden or buried intakes and these intakes hidden or buried intakes are having advantage or potential of masking the radar reflections of the engine phase.

Means these intakes can hide the engine from radar so the presence of the engine will not be felt so that will also be one of assignments for the intake. Apart from this these intakes whatever we have studied they have one kind of cross section at the inlet and the same kind of cross section at the outlet but then there can be an intake which would have different cross sectional at the inlet and difference cross section at the outlet and then this might be due to the optimization or might be due to the requirement for connection.

So there is a rectangular shape at the inlet and then this shape transforms to the circular shape at the output. So this is rectangular to circular or rectangular to elliptical shape transformation type of intake. So, such intakes are also designed and all this shapes are practically dependent on the given speed range of the aircraft or flow regime of the aircraft. So the aircraft which if it is sub sonic and then there are different kinds of intake and different kinds of shapes and if it is supersonic the it will be a different kind. But these are general guidelines or general shapes which are followed for the aircraft.

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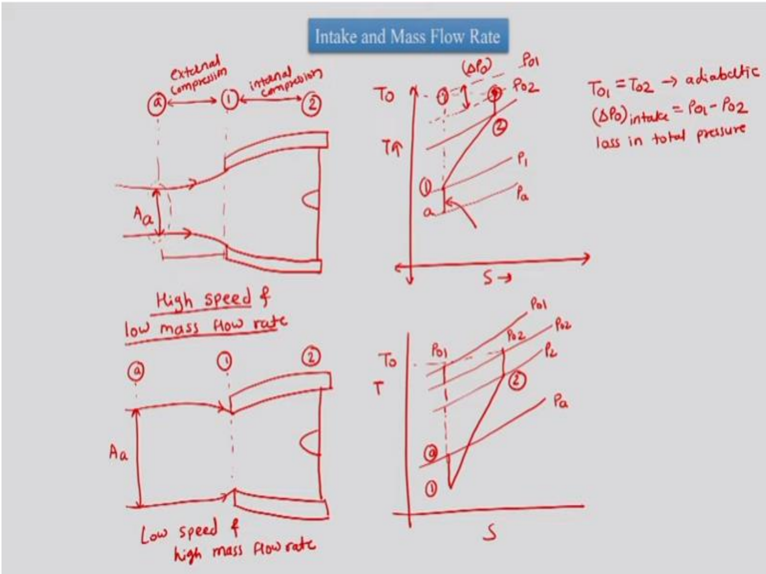

Now suppose we have intake and then that intake how does the flow through the intake would change in case of different conditions and then how mass flow rate would alter that is what we are going to see here. So this is the intake suppose and then in case of high speed we will have flow through the intake like this so this is flow through the intake in case of high speed. Since the captured stream to area which is suppose atmospheric Aa is less than A1 or maybe A2 in this section then this is leading to low mass flow rate.

So a stream line is approaching the intake and then we are considering a stream line which will heat the in the lip of the intake and then this is the minimum area of the between the two stream lines which are hitting the lip and so this area we are calling it as captured stream tube area and this area is minimum. So this is leading to lower mass flow rate and then what would happen in this case we are having a divergence from here ga station a to 1 and then again there is divergence from 1 to 2.

So if we plot T-S diagram then we can see that at station 1 there is at station *a* is the pressure which is Pa and then from a to 1 there is rise in pressure. So 1 is here this is Pa this is P1 and then from 1 to 2 ideally it would have gone like this in case of ideal where we expect the flow to be isentropic we expect the flow to be adiabatic and reversible this would have been P01 but what would happen in reality is would not reach to the state and we will reach here.

So this is 2 and since it is 2 so we will reach here which is 2 at 2 if we go isentropically towards total conditions then we will be at P02. So this is P02 this is this would have been P01 so this is the loss in total pressure at the intake delta P0 in the intake but we should note here that the total temperature is same. So T01 = T02 since flow is adiabatic in the intake but there is delta P0 in the intake and that is P01 – P02 so there is loss in total pressure in the intake. And then this raise in pressure from a to 1 is external compression and then this 1 to 2 is internal compression.

Now this is what we discussed for high speed and low mass flow rate intakes now when it is working with low speed then the stream line pattern will be different and stream line approaching stream line will approach like this so there is little acceleration at the entry so we would have captured more area at station a than the phase area of the intake at station 1. So if we try to plot the TS diagram then we are here at station a and then we will say that it is Pa but P1 as lower pressure then this is a to 1.

So there is expansion in the process a to 1 velocity will increase and then 1 to 2 is this process 1 to 2 in reality we will reach 2. But if we would have followed the isentropic path then we would have reached this as P01 and now we would have reached P02 here but both would have same total temperature. So this is P2, P02 and P01 and both would have both the kind of flows would have same things like there will be delta P0 which is total pressure loss there is same total temperature as of the inlet of the intake to the exit of the intake but the second option is for low mass flow rate sorry low speed and high mass flow rate.

So these are the flow patterns in the intake which are telling us how would be the stream lines around the intake. So now we will move and then see how we can have variation in the said thing which is external and internal compression.

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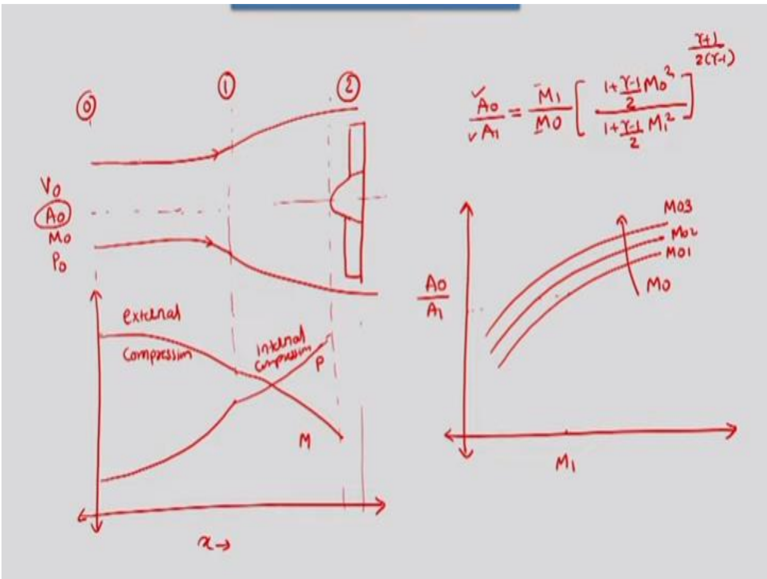

So this is what our intake and this is suppose a turbo fan composition where we have a fan now the flow is approaching the intake and then this is the inlet section of the inlet then we have V naught A naught M naught and P naught are the pressure at the naught condition and which is atmospheric conditions 0 and this is 1 and this is 2. So I we plot the variation as what we said then from 1 to 0 to 1 we have decreasing increase in pressure and decrease in Mach number.

So we have increase in pressure further there is increase in pressure but at different rate for 1 to 2 section which is entry to the fan. Similarly in case of this is for pressure similarly in case of Mach number Mach number this is x Mach number is decreasing till section 1 and there is further decrement in Mach number till the section 2 so this is Mach number. So this is how we will have external compression and internal compression for the intake and this is what capture stream to area.

We can know that the area Mach number relation and then we can write down the expression for

$$\frac{A0}{A} = \left(\frac{\mathrm{M1}}{\mathrm{M0}}\right)\left(\frac{1+\frac{\gamma-1}{2}M0^2}{1+\frac{\gamma-1}{2}M1^2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

This is the relation between the captured stream to area and inlet area of the intake and this is the flight Mach number and this is the Mach number at the inlet. So this we can plot where we have

A0 upon A1 and then 1 on the x axis this graph would look like this where we have increase in M0 in this direction where M01, M02, M03 will take place.

So this is how if for a given M0 which is free stream Mach number and given M1 if we have this much area ratio for A0 upon A1 that is for given A1 we will get this much of A0. Now if we increase the free stream Mach number then we get more capture of the stream area or more captured stream to area this is how we will interpret this curve.

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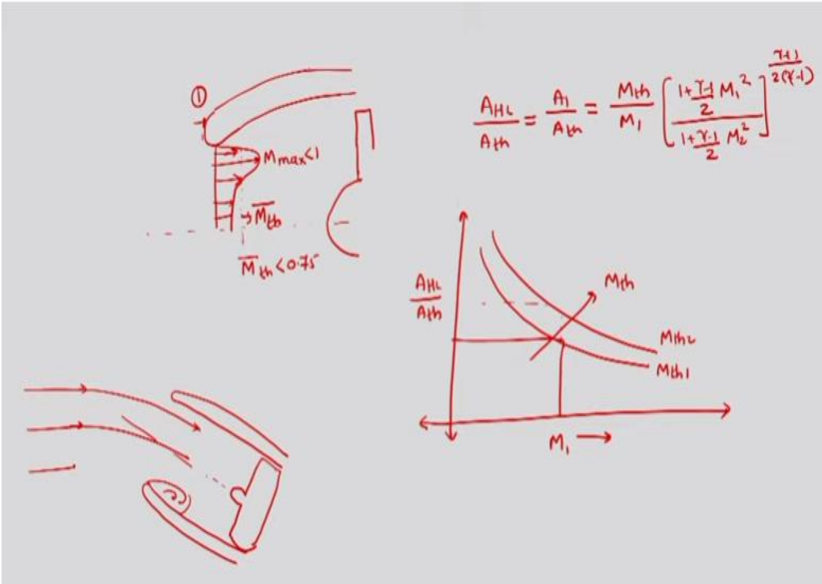

Having said this this is for internal and external compression and we see that there is 1 curve or bluntness to the intake and then that bluntness leads to expansion of the flow at the intake. So this M1 would have been the area M1 would have been the Mach number this location which is 1 now beyond that there is decrementing cross sections so flow will exhilarated and then we can feel that the Mach number profile will be like this where flow as accelerated to high Mach numbers till certain extent and that high Mach number is Mach number max and we expect it to be lower than 1.

But suppose at this minimum cross section or throat if we find out what is the mass flow average Mach number then that is m throat which is mass flow average and our expectation is that with this contraction which is acting as the nozzle m throat should always be less than 0.75 such that flow should not encounter any supersonic pockets in the intake. This is leading to an expression which is highlight which is the area of the inlet of the intake which is also called as the highlight divided by A throat

$$\frac{AHL}{Ath} = \left(\frac{\text{Mth}}{\text{M1}}\right)\left(\frac{1+\frac{\gamma-1}{2}M1^2}{1+\frac{\gamma-1}{2}M2^2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

So for a given composition or given highlight area to A throat area which both are known to us if we plot them with different M1 then this is variation fro given M throat Mach number. So if highlight area which is this A1 to the throat area if we increase then throat Mach number will increase if we decrease then throat Mach number will decrease if we increase the Mach number M1. And then this graph would have M throat 1, M throat 2 and this direction M throat increases.

So for a given Mach number we will have this as the ratio of highlight area M throat area for given M throat Mach number but that area ratio will increase for the incrementing M throat Mach number this is what the interpretation of this curve is. Having said this we have to take care for the bluntness so that it should not have led to the supersonic flow in the intake. Then we can see that the same intake would have different flow pattern depending upon the angle of a tag and we have seen that this is the flow pattern when we have intake perfectly aligned with the velocity vector.

But now if intake is not aligned with the velocity vector we can plot the curve and it would look like this and flow is coming like this due to which we have a big separation here in this region which would lead to lower mass flow rate. So intake should be properly designed to cater a range of angle of a (()) (28:48). Having said this we will move towards the supersonic intakes. Supersonic intakes can have different types and they can be either internal, compression external compression or mixed compression.

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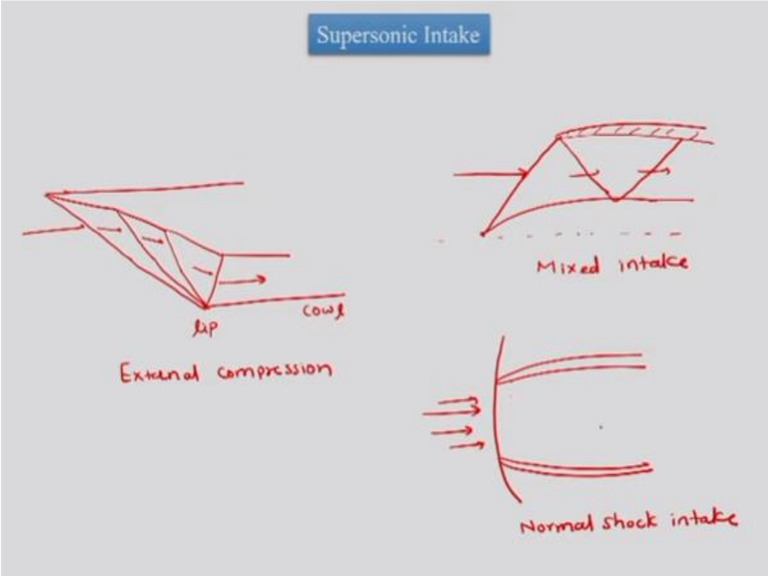

So external compression intakes will be composed of different rams we know that supersonic flow means flow with Mach number more than 1. So if Mach number is more than 1 then we will have shock when flow turns to itself so there will be one ram which would recreate one shock and that shock is this there is second ram this will create second shock there is third ram which will create third shock. And then we expect all the shocks to meet at locations which will are called limits as cow and this location will lip up the cow.

So flow while passing will get turned accordingly and then it will become parallel to the wall. So this is external compression intake for supersonic aircraft now there can be internal compression intake and then there can mixed compression intake. So mixed compression intake would have both external compression due to the shock and then there is a duct in which rest of the compression would take place.

Due to the shape and hence associated shock structure so this is the aircraft so there will be a shock which is originated from the lip or from the point and then this shock will reflect inside so due to the first shock there will be compression which is external and due to internal shocks there will be compression which is internal to the duct. So this is a mixed intake then we would have these all shocks are having certain angle which is lower than 90 with the velocity vector so those are all oblige shocks hence there is a different types of intakes which can have normal shock at the inlet.

And this normal shock inlet is a special so this is normal shock intake where major pressurize in static case would happen with the shock and then corresponding total pressure loss would also happen with the shock and rest of the pressurize will take place in the diffuser or intake. There are different normal shock position conditions.

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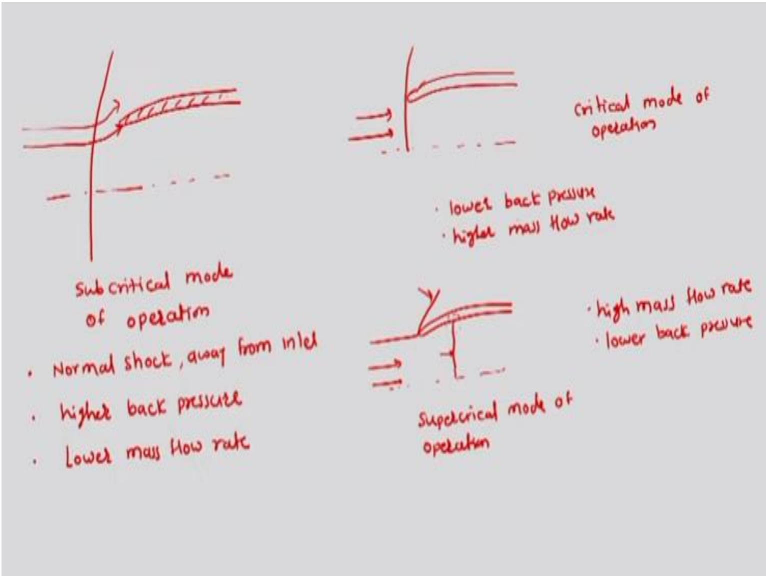

So if normal shock is present in the intake before the entry then this is called as sub critical operation or sub critical mode of operation in this case flow will approach and there is spillage where lesser mass flow will go through the intake so here have normal shock highlights are normal shock which is sitting away from inlet this will happen to higher back pressure. Back pressure means pressure inside the engine and then this leads to lower mass flow rate now this shock can be adjusted perfectly at the inlet like this.

In that case no spillage will take place and maximum mass flow rate will happen but this is at the lower operating engine operating pressure. So this is at lower back pressure and this operation is called as critical mode of operation and this has higher Amda. Now there is third mode of operation we would have same shock which is exactly at the inlet would happen inside the intake. When in this case there will be an external shock which is appearing at the top and then there is an internal shock.

This shock structure at the world would vary for the viscos flow since there is shock base boundary interaction. So flow will approach and then this is called as super critical mode of operation of the intake. Here we get higher mass flow rate and this is with lower rather further lower back pressure. So these are the different modes of operation of the normal shock base supersonic intake.

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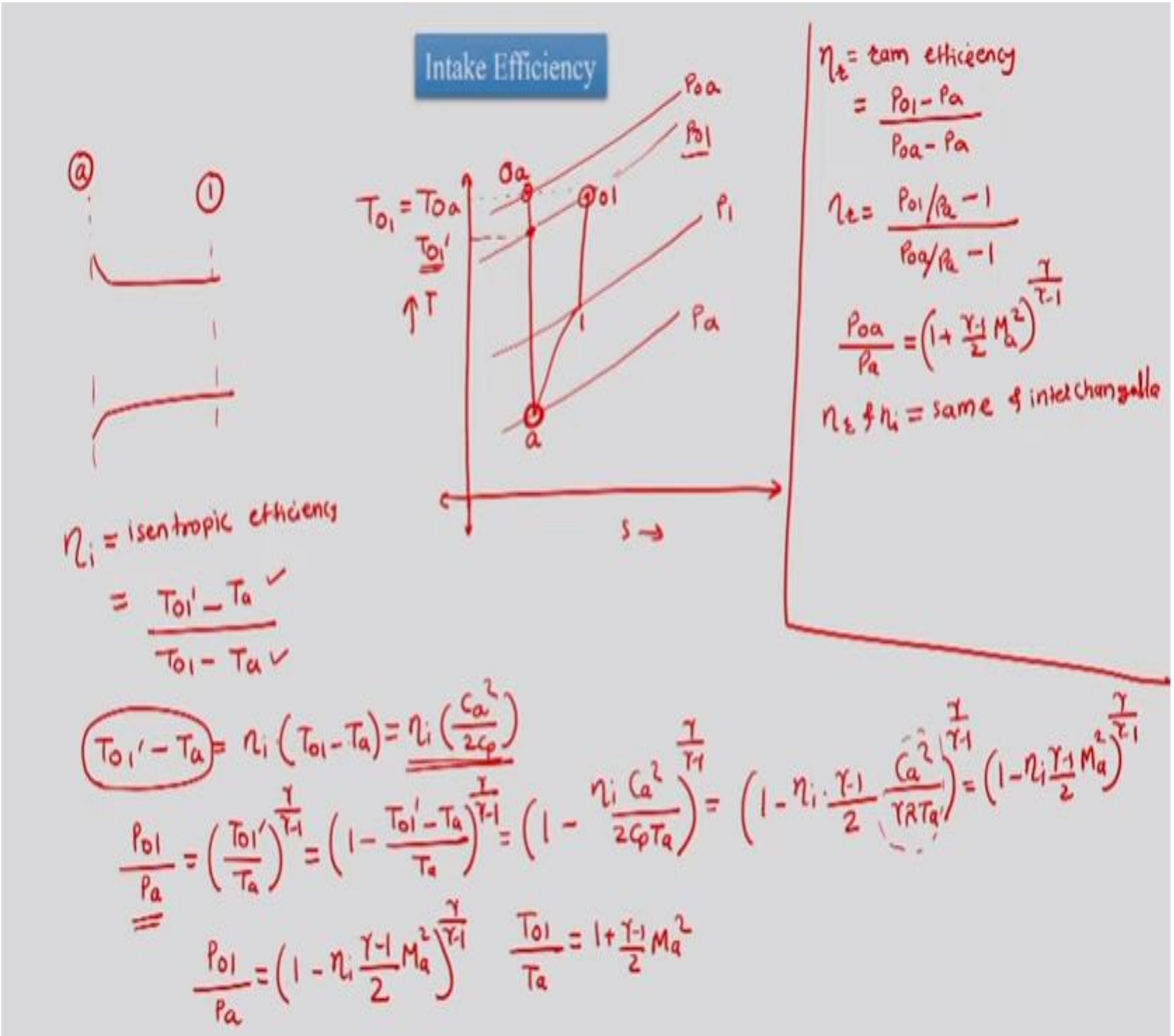

Now we will find out the intake efficiency formula suppose we have this condition which is atmospheric at the inlet and then this exit of the intake so this condition is 1 then we will define isentropic efficiency of the intake which is isentropic efficiency which is defined as

$$\text{isentropic efficiency, } \eta i = \frac{\text{T01'} - \text{Ta}}{\text{T01} - \text{Ta}}$$

So this is basically related with the convergent of kinetic energy into the pressure rise in ideal case and this is conversion of kinetic energy into the pressure rise in real case.

So this is coming as the difference between the total and static temperature in ideal case, total and static temperature in the real case. This can be well understood if we plot the Tl diagram or the intake so this is T and S axis so we have we are here at state a so we are at Pa at Pa we have total pressure which is P0a okay. But in the process of diffusion we will reach P1 and then at this is the static pressurize in the process of diffusion in the diffuser or in the take.

So there will be total pressure which is P01 in the exit of the intake but since the process is adiabatic both will have same temperature which is T0a = T01. So this is the case which we would have so this is a this is 1 this is 01 this is 0a but if isentropically we would have done then we would have reached P01 pressure at lower total temperature which is T01'. This is what the total temperature we would have reached at the P01 pressure.

So we can write down this formula as

$$T0' - Ta = \eta i \frac{Ca^2}{2\ Cp}$$

since basically we have from this formula we have isentropic efficiency as a ratio of two temperature difference where we are taking numerator as it is on left hand side and denominator we are multiplying by isentropic efficiency. So we have denominator T01 – Ta but we know T0 is equal to we know the steady state energy equation which is $h0 = h + C^2/ 2$ or $V^2 / 2$ so we can write it as

$$T0 = T + C^2/ 2Cp.$$

So we have T0 – T is $C^2/ 2Cp$ so this we can make use and we can write down this as isentropic efficiency into $Ca^2 / 2Cp$. So having said this we can further use this for finding out the rest of the relations where we can write down P01/Pa = T01 P01/ Pa is here we have saying P01 pressure ideally would have reached T01' as temperatures so (T01'/Ta). So this expression can be written as T – T01 dash – Ta upon Ta so this is just a rearrangement bracket raise to gamma upon gamma – 1 and this rearrangement helps us to give this T01' – Ta in terms of efficiency.

So we get

$$\frac{Po1}{Pa} = \left(1 - \eta i \frac{Ca^2}{2\ CpTa}\right)^{\frac{\gamma}{\gamma-1}}$$

but we know that Cp can be written as $\gamma R/(\gamma - 1)$. so this we can write as

$$= \left(1 - \eta i \left(\frac{\gamma - 1}{2}\right) \frac{\mathrm{Ca}^2}{\gamma \mathrm{RTa}}\right)^{\frac{\gamma}{\gamma-1}}$$

and this Ca square by gamma Rta is practically Ma^2

$$= \left(1 - \eta i \left(\frac{\gamma - 1}{2}\right) Ma^2\right)^{\frac{\gamma}{\gamma-1}}$$

So this is how we can find out what is the total pressure at the exit of the intake.

So we know static pressure at the inlet of the intake we know Ma and then knowing the isentropic efficiency we can find out P01 which is exit total pressure at the intake and this is the formula but we know that $\frac{T01}{Ta} = 1 + \frac{\gamma-1}{2} Ma^2$ which is valid since process is adiabatic. For total conditions we need reversibility but for total temperature we do not need reversibility.

Further having said this we need to define one more efficiency for intake which is said as ram efficiency and ram efficiency is defined as the defined on the basis of actually pressurize P01 – Pa which is maximum actual maximum pressurize divided by ideal maximum pressurize we would have gone from Pa to P01 which is maximum pressurize in actual case and ideally we would have reached prompt Pa to P0a.

From Pa we reached to P0a P01 but ideally we would have reached Pa2 to P0 so this is what the definition of ram efficiency is. So ram efficiency can again be said

$$\eta r = \frac{\left(\frac{\mathrm{P01}}{\mathrm{Pa}} - 1\right)}{\left(\frac{\mathrm{P0a}}{Pa} - 1\right)}$$

here we know that

$$\frac{Po}{Pa} = \left(1 + \frac{\gamma - 1}{2} Ma^2\right)^{\frac{\gamma}{\gamma-1}}$$

Practically speaking the ram efficiency or isentropic efficiency also termed as diffuser efficiency are same and they are interchanging.

This efficiencies are more used for subsonic intakes in case of supersonic intakes total pressure ratio or pressure recovery factor is said to be important with this we end the discussion about the intake and then we will use this discussion on intake or his formulation for intake for the valuations where we have to do calculations for the turbo jet, turbo prop or turbo fan kind of engines are also maybe in the examples thank you.