IC Engines and Gas Turbines
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Lecture – 50
Nozzles and Diffusers: Introduction, Intake efficiency, Nozzle efficiency

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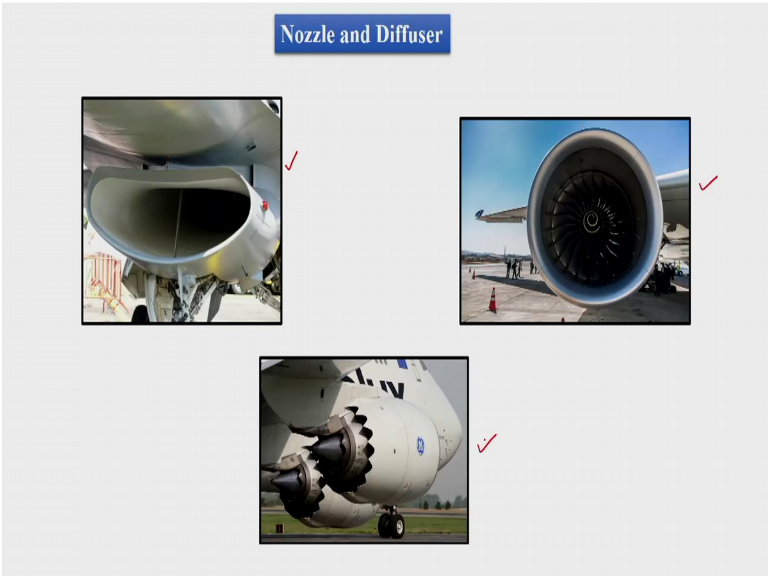

In today's discussion we will talk about Nozzle and Diffuser. Here we are talking from the perspective of the aircraft engine where gas turbine cycle is used. The engines what we see generally in civil or military aircrafts those are based upon the gas turbine power cycle.

We had seen earlier that in case of the power production where they going to generate electricity using the gas turbine; we would have shaft power as an output. But if we have the aircraft engine where we need to have propulsion as an our objective, then in that case we will have the output as power which is a thrust power, not as the electrical power.

So, in that case of aircraft engines we will have compressor would be run by turbine. So, turbine would not produce, mechanical work more than required for the running compressor. However, in case of aircraft propulsion we have nozzle which is placed after the turbine which would generate the kinetic energy and hence that would be used to get the propulsion active ok.

So, in that case we have something called as intake and then we have something called as nozzle. So, these are two extreme entities in an aircraft intake is also called as diffuser and the nozzle is what propulsive nozzle or propelling nozzle what we are going to talk about; so nozzle and diffuser. In this first slide we can see that there are two intakes tied to different two types of intake shown; this is an intake and this is also an intake.

But this slide or this figure is more for the nozzle which is at the outlet of the, which is at the, toward the exit of the gas turbine. So, these are the components for today's discussion.

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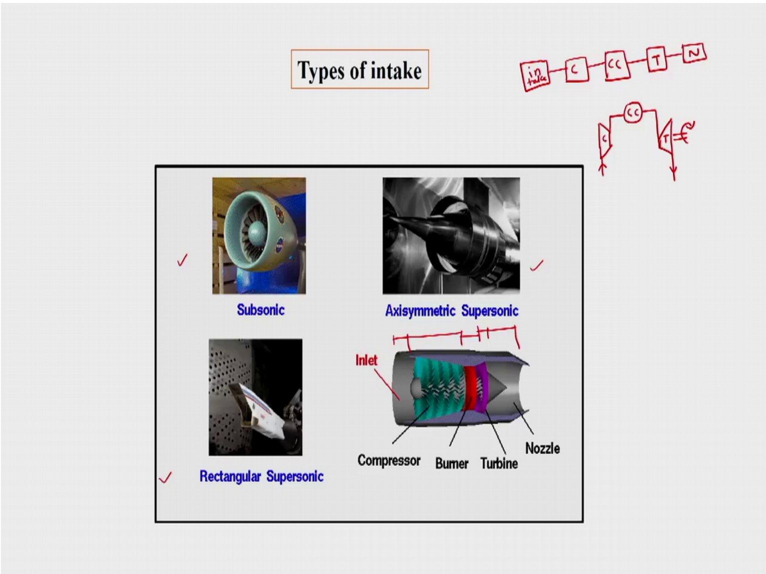

So, we will start with types of intake we have seen that aircrafts can move aircraft generally move from the subsonic speed to the very high speed which is supersonic speed.

So, for the subsonic typical intake is what we have seen in the civil aircrafts this is a typical subsonic intake. But if we want to have an axisymmetric supersonic flow to be coming into the engine, then we have axisymmetric intake there is a possibility of rectangular intake; this is a two dimensional intake mostly for the supersonic engine.

In general in an aircraft we have seen till time that there is a compressor, then there is a combustion chamber and then there is a turbine. So, these parts we have seen we have sketched the diagram like this. So, this is compressor then flash flow will come into the compressor, then we will have combustion chamber and then we have the turbine. So, this is what we had seen in case of open cycle gas turbine power cut.

We had now talked about any intake over here, but this is more for the electricity generation. Now here we can see that there is an intake; so before the compressor there is an intake. So, we can see that this is intake, then this is compressor, then this is combustion chamber, then turbine and then nozzle.

So, then after turbine we have nozzle. So, a typical aircraft engine would have all these components where we would have initially fluid or air coming into the intake.

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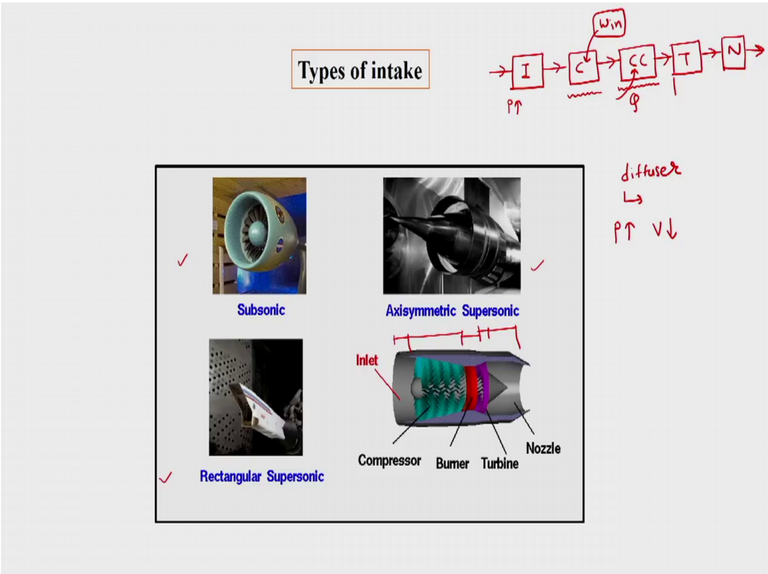

So, this is intake then air will come into the intake; then from the intake it will go to the a compressor, from the compressor it will go to the combustion chamber, then come from combustion chamber, it will go to the turbine and from the turbine it will go to the nozzle.

So, this is the complete path of the air inside the gas turbine engine then why should we have intake? Our main objective for the aircraft engine is to have combustion or rather heat addition at high pressure such that we should have high temperature and high pressure gas at the entry to the turbine. So, for that we have to increase the pressure of air using a compressor.

So, while increasing the pressure into the compressor we need to give W in here and we Q in into a combustion chamber. So, this is W in which we have to give and then by meaning intact we want to reduce this W in such that our requirement of the work would decrease in case of aircraft propulsion. So, that here intake is expected to rise pressure before going to the compressor. So, what would happen is, compressor would rise the further pressure and then the pressure rise requirement from the compressor would decrease.

So, this is the major philosophy for having intake and then in case of intake then we would practically have intake as a diffuser. Since we know the diffuser is a duct where we have pressure increased and velocity decreased. This is what we have seen in case of incompressible flows also where we can apply Bernoullis equation and we can see that in case of diffuser we will have pressure rise and we will have velocity decreasing.

So, the same phenomena is implemented in case of aircraft engines where ducts are designed such that those ducts would ultimately give rise to the pressure and such that a compressor would have higher pressure gas air which is coming and its inlet. So, this is the idea of having intake.

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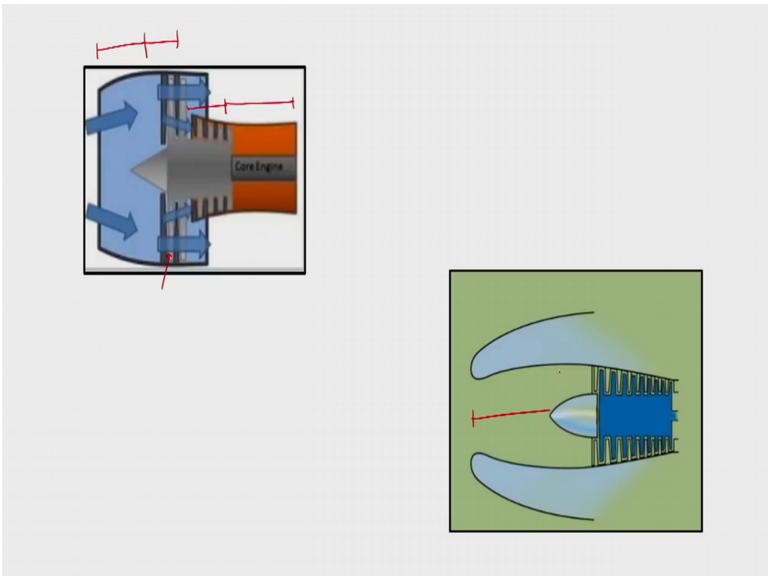

Then this is a typical intake for turbo fan engine. So, we have fan over here and then we have compressor and then combustion chamber. So, air first goes from the intake, then to the fan and then it gets bypassed somewhere air would bypass the gas turbine and then it will some air would go into the compressor and then it would go to the combustion chamber and then carry on. So, this is what it would happen in case of a turbo fan engine.

In general in an engine; we would have different shapes of intake as we would have seen as we have seen in earlier picture. This is one of the pictures of the intake where this air would get compressed during its path in the duct which is intake.

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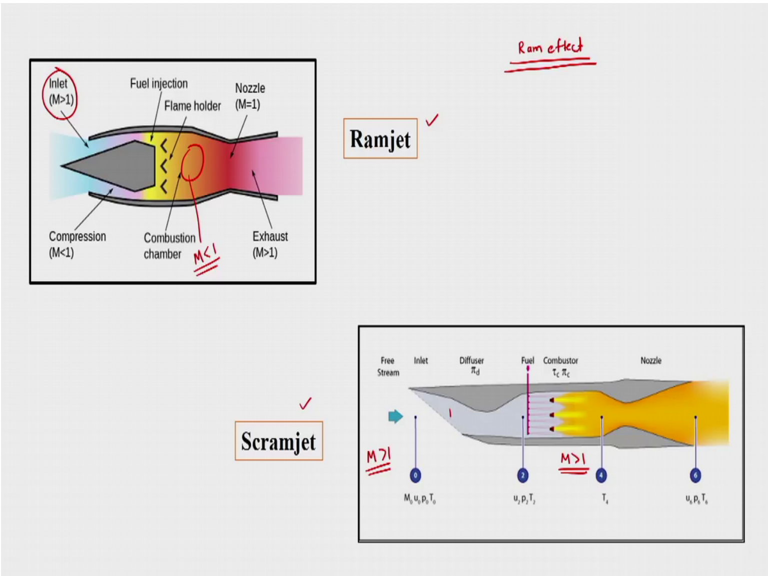

So, practically pressurize and decrement of velocity are the objectives of the intake. So based upon the requirement we have different types of intakes. So, we have seen the intakes for subsonic flows or the intakes for the engines which run with turbofan, but the new generation engines which would have we had talked about as a ramjet and scramjet engines. So, they have different types of intake.

So, their intakes requirement is something like where we will not have any turbo machinery or we will have no rotating part. So, in case of turbo jet engine we had seen that there is compressor which is run by turbine. And we have also discussed this point in our aircraft engine lecture that when we do not need any compressor then we would not need any turbine. Then actually in case of ramjet and scramjet we take care of if effect which is called as ram effect; here inlet momentum of the air is used to increase its pressure.

So, we try to increase the pressure of the air with its own movement; so this is what a ram effect is all about. In general using this effect only effectiveness or efficiency of an intake is defined as the ram efficiency ok, but before that we will revisit the ramjet and a scramjet; intake in case of ramjet we know that at the inlet we have flow which is more than mach 1.

As definition of ramjet we would have combustion taking place here into the combustion chamber where mach number is less than 1. So, we have to go from mach number more than 1 to mach number less than 1. So, intake is such a way defined here that the structure of the flow would lead to the subsonic flow into the combustion chamber. So, ramjet operates with mach number less than 1 into the combustion chamber; if we go into the details of gas dynamics then we will come to know that there will be shock which will be sitting into the intake in front of the intake and in that compression which is not mechanical compression, but the thermodynamic compression would lead to rise in pressure instead of having compressor.

So, we take care of the flow regime which is supersonic flow regime for rising the pressure in during the design of the intake. However, if we go back and see in these cases the flow is subsonic where mach number is where mach number is less than 1 at the inlet. So, since mach number is less than 1; we can see the diverging passage is designed as the intake.

Since we know that in case of incompressible or subsonic flow the area increase is treated as the diffuser; so this is a diffuser. So, intake acts as a diffuser where we have diverging passage and then that diverging passage rises the pressure. In case of ramjet we would first have some shocks and those shocks since the flow is greater than 1 mach number. So, it is a supersonic flow; so we would have some shocks appearing and then those shocks would give rise to the pressure after passing through the shock.

And then we will have combustion, so ramjet intake is defined or designed to have certain structure of the shock we will define the efficiency of the intake then we will come to know what kind of requirement we would have. In case of scramjet we would have mach number greater than 1 at the inlet and then we would have mach combustion which is again happening at mach number greater than 1.

So, both the sides we have mach number more than 1. So, what would happen over here into the intake is we actually does not reduce the flow velocities to the extent that it will go to the subsonic speed. So, we would just reduce the flow speed so that it will become lower supersonic and then we will have fuel added into the combustion chamber and then combustion will take place still in the supersonic flow regime and then we would have the nozzle.

So, this is what the requirement of then intake in case of scramjet engine. So, we have scramjet engine and the requirement for the scramjet engine would be to have the still supersonic flow existing into the combustion chamber.

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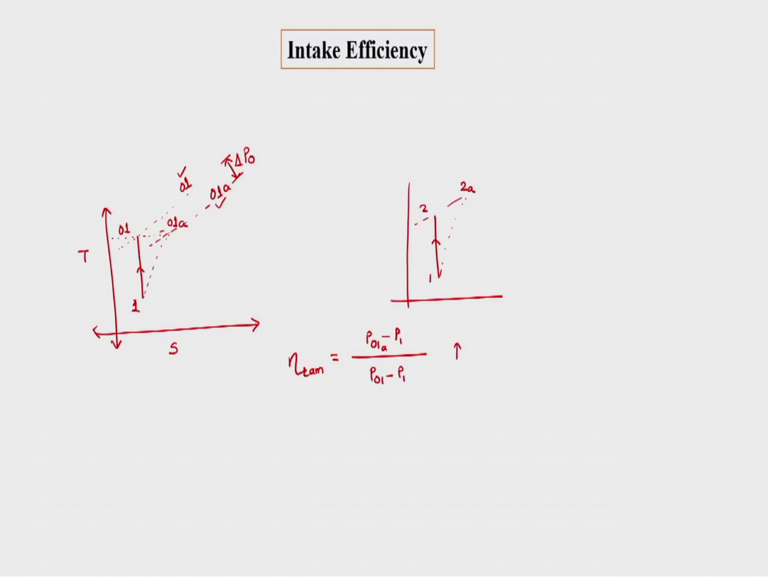

So, we will define the intake efficiency or which is called as ram efficiency. So, while defining ram efficiency first we will try to plot the T S diagram, then we can understand what is practically happening in case of a intake. So, we know that in case of gas turbine first compressor Brayton cycle we have first in case of Brayton cycle, we first have compressor which takes 1 to 2 as isentropic compression. And then we have seen that if the compression is not isentropic it is going not in vertical direction, but we will lead to some 2 a point this is what we had seen.

So, this is the compressor, but before going to the compressor we have intake an expectation from the intake again over here is to go vertically from 1 to 2 and then from 2; we will have compressor further going straight vertically in an isentropic process. So, this is what going to happen, but we would like to have the pressure rise in the intake such that instead of going to have only static pressure rise, we would expect to have it to reach the total pressure which is not 1.

We have defined total or stagnation conditions as the conditions where we would have 0 velocity we would have isentropically stop the fluid and reach the 0 velocity. So, 1 to 01 this is what our expectation from the intake is. So, we want flow to go from 1 to 01 at the exit of the intake that is our expectation, but what would happen in this case is we would not go to that level and we would go to some 01 a this is what we would go to.

And here in this case this is 01 and this is 01 a; so this is the decrement in total pressure delta p naught in the intake; so this is the loss in the intake. If the process would have been isentropic then we would have reached this total pressure if the since the process is not isentropic, we have reached this total pressure and hence there is a loss in total pressure which is delta p naught in the intake. And intake or the diffuser design should have taken place such that we should have minimum loss in the intake; so this is what the major idea is.

So, using this concept we can see that the ramjet and scramjet intakes have basically they are pressurized not with the mechanical pressure, they have pressurized due to the shock which is a thermodynamic effect, but that thermodynamic compression basically leads to the problem of loss in total pressure.

So, shock which leads to sudden rise in pressure that actually is a non isentropic process. So, we have greater loss in total pressure intake in case of scramjet and ramjet intake. So, the design of scramjet and ramjet intakes is a more challenging task and in case of the subsonic intakes. So, here we can define the ram efficiency as what is the actual rise in total pressure is P naught a from P 1 to the ideal rise in the pressure.

So, this is the ram efficiency; this is how we can define which intake is good and which intake is bad the requirement is to have higher and higher ram efficiency ok, then we will go to the part of discussion for nozzle.

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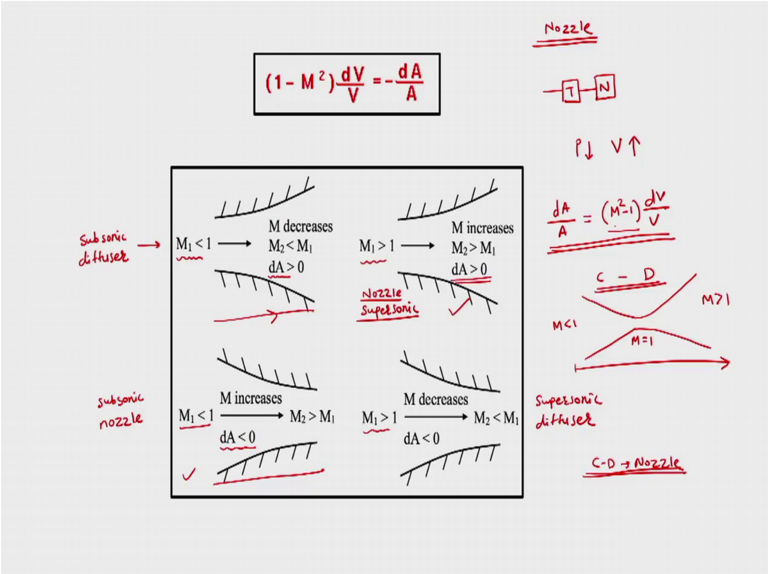

As we had seen that we have turbine and after the turbine we have nozzle the job of nozzle as job of it is inverse to the diffuser. Diffuser we have seen that, it rises the pressure and decreases the velocity at the expense at the effect of rising enthalpy.

But in case of nozzle at the expense of enthalpy drop we have decrease in total decrease in pressure and we have increase in velocity. So, in case of nozzle pressure decreases and velocity increases this is what it would happen in case of a nozzle. So, with the nozzle, we have following expression which is governing between area and velocity. So, we have this expression which says that dA by A which is area change in case of a duct is equal to m square minus one into dV by V.

So, if we look into this expression carefully then we can understand that if I have a diverging cross section which has area increase. So, that if I have subsonic fluid at the inlet then what would happen? We have subsonic flow at the inlet and then we have area increasing. So, velocity has to decrease; so this acts as a diffuser. So, this is a subsonic this is a subsonic diffuser, but if we have mach number more than 1; in this diverging section then what would happen mach number is more than 1, section is diverging.

So, we have this side to be positive; so this has to be positive. So, velocity will increase. So, this acts as nozzle which is a supersonic nozzle. Similarly, if we have converging section; so dA by A is negative, so dA by A is negative. So, this side is negative if we have subsonic flow.

So, this is also negative this has to be positive. So, this acts as subsonic nozzle and here we have mach number more than 1; so mach number more than 1. So, this is positive, but we are decreasing area. So, this term is negative, but this is positive. So, this has to be negative; so mach number decreases, so this acts as supersonic diffuser.

So, we see that if we just draw a duct then we cannot say whether it is some nozzle or diffuser it depends upon what is the inlet mach number if we know a duct. So, supersonic diffuser would have convergent section, but subsonic nozzle has convergent portion convergent section. So, supersonic diff nozzle has diverging portion, but we can have we have subsonic diffuser as diverging portion.

So, what we will have in general if we want to go from subsonic to supersonic; then we can have this first subsonic nozzle which is a converging portion, then we will go from mach number less than 1 to mach number 1 to the minimum section we say that dA by A is 0 then mach number is 1. And then from there we will add supersonic nozzle where we are having mach number more than 1 and leading to that condition.

So, we can go from subsonic mach number or supersonic mach number in case of a nozzle if we have convergent and divergent sections together in that case it is called as C D nozzle ok. So, we have to implement such a nozzle in case of the engine if we are in such requirement. However, in general case for civil aircrafts at least we see that converging nozzle is present.

So, we have only subsonic flow at the entry to the nozzle and then it leads to sonic outlet or maybe subsonic outlet at the exit.

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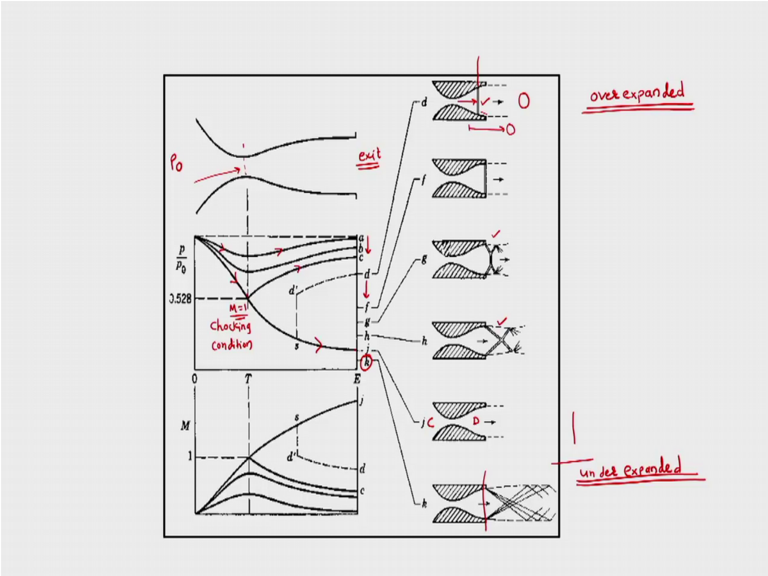

But we will see how nozzle flow takes place, this is a reservoir condition and then we have convergent divergent nozzle and then this is the exit condition. So, let us pretend that the reservoir and the exit both are at the same pressure; if both are at the same pressure then there will not be any flow taking place into the nozzle.

But now if we decrease the pressure at the exit then flow will start taking place. So, initially this portion which is a converging portion acts as a nozzle for the subsonic flow. So, we can see that pressure is decreasing, but once it reaches to the minimum cross section; it encounters an increasing area since area is increasing it is acting as the diffusers of pressure is increasing.

And this process continues; this process continues till a point where we reach mach number 1, in a case where we are having particular exit condition. And for that particular exit condition, the flow expands into the subsonic nozzle and reaches mach 1, but further pressure is not sufficient and outlet to expand. So, pressure rises there onwards; if we further decrease the exit pressure then in that case the portion in the convergent section will not change.

So, the expansion pattern in the convergent section will not change and then this is called a choking condition. So, once choking condition is reached then what would happen? Then we will encounter a shock here onwards into the outlet section and then we have a shock present till the shock flow is expanding into the diverging section, but we do not have sufficient outlet pressure flow. If continues to expand into the outlet section; then it will have a pressure which is much lesser than the outlet pressure. So, flow would have over expanded.

So, since fluid cannot be having over expansion condition. So, as to limit its expansion there is a shock. So, after the shock flow would have rising pressure there onwards we have diverging section. So, this diverging section for the subsonic flow would treat as a diffuser and then at the exit flow will have the pressure as the exit pressure. So, this presence of the shock is going to have the pressure at the outlet as similar to the pressure of the atmosphere.

So, the shock pattern differs as we decrease the outlet pressure. So, initially normal shock in the duct become the oblique shock in the outlet and then oblique shock will further reduce its strength as we keep on decreasing the pressure. And for a particular condition we have the complete supersonic expansion into the conversion as well as divergent nozzle.

But if we further decrease the pressure to this value then we would have a case which is called as under expansion under expanded nozzle. So, here in this case nozzle is improper since it is not expanding the flow to the desired exit pressure. So, since it is not properly expanding the nature creates something which is called as expansion pan so that the flow reaches the pressure which is desired value at the outlet.

So, this is the general idea of the flow what is going to take place in case of a nozzle, but in case of aircraft power requirement is to generate higher and higher kinetic energy using a nozzle such that, that kinetic energy would fetch us to the required thrust. So, we have to take care for the proper flow dynamics or gas dynamics into the nozzle.

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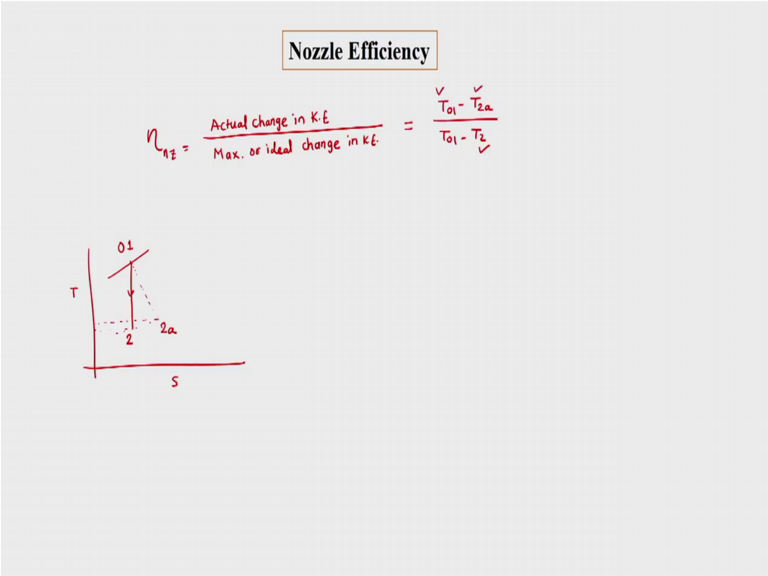

Then we have to define what do we mean by the nozzle efficiency. So, nozzle efficiency is defined as efficiency of nozzle. So, for that again we will draw a T S diagram. So, we are here at naught conditions 01 condition at the entry to the nozzle; if the flow would have expanded completely into the nozzle then it would reach a very high velocity over there. So, this isentropic expansion would fetch us to this condition which is called as 2 suppose.

But we cannot go to this condition we will end up in a condition which is 2 a due to the losses which is a frictionless. So, we would have come here; so instead of 2, we have come to 2 a. So, this is the loss which is a frictionless nozzle efficiency is defined as actual K E gained actual change in K E actual K E change in kinetic energy divided by maximum or ideal change in kinetic energy.

So, this kinetic energy can be represented in terms of the temperature. So, we have T 01 minus T 2 a divided by T 01 minus T 2. So, this is total temperature at the outlet to the turbine and this is static temperature at the outlet the nozzle; in real case and this is static temperature at the outlet to the nozzle in the ideal case. So, this is what nozzle efficiency is and this is how we can compare performance of two nozzles.

The nozzle having higher efficiency is desirable. So, this is how we complete the discussion on the nozzle and the index which is diffuser. So, this completes the complete discussion on different parts of a gas turbine, we have seen in the class in the discussion that there is a cycle which is called as gas turbine cycle or Brayton cycle; it may be closed, it may be opened depending upon our requirement. And then we have seen the different attachments to the gas turbine cycle then we have seen different components or different up before that we have seen different applications like aircraft propulsion.

Then we are seen different components like compressor we have seen centrifugal compressor and axial compressor. Then we have seen the turbines which are which is radial turbine or axial turbine and then we have seen the intake or diffuser and nozzle in case of particularly in case of aircraft engines. So, this ends our discussion for this course which is IC engine and gas turbine particularly for the part of the gas turbine.

Thank you.