Thermal Engineering: Basic and Applied
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Lecture - 28
Use of Nozzles in Steam Power Plant, Flow Analysis of Steam in Nozzle

I welcome you all to this session of thermal engineering, basic and applied. And today we shall discuss about the flow nozzles. You know that in the context of steam power plant, which is a module of this course, we have discussed that flow nozzles are also very important, rather these are mandatory components. If we try to recall in the schematic depiction of the steam power plant, we did not mention about the flow nozzle but, we had mentioned about four major components like steam generator, steam turbine, condenser and pump.

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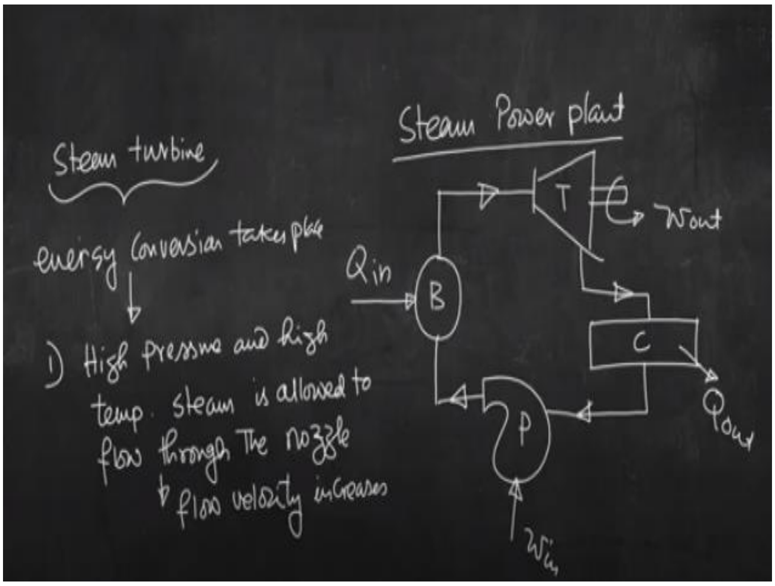

So if we try to draw the schematic of a steam power plant and we can see the major components. So this schematic depiction shown in the slide has been used many times. We started our discussion with the steam power cycle. We have briefly discussed about the basic thermodynamics, which is important to understand the processes, which are there in the steam power cycle.

We have also discussed about several steam power cycles, starting from the Carnot cycle, Rankine cycle, modifications of the Rankine cycle and we have also discussed about binary cycle. Then we have discussed about the steam generator or boilers. Now before going to discuss about steam turbine, today we shall discuss about the flow nozzles. We cannot see the nozzle in this schematic depiction, but again nozzles are the mandatory components in the context of the operation of the steam power cycle.

So the sole purpose is to produce steam and when it is coming from the boiler, it has high temperature and pressure. That high temperature and pressure or high energy to be precise, should be converted into the another form of energy that is work. Now how can we have this conversion?

So at the exit of the boiler, steam which is being produced, that steam is having high temperature and pressure. If we look at the exit of the turbine, we are getting again steam but that steam is having low temperature. So turbine is a device in which high temperature steam is doing some work and the steam leaving the turbine is at low temperature. So basically temperature has dropped, pressure has reduced and at the cost of this reduction in pressure and temperature, we are getting some work output. So energy conversion takes place in the turbine. Now when we are talking about energy conversion, it takes place in two ways. So at least we have understood about steam turbine.

I am sure that you all have studied about hydraulic turbines. So what is done and where these hydraulic turbines are used? We have studied that hydraulic turbines are used to generate electricity in a hydraulic power plant or hydel power plant. And we have seen that we use the energy that is stored in the water. In a hydraulic power plant, water is allowed to flow through a penstock and finally, if it is an impulse turbine then water is taken to the nozzle before it enters the impulse turbine blades. So basically stored energy of the fluid is converted into the kinetic energy.

So here also when you are talking about steam turbine, you know the energy which is remaining stored as internal energy plus that high pressure and temperature is now converted into another form of energy in the turbine. And this conversion takes place following two ways.

So in the steam turbine, this energy conversion takes place in two ways. First high pressure and high temperature steam is allowed to flow through the nozzle. Nozzle is again a mechanical device which is having gradually decreasing area. If a device which is having gradually decreasing area in the direction of flow that is nozzle and if it is having gradually increasing area in the direction of flow that is diffuser. Sometimes a device may have decreasing and then increasing area and that is called a convergent divergent nozzle. So when that high pressure and high temperature steam is allowed to flow through the nozzle, then at the reduction of that high pressure velocity increases. So we can see that, initially steam will be allowed to pass through the flow nozzle and while passing through the nozzle, at the cost of the pressure drop, flow velocity will increase.

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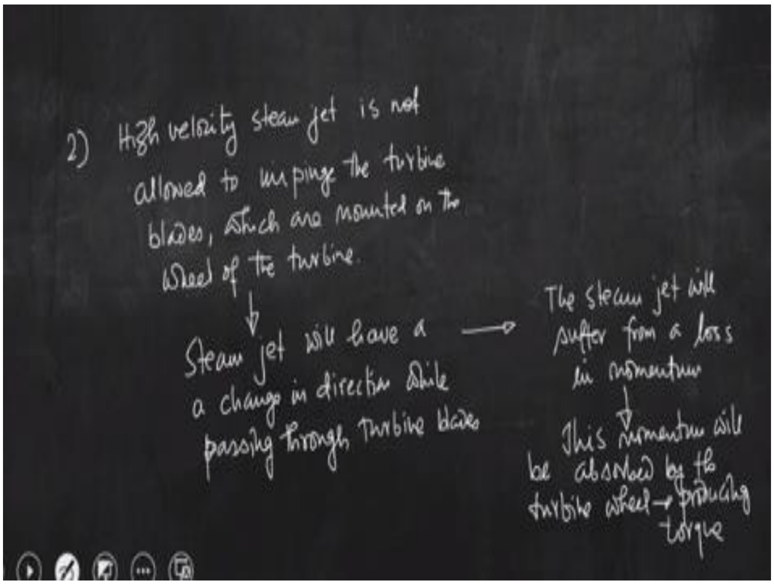

Second is high velocity steam jet. The nozzles are designed in such a way that while steam is passing through the nozzle, there should not be any drop of temperature. So temperature should not be allowed to reduce while steam is passing through the nozzle, so there is no chance of having reduction in steam temperature theoretically. That means, we are also going to get steam at the exit of the nozzle, and since the velocity of the steam will be increased, so we are writing steam jet. So steam will come out of the nozzle in the form of a jet. So high velocity steam jet is now allowed to impinge the turbine blades which are mounted on the wheel of the turbine. Now what would be the consequence?

So steam is coming out of the nozzle in the form of a jet, and that jet impinges turbine blades which are mounted on the wheel of the turbine. Now you have studied about hydraulic turbines as well as pumps. So blades are having some shape and we can say blades are twisted. So when steam jet impinges turbine blades and then there will be a change in the direction of steam. So the consequence is that after impingement, steam direction will be changed. Due the change in direction, there will be a loss of momentum. So when steam is coming out of the nozzle in the form of a jet and that jet impinges turbine blades and that jet will have deflection because of the inherent structure of the turbine blades. As there is a change in direction of the steam jet, the jet will suffer a loss of momentum.

So steam jet will have a change in direction while passing through turbine blades. Then the steam jet will suffer from a loss in momentum. So you know that nothing is lost. So this loss in momentum will be absorbed by the turbine wheel and the ultimate consequence is that it will produce torque. So what is producing torque?

Torque will be produced by the steam jet because of some mechanical arrangement. That means, steam is allowed to have deflection in its flow path. And because of this reason, steam jet will suffer a loss in momentum and that momentum will be absorbed by the turbine wheel which in turn will produce torque. And because of that the turbine wheel will be rotated.

So this is how the energy conversion takes place inside the turbine. So today just I wanted to discuss that when the high pressure, high temperature steam is passing through the turbine, how we are having energy conversion. Eventually you are getting steam at the exit of the turbine but that steam is having low temperature. So now we can see that it is not only the turbine itself rather inside the turbine also we need to have a few flow nozzles. And this is why I have taken this particular aspect today in the beginning, so that we can have a fair understanding about the utility of flow nozzles in the context of steam power plant.

So when steam is coming out from the boiler or steam generator that steam is not directly taken to the turbine blade. Rather steam is allowed to pass through the flow nozzles and then only that high velocity steam jet will be taken to the turbine blades. And we have seen by how we are getting energy conversion which is taking place inside the turbine.

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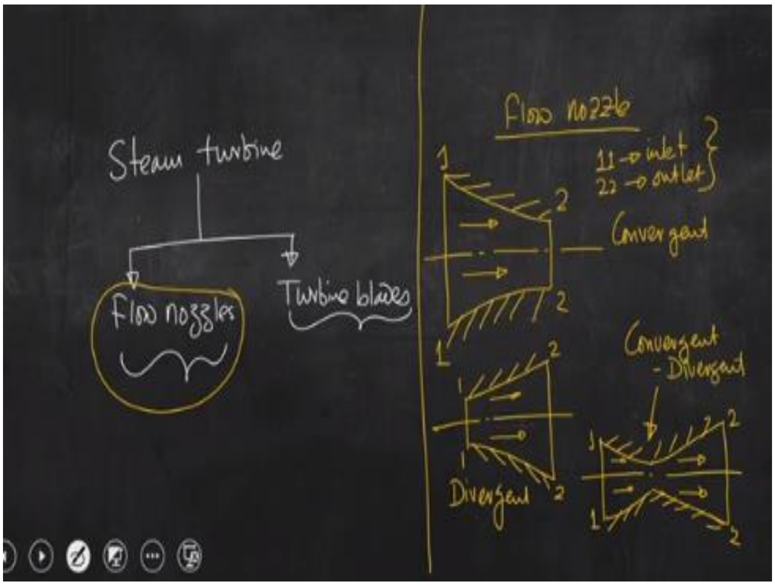

So steam turbine is the assemblage of flow nozzles and turbine blades. So these two mechanical parts together is the steam turbine. Today we shall briefly discuss about the flow nozzle. So why flow nozzle is very important that we have understood. Flow nozzle is a mechanical device through which steam is flowing. So when steam is flowing, we need to have the analysis of that flow essentially because the entire objective of the flow nozzles is to produce steam jet.

So the shape of the flow nozzle is drawn in the slide with flow direction. So we can understand that in the direction of flow, there is a decrease in the cross sectional area. When the area is reducing, the velocity will increase, as the mass flow rate is remaining same. Since the fluid here is steam, so it is very difficult to say that the density will remain constant. So density will also be varying when steam is flowing from one part of the nozzle to the other part of the nozzle. So we also need to understand that for a given mass flow rate of steam, which is produced by the steam generator, if we take a particular nozzle, then the nozzle area at its exit is very important, so that we can get required velocity.

Because the steam jet which will be produced at the exit of the nozzle, that steam jet will be now directed to flow through these turbine blades. While it is passing through the turbine blades, first it will impinge. So the rate at which it will impinge on the turbine blades depends on the velocity of steam at the exit of the nozzle.

So you can understand the area at the exit of the nozzle is also an important parameter to be looked at for the efficient energy conversion, which will take place in the turbine. So the convergent type flow nozzle is drawn in the slide. There are two sections as shown in the diagram, 11 is inlet, and 22 is outlet. Now similarly we have drawn the divergent type flow nozzles. And the flow direction is also shown in the diagram. This has opposite flow configuration compared to the convergent type.

And the nozzle normally has gradually decreasing area in the direction of flow. So basically convergent type is the typical shape of a nozzle. So the divergent type can also be said as diffuser because in the direction of flow, the area increases. And we may have another one type of nozzle. That is shown in the slide with 22 as outlet, and 11 as inlet and the flow direction is also been marked. So this is neither purely convergent type nor purely divergent type. So this is called convergent-divergent type. So these are the different types of flow nozzles. So now let us consider the flow through a nozzle.

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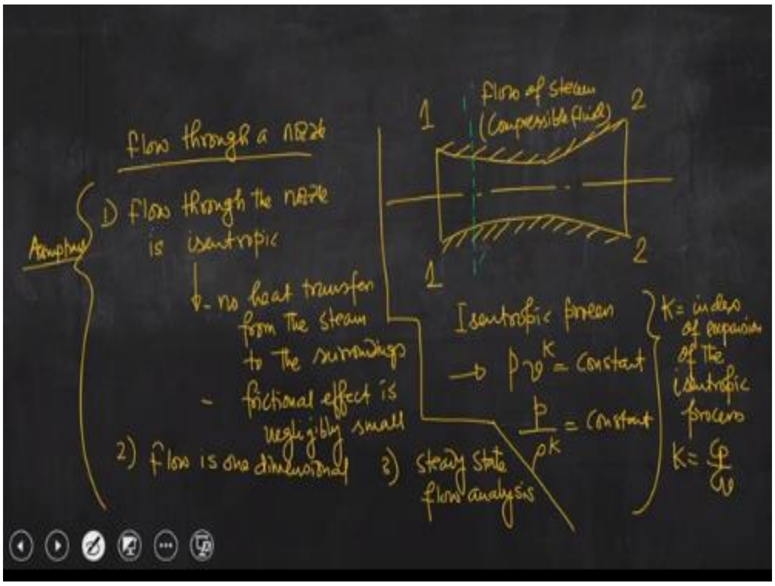

Flow through a nozzle

I hope you have understood that the basic objective of studying the flow through nozzle is to know the velocity which the steam will have at the exit because that is an important parameter. And to get that velocity, we should know what would be the area at the exit of the nozzle. So we take a few assumptions. What are those?

1) We consider that flow through the nozzle is isentropic. That means when steam is flowing through the nozzle, there will not be heat transfer from the steam to the surroundings through the nozzle wall. So basically let us consider the convergent-divergent type with outlet 22, and inlet 11. We can see that the walls of the nozzle are insulated, so there is no heat transfer.

And also the frictional effect is negligibly small. While we are talking about frictional effect, we consider both internal friction plus external friction. Internal friction is friction between the fluid layers. So when steam is flowing through the flow nozzle, friction of the fluid molecules between two adjacent layers is neglected. Together with that the friction of fluid and the solid wall is also neglected that is external friction. So here both the frictional effects are neglected.

Now it is an isentropic process, so basically flow through the nozzle is isentropic and we have assume that there is no friction. And we are assuming that the flow is compressible. So flow of steam we are assuming that is compressible fluid. So we are assuming that

$$pv^k = \text{Constant} \;\; \Rightarrow \frac{p}{\rho^k} = \text{Constant}$$

$$k = \text{Index of expansion of the isentropic process; } k = \frac{C_p}{C_v}$$

This we have studied, so I am not going to discuss on this part. So I have written the specific volume in terms of density. So we have assumed that the flow is isentropic. For the isentropic process, we are mathematically modeling the flow using this equation.

2) We can assume that this flow is one dimensional.
3) Steady state flow analysis.

So basically these are the assumptions we are considering; isentropic flow, no heat transfer, 1-d flow and steady state flow analysis. And for the isentropic process, we have mathematically modelled the system using the above equation.

Now if we stick to this particular geometry then let us see how we can write the equations. So pertaining to this configuration, if we consider certain section of the duct at any section, and we assume that area of the cross section is A which is normal to the flow direction. So let us say, we assumed that is the cross section is 1'1' and area of that cross section is A is the surface area normal to the flow direction.

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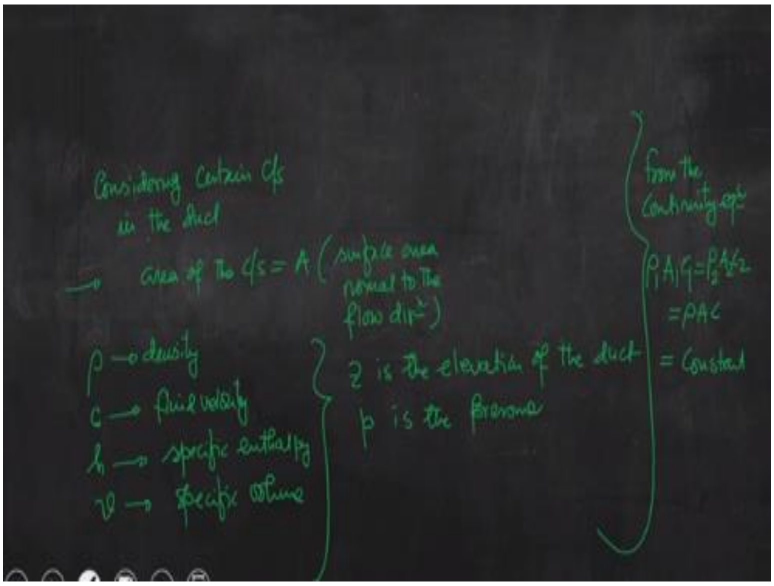

So at that particular section, we have assumed

$$\rho = \text{Density};\ C = \text{Fluid velocity};\ h = \text{specific enthaply};\ v = \text{specific volume}$$
$$z = \text{elevation of the duct from the datum};\ p = \text{pressure}$$

So we have assumed one particular cross section in the duct and A is the cross sectional area of that particular surface which is normal to the flow direction. We have also assumed the fluid properties like density, specific enthalpy, specific volume, pressure, fluid velocity, elevation of the duct. So now, from the continuity equation, we can write

$$\rho_1 A_1 C_1 = \rho_2 A_2 C_2 = \rho A C = \text{Constant}$$

Because mass flow rate of steam is constant. So if we take log both sides and differentiate it, then we can write

$$\frac{dA}{A} + \frac{d\rho}{\rho} + \frac{dc}{c} = 0 - - - - (1)$$

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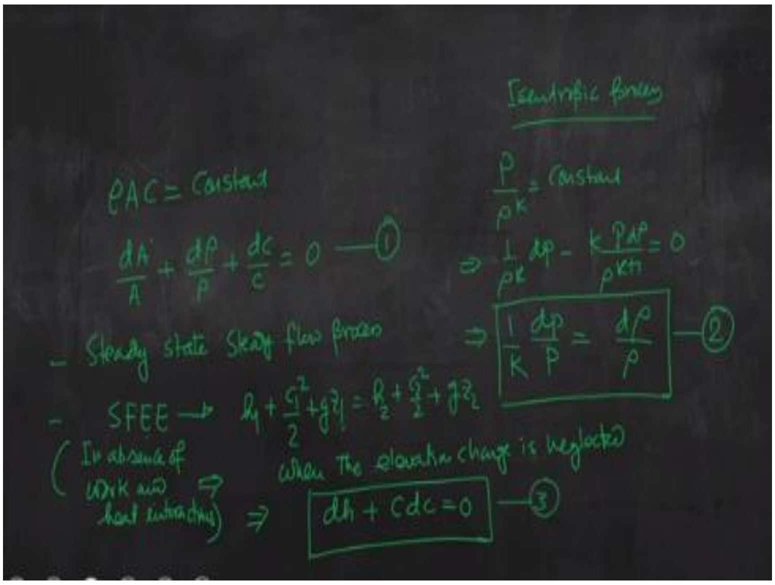

So this is what we have obtained from the mass conservation equation and if we take log both sides and we differentiate it we will be getting this equation 1.

Few minutes back, I have discussed that the objective of the flow analysis through the nozzle is to know the area at the exit of the nozzle to get the desired flow velocity of the steam. And that velocity is essential, because higher the velocity of the steam jet higher will be the impingement, and more will be the deflection. So momentum will be absorbed by the turbine wheel and that will depend not only on the steam velocity at which steam is impinging the blades but also the blade angle. But it will largely depend on the velocity of steam that you are going to get at the exit of the nozzle.

But there are several other issues that we shall discuss. Now if we look at the equation-1, then somehow we could relate area with the velocity of steam along with the steam property that is density. We have discussed that we are considering steam as the compressible fluid. So density of steam is not remaining constant throughout the nozzle. So density will vary. So we have also taken that particular effect into account while arriving at this equation. So our objective is to get velocity with area. So we need to know what would be the area of nozzle at its exit, knowing the area at its inlet, and then we can calculate velocity. So we have to relate this $\frac{d\rho}{\rho}$ in terms of other known quantities, because the density will have continuous variation in the flow path.

So we know the area of the nozzle at the inlet, we can design the area of the nozzle at the outlet and that is very vital parameter, essentially to have the variation of the flow velocity. So the density will change. So now, we have to relate this change in density with some other known parameter, so that we can close this equation.

$$\text{From the Isentropic process, } \frac{p}{\rho^k} = \text{Constant}$$

$$\Rightarrow \frac{1}{\rho^k} dp - k \frac{p}{\rho^{k+1}} = 0$$

$$\Rightarrow \frac{1}{k}\frac{dp}{p} = \frac{d\rho}{\rho} - - - - - - (2)$$

So this is another important equation. As I told you that our objective should be to relate $\frac{d\rho}{\rho}$ with some other known quantity. So this is the equation for that. So if we plug in the value of $\frac{d\rho}{\rho}$ in terms of $\frac{dp}{p}$ in equation-1, we will be getting the new equation. Now we have also assumed that the analysis is steady state analysis. So let us we recall the steady state steady flow energy equation or SFEE. So while this process is getting executed there is no heat and work interaction. From the schematic, we can see that steam is flowing through the nozzle, and while the steam is flowing through the nozzle, the process will be completed, but to complete this process, we do not have heat and work interaction. Because we are keeping the walls of the nozzle insulated. So there is no heat loss.

$$\text{SFEE (In absence of work \& heat interaction)} \rightarrow h_1 + \frac{c_1^2}{2} + gz_1 = h_2 + \frac{c_2^2}{2} + gz_2$$

Remember that while writing this equation, we have considered the work that needed to maintain the flow in the presence of pressure. So this aspect I have discussed when I have discussed about the basics of the thermodynamics. We will be required to recall those aspects frequently, while discussing several aspects of different modules of this course. But while writing this equation, we have taken into account the work done which is needed to maintain the flow because there will be continuous flow through this convergent divergent nozzle or the fluidic channel. So to maintain the continuous flow, the work is needed and that work is already taken into account in this equation.

So this is what we are writing in absence of work and heat interaction that means work between system and surroundings and heat interaction between system and surroundings.

As the nozzle is not kept in a vertical configuration or nozzles are tried to be kept in a configuration which is having very small inclination angle, for that case, we can trivially ignore the change in elevation. So we can write

$$h_1 + \frac{c_1^2}{2} + gz_1 = h_2 + \frac{c_2^2}{2} + gz_2$$

$$\Rightarrow dh + cdc = 0 - - - - - (3)$$

$dh = h_2 - h_1$; and if we integrate the equation we will get this equation.

So this is another equation, because we are trying to relate velocity with other properties.

See we have already mentioned the properties that is density, fluid velocity, specific enthalpy, specific volume and the pressure and again you have to keep in mind that this is the flow of a compressible fluid through a duct having gradually varying area. Next we can write the property relation.

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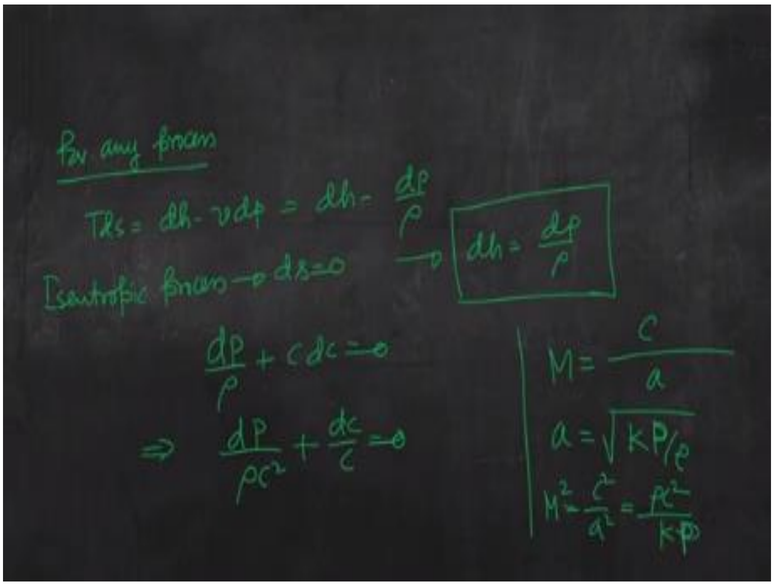

For any process we can write this property relation

$$Tds = dh - vdp = dh - \frac{dp}{\rho}$$

Now we have assumed that process is isentropic. So for isentropic process $ds = 0$. There is no change in entropy. So we can write

$$\text{Isentropic Process} \rightarrow ds = 0 \rightarrow dh = \frac{dp}{\rho}$$

Now placing this expression in equation-3 we will get

$$\frac{dp}{\rho} + cdc = 0$$

$$\Rightarrow \frac{dp}{\rho c^2} + \frac{dc}{c} = 0 - - - - (4)$$

So we have divided the equation by c^2 and then we can write this equation. Why you are doing so? Because we are talking about the flow through a duct which is having gradually varying area, initially decreasing then increasing. And it is again the flow scenario of a compressible fluid. Now we need to know what is Mach number? So Mach number is basically defined as the ratio of velocity of fluid at any particular section at any pressure and temperature to the local sonic velocity at that particular section at the same pressure and temperature.

$$M = \frac{c}{a}; \text{ where } a = \sqrt{\frac{kp}{\rho}}$$

$$\Rightarrow M^2 = \frac{c^2}{a^2} = \frac{\rho c^2}{kp}$$

$$\Rightarrow \rho c^2 = kpM^2$$

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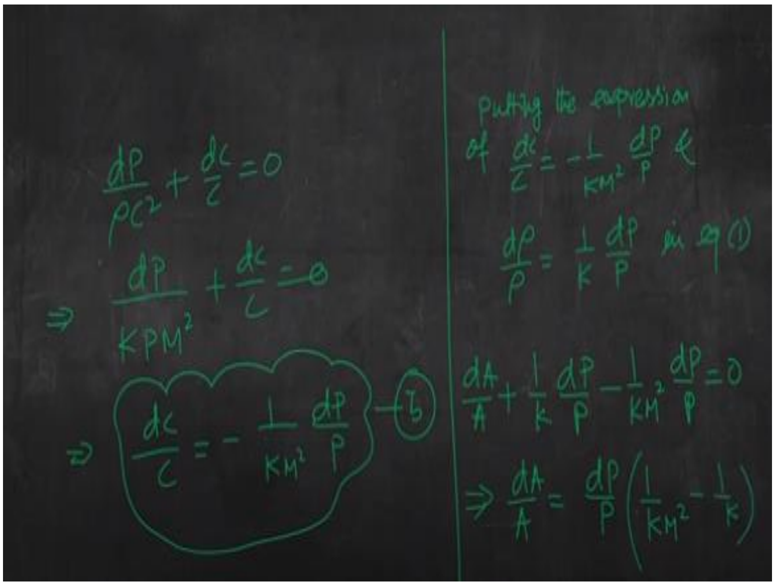

So we can write

$$\frac{dp}{\rho c^2} + \frac{dc}{c} = 0$$

$$\Rightarrow \frac{dp}{kpM^2} + \frac{dc}{c} = 0$$

$$\Rightarrow \frac{dc}{c} = -\frac{1}{kM^2}\frac{dp}{p} - - - - - - (5)$$

So if we try to write all these equations, and then we can relate the area of the flow nozzle in terms of the known quantities. So what we can do? We can plug in the value from equation 2 & 5 into equation 1.

From equation-1,

$$\frac{dA}{A} + \frac{d\rho}{\rho} + \frac{dc}{c} = 0$$

From equation-2,

$$\frac{d\rho}{\rho} = \frac{1}{k}\frac{dp}{p}$$

From equation-5,

$$\frac{dc}{c} = -\frac{1}{kM^2}\frac{dp}{p}$$

So putting the equation 2 & 5 in equation 1

$$\frac{dA}{A} + \frac{1}{k}\frac{dp}{p} - \frac{1}{kM^2}\frac{dp}{p} = 0$$

$$\Rightarrow \frac{dA}{A} = \frac{dp}{p}\left(\frac{1}{kM^2} - \frac{1}{k}\right)$$

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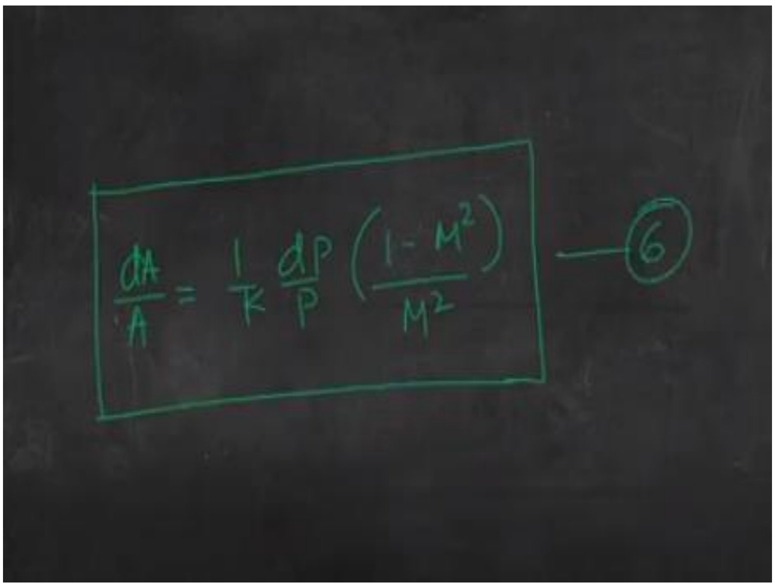

So that means finally we can write

$$\frac{dA}{A} = \frac{1}{k}\frac{dp}{p}\left(\frac{1-M^2}{M^2}\right) - - - - - - (6)$$

So this is the relation we wanted to derive in today's class. This is very important relation. So we could write $\frac{dc}{c}$ and $\frac{d\rho}{\rho}$ using some known quantity, and finally we have written $\frac{dA}{A}$ using the expression of $\frac{dc}{c}$ and $\frac{d\rho}{\rho}$. And the quantities which are there in the right hand side of equation-6 are known. We know the Mach number and this k is also known as it is the index of expansion for the isentropic process, we also know the pressure drop that we are going to have. So basically, if we know the M then probably we also know the velocity of fluid at any particular section as compared to the local sonic velocity at that section given the pressure and temperature same.

So using this relation, we can find out what would be the area at the exit of the nozzle to obtain the velocity which is needed, knowing the drop in pressure and the index of expansion of the isentropic process. So the physical significance of this equation is tremendous, that we shall discuss considering several cases. And that part we shall do in the next class. So with this I stop here today, and we shall continue our discussion in the next class. Thank you.