Thermal Engineering: Basic and Applied
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Lecture – 32
Nozzle Efficiency and Factors that Affect the Efficiency

I welcome you all to the session of thermal engineering basic and applied. And today we shall discuss about the nozzle efficiency and then we shall identify several factors that affect the nozzle efficiency. Now if we try to recall in this module of this course we have discussed about the nozzle in detail starting from the flow analysis through the nozzle then we could establish the design aspects of the nozzle. So when there is a flow through a channel, we have studied that the shape of the channel or the flow configuration is convergent type or convergent divergent type or divergent type.

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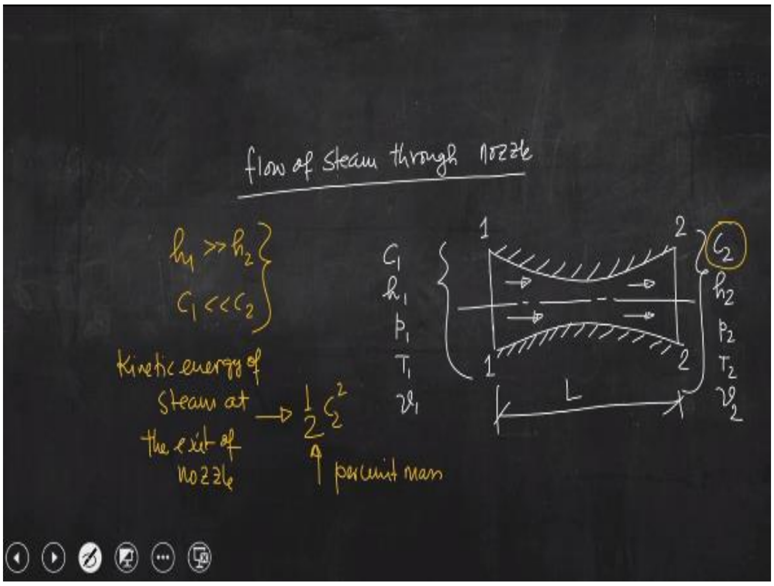

Flow of steam through nozzle

So if we consider a flow of steam through a duct having shape as shown in the slide, then there is section 2 2 and section 1 1 and we are assuming that the walls of this duct are insulated, so, there is no heat loss. Also we are assuming the flow direction as shown in the slide. What is the basic objective of having this particular device for the operation of this steam power plant?

We have discussed that the steam which is produced in the boiler or steam generator that stream should be taken to the turbine for generating or producing work. Now when steam is allowed to go into the turbine, it is allowed to pass through the nozzles and then steam jet which is coming out rather I shall say the steam which is coming out from the nozzle in the form of jet strikes the turbine blades. And when there is a deflection of the steam jets, there will be a change in momentum. In, fact there will be a loss of momentum and that momentum will be absorbed by the wheel of the turbine runner. So, the basic objective of having this flow nozzle is to produce steam jet. That means the stream which is coming out at the exit of the nozzle will have good enough velocity, so that the jet will be having high kinetic energy before that strikes the turbine blades.

So now why I am discussing this particular aspect again? Because it is again a mechanical device. So while someone is designing the steam nozzle, the designer must be careful about the efficiency of the nozzle. So why not to look at the efficiency of the nozzle as by knowing this particular parameter, we can predict the available kinetic energy of the jet at the exit of the nozzle.

Now coming to the diagram in the slide, as the stream is passing through the duct of this particular shape that is initially having decreasing area then again it is increasing gradually. So at the inlet, the conditions are like velocity of the stream is c_1, enthalpy h_1, pressure p_1 and temperature T_1 and we are assuming that the length of the nozzle is very small that is L and if it is short then we can ignore the change in elevation. So the outlet conditions are velocity c_2, enthalpy h_2, pressure p_2 and temperature T_2. Specific volume at outlet is v_2 and at inlet is v_1.

Now steam is having high enthalpy at the inlet of the nozzle and that enthalpy should drop. At the cost of that drop of enthalpy, we are getting high velocity. So our objective is that the velocity of stream leaving the nozzle should be high, so that the kinetic energy will be higher. Higher is the kinetic energy, higher will be the momentum transport to the shaft of the runner and that eventually will produce higher amount of work output from the turbine. So, this quantity is very important. Because still we are having some velocity at the inlet of the flow nozzle and we are having high enthalpy as well. So $h_1 \gg h_2$ and $c_1 \ll c_2$.

So we are playing with these 2 quantities using this device and with an objective of having higher velocity of stream at the exit at the cost of the reduction of enthalpy at the exit. So the entire objective is to have high kinetic energy and we write it per unit mass flow rate of steam.

$$\text{So, kinetic energy of steam per unit mass at the exit of nozzle} = \frac{1}{2}c^2$$

So higher is the c_2 higher will be the kinetic energy. So now first let us look into the change in velocity of stream as it passes through the nozzle. So while you are talking about the efficiency of the flow nozzle, that means we need to look at the change in velocity of steam as it passes through the nozzle vis-a-vis the drop in enthalpy of steam as it flowing through the nozzle.

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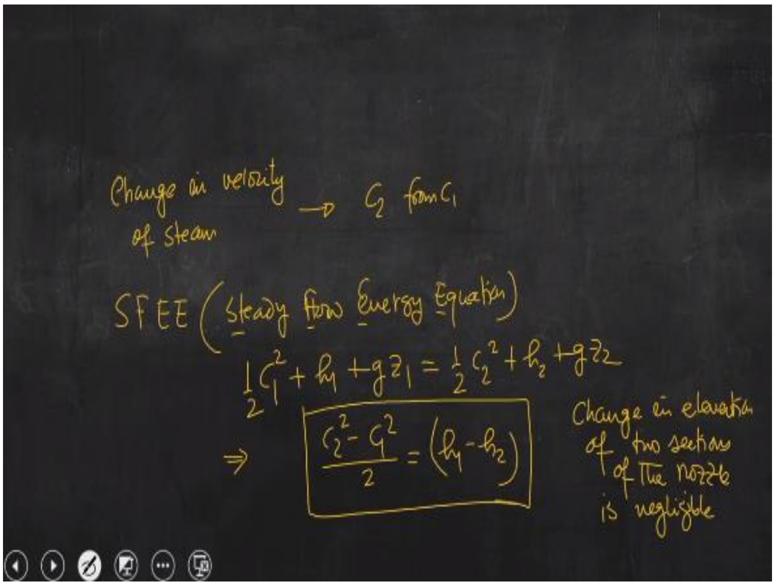

So the change in velocity of steam is from c_1 to c_2 and this change in velocity we are getting at the cost of the enthalpy drop. So now let us look at the steady flow energy equation (SFEE). Why? Because we are having enthalpy drop and that is the heat drop. At the cost of that heat drop or enthalpy drop, we are getting the kinetic energy. So basically energy is getting converted from its one form to another form. So we need to write what is the amount of kinetic energy that is available at the exit of the nozzle and that kinetic energy is what fraction of the enthalpy drop. So that is very important while someone is designing the nozzle.

So now we ignore the heat and work interaction because already we have discussed that there is no heat interaction and the work is essential to maintain a flow in the presence of pressure. So we need to provide work but that work is already taken into account in the enthalpy that you have studied in thermodynamics course.

So basically if we write SFEE in absence of heat and work interaction, we can write

$$\frac{1}{2}c_1^2 + h_1 + gz_1 = \frac{1}{2}c_2^2 + h_2 + gz_2$$

And we have assumed that the nozzle length is short so that the change in elevation can be neglected. So we are left with

$$\frac{c_2^2 - c_1^2}{2} = (h_1 - h_2)$$

So we can see from this particular equation that we are having this change in velocity at the cost of the enthalpy drop. So to arrive at this equation you have assumed that change in elevation of 2 sections of the nozzle is negligible.

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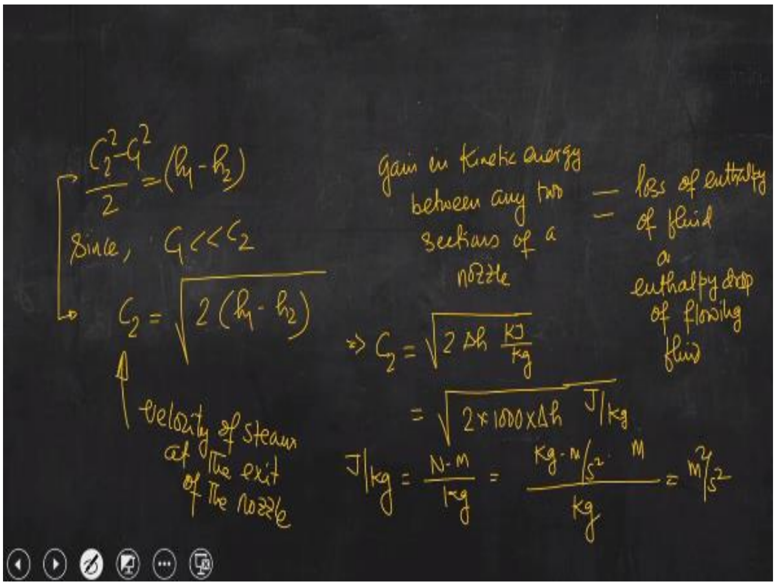

And since $c_1 \ll c_2$ so we can write

$$c_2 = \sqrt{2(h_1 - h_2)}$$

So this is the velocity of steam at the exit of the nozzle. So if we can design the nozzle in such a way that there will be higher enthalpy drop, then we can maximize this quantity which in turn will ensure that the kinetic energy of jet which is available at the exit of the nozzle that is at the inlet to the turbine blade will be high. We will be discussing this particular aspect again when we shall discuss about the steam turbines. Now mind it that $h_1 - h_2$ is kJ/kg. So that means we can write here that gain in kinetic energy between any 2 sections of a nozzle is equal to loss of enthalpy of fluid or simply enthalpy drop of flowing fluid.

So the fluid which is passing or flowing through the nozzle; the enthalpy drop of that particular fluid is nothing but the gain in kinetic energy of the fluid between any 2 sections of the nozzle. So, now we can go one step further and we can write

$$c_2 = \sqrt{2\Delta h \frac{\text{kJ}}{\text{kg}}}$$

So now we need to convert it because this is velocity. So our objective should be to write the right hand side in terms of m/s that is the unit of velocity.

$$c_2 = \sqrt{2 \times 1000 \times \Delta h \frac{\text{J}}{\text{kg}}}$$

$$\text{Now } \frac{\text{J}}{\text{kg}} = \frac{\text{N.m}}{\text{kg}} = \frac{\text{kg}.\frac{\text{m}}{\text{s}^2}.\text{m}}{\text{kg}} = \frac{\text{m}^2}{\text{s}^2}$$

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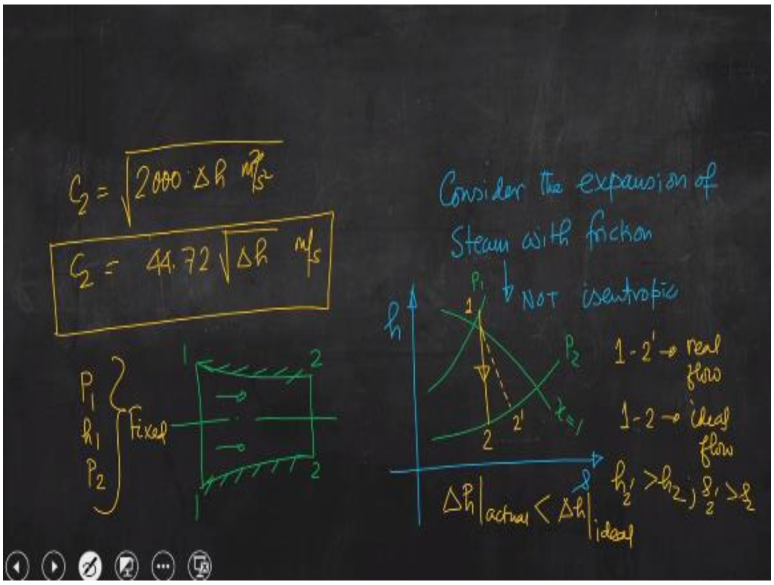

$$c_2 = \sqrt{2000 \times \Delta h \ \frac{\text{m}^2}{\text{s}^2}}$$

$$\Rightarrow c_2 = 44.72\sqrt{\Delta h} \ \frac{\text{m}}{\text{s}}$$

Why I am doing this because, when we shall solve numerical problem, we will be using this formula frequently. That is why I have derived the expression of velocity in terms of the enthalpy drop as I will be frequently using this for the velocity.

Now when we have analyzed the flow through the nozzle, we have assumed that the flow can be modeled by an isentropic process, but in reality the frictional effect cannot be ignored. So we have assumed that there is a flow of a fluid which is steam and we have assumed that it is a compressible fluid and we have also assumed that the flow can be modeled by an isentropic process.

Though there is no heat loss from the flowing steam to the surrounding because walls of this nozzle are insulated, but still we cannot ignore the frictional effect. So long as the frictional effect is there, it is very difficult to model the flow by an isentropic process. So, it is not the isentropic process. Now if the process is not isentropic then frictional heating will be there and if that heating is there, then the enthalpy at the exit of the nozzle should not be h_2 rather it should be $h_2{}'$. So assuming the enthalpy drop $(h_1 - h_2)$ we could write the expression of velocity at the exit of the nozzle using this formula. But that should not be the case because accounting for the effect of friction that would be there in real application, the enthalpy at the exit of the nozzle will not be h_2 it should be $h_2{}'$. So, we are assuming that enthalpy should be something else not h_2. So, what would be the enthalpy that is very important to know and since the enthalpy drop should not be Δh that is why a particular term is coming in into the picture that the nozzle efficiency.

That means ideally we all are thinking that the enthalpy of steam at the inlet is h_1 and we are assuming that the enthalpy of steam should be h_2 and that would be obtained from any Mollier diagram because the process is isentropic. But as I told you, frictional effect cannot be ignored. We can try to minimize but we cannot ignore. So considering the frictional effect it will not be practical to model the flow by an isentropic process and hence the enthalpy at the exit of this nozzle should not be h_2 rather it should be $h_2{}'$. So that means actual enthalpy drop will be something which is lesser than the ideal enthalpy drop and considering this aspect nozzle efficiency will be there.

So let us consider the expansion of steam with friction that means it is not isentropic. If it is not isentropic let us look at the h-s diagram, Mollier diagram that you have studied. This is a very useful diagram in the context of the calculation of steam properties because from the same chart we can calculate the specific enthalpy, specific entropy for any given pressure, temperature and dryness fraction. So now, we try to plot the process, which is there in real flow, when that real flow is taking place in a nozzle.

So basically there are 2 pressure. When there is a flow through a nozzle and if we consider the nozzle is as shown in the slide with section 1 1 and section 2 2. So, when there is a flow we are assuming that the inlet pressure is fixed and outlet pressure is fixed. So for the given inlet and outlet pressure we can write and plot in the diagram as p_1 & p_2. Say there is a line $x = 1$ as shown in the diagram and you are assuming that this is the expansion.

So the isentropic expansion is represented by say point 2 and point 1. So, there are 2 constant pressure lines and there is line of dryness fraction that is $x = 1$. So, now we are assuming that this is the flow when there is no friction and it is isentropic process. And that is what we have used till now to model the flow through a nozzle but in reality we will be having some sort of irreversibility and there comes the point 2'.

So you can understand that from this particular case, 1- 2' is the process in real application or real or actual flow and 1- 2 is the ideal flow. And we can say that $h_2' > h_2$. So now let us assume that steam is having constant enthalpy at the inlet to the nozzle. So p_1, h_1 and p_2, these 3 are fixed. If this 3 properties are fixed so we know that the expansion will takes place between these 2 pressures. So when someone is designing the nozzle he or she knows that this is the pressure drop and the designer also knows the enthalpy at the inlet and then we can see that the actual enthalpy drop $h_1 - h_2'$ is lesser than the enthalpy drop due to ideal flow. And hence $\Delta h_{actual} < \Delta h_{ideal}$. If Δh_{actual} is less, then the velocity of steam at the exit of the nozzle will also be less. And that is very important.

So till now we have discussed about friction. So by how we can visualize the effect of friction on the flow when that flow takes place through a nozzle.

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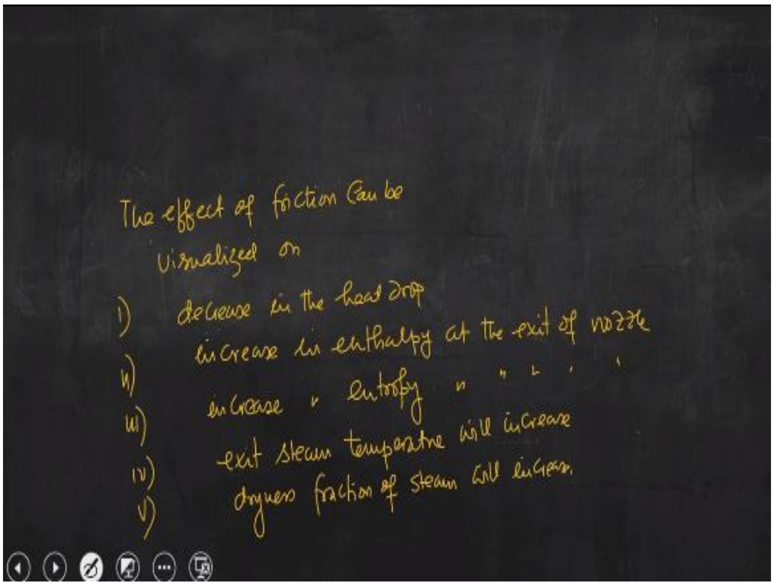

So the effect of friction can be visualized on

1) Decrease in the heat drop

2) Increase in enthalpy at the exit of the nozzle. So enthalpy is increasing because $h_2' > h_2$. So the effect of friction can be visualized on the decrease in the heat drop and increase in enthalpy at the exit of the nozzle.
3) Similarly increase in entropy at the exit of the nozzle. So this effect is realized not only on the decrease in heat drop but also increase in enthalpy at the exit of the nozzle and increase in entropy at the exit of the nozzle. And we all have studied in fluid mechanics that if frictional heating is there due to viscous dissipation, that means heating is there due to frictional effect, the temperature of fluid will be increased.
4) So now if we consider that the frictional effect is there, that heat due to frictional effect will increase the temperature of steam at the exit of the nozzle. So that means exit steam temperature will increase and finally very important point is that the point 2' is closer to the $x = 1$ line. I have drawn $x = 1$ line only to indicate that it is because of the entropy increase, the steam temperature will also increase, so that means stream will be closer to the saturated stream.
5) So the dryness fraction of steam will increase. Maybe we are getting lesser velocity of steam at the exit of the nozzle that means considering the frictional effect, we are not getting the velocity that we are supposed to get but we can increase the steam quality at the exit of the nozzle that is also very important considering the turbine blade erosion problem. So the steam temperature or dryness fraction these 2 are almost interrelated.

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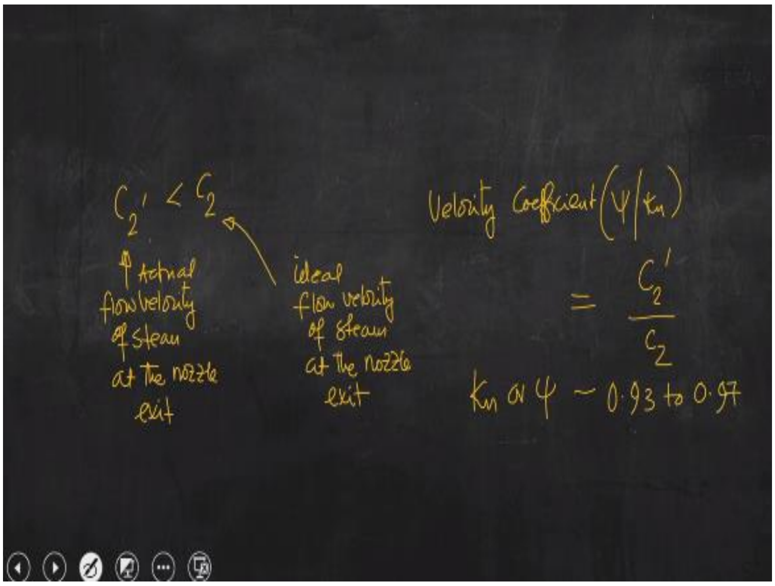

Now we have understood that $c_2' < c_2$. Here c_2' is the actual flow velocity of steam at the nozzle exit and c_2 is ideal flow velocity steam at the nozzle exit. So $c_2' \neq c_2$ and because of this reason one coefficient is defined that is called velocity coefficient. That is symbolized either by ψ or K_n. In some books the velocity coefficient is denoted by ψ. There are a few books wherein the velocity coefficient is denoted by K_n.

$$\text{Velocity coefficient}, \psi \text{ or } K_n = \frac{c_2{}'}{c_2}$$

So you can understand the velocity of steam that is available at the exit of the nozzle in actual condition is always less than the ideal condition and ratio of these 2 velocities is known as velocity coefficient. And the velocity coefficient magnitude is 0.93. So K_n or ψ varies from 0.93 to 0.97 for different surfaces. Why this value is changing from 0.93 to 0.97? It depends on the surface of the nozzle.

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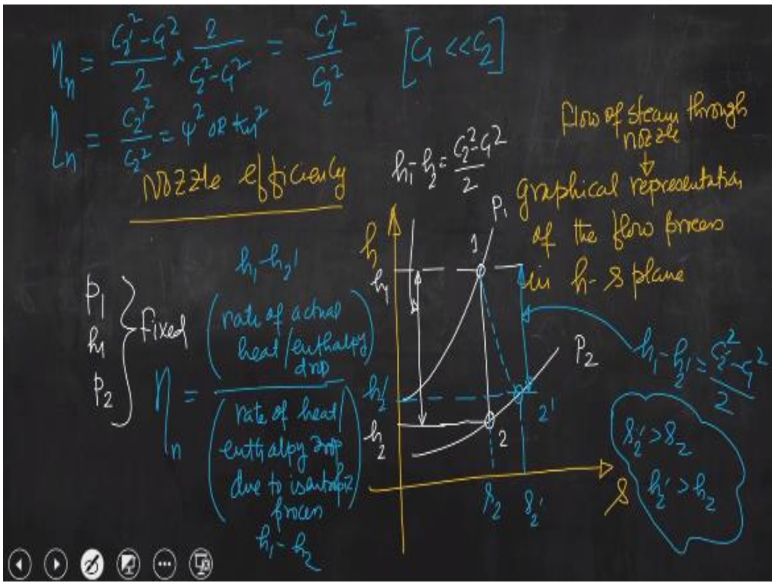

Nozzle efficiency

Now coming to the important point that is nozzle efficiency. In fact we started our discussion on this particular terminology that is nozzle efficiency. As nozzle is a mechanical device in which there is a conversion of energy that means at the cost of the reduction of enthalpy of the flowing steam we are getting kinetic energy. Now suppose we are telling that this should be the enthalpy drop and at the at the cost of that reduction what would be the change in kinetic energy that we can get from the steady flow energy equation. But accounting for the essential effect that is fluid friction, the actual gain in kinetic energy will be always less than the ideal gain in kinetic energy and that is how the nozzle efficiency is coming into the picture. So we need to write the mathematical expression for nozzle efficiency. But instead of writing the mathematical expression, first let us try to look at it from the graphical representation of the flow process in h-s plane.

Graphical representation of the flow process in a nozzle in h-s plane

So we are trying to represent the flow process of steam through nozzle in h-s plane. So the X-axis represents s and Y-axis is h in the h-s plane. I have already told you that p_1, h_1, p_2; these three quantities are fixed. So, we have drawn lines representing $p_1$and p_2. We are taking one particular point on the pressure line p_1 that is point 1 and if we try to map the process 1-2 then we can plot point 2 as shown in slide. So this is isentropic process that is the ideal process but in real application the process would be like 1-2'. So the point 2' is plotted as shown in the slide. So now basically you plot $h_2', h_1,$ and h_2. So you know that

$$h_1 - h_2 = \frac{c_2^2 - c_1^2}{2}$$

$$h_1 - h_2' = \frac{c_2'^2 - c_1^2}{2}$$

So, this is what we can write and because of the fluid frictional effect, thermodynamic irreversibility will be there. And if we try to plot $s_2$and s_2', then we can see that $s_2' > s_2$ and $h_2' > h_2$. Now basically what is the nozzle efficiency? Ideally we are supposed to get this change in velocity because of this enthalpy drop as per the above expression, but in real case we are getting something else. So the ratio of these 2 quantities is the nozzle efficiency. Whenever someone is designing the flow nozzle, he or she considers the fact that the pressure at the inlet and exit of the nozzle are fixed. Enthalpy of steam at the exit of the nozzle is also fixed because that is coming out from the boiler. So knowing all these 3 quantities, if we map the process in this h-s plane, then we can see that the point 2' is going closer to $x = 1$ line. The dryness fraction becomes higher, steam temperature increases because of the frictional effect. But at the cost of that particular favorable aspect, we are going to have compromised velocity at the exit of the nozzle. So velocity of steam at the exit of the nozzle is less and hence the nozzle efficiency η_n comes into picture as the very important term. And it is defined as the ratio of rate of actual heat drop or enthalpy drop to rate of heat or enthalpy drop due to isentropic process.

$$\text{Nozzle efficiency}, \eta_n = \frac{\text{rate of actual enthalpy drop}}{\text{rate of enthalpy drop due to isentropic process}}$$

$$\Rightarrow \eta_n = \frac{h_1 - h_2'}{h_1 - h_2} = \frac{c_2'^2 - c_1^2}{2} \times \frac{2}{c_2^2 - c_1^2} = \frac{c_2'^2 - c_1^2}{c_2^2 - c_1^2}$$

$$\Rightarrow \eta_n = \frac{c_2'^2}{c_2^2} \quad \text{as } c_1 \ll c_2$$

$$\Rightarrow \eta_n = \psi^2 \; or \; K_n^2$$

$$\text{where } \psi \; or \; K_n = \text{velocity coeffient}$$

So if you try to summarize today's discussion then we have tried to discuss about nozzle efficiency. First we have discussed why this particular terminology or aspect is coming into the picture. We have discussed that since nozzle is again a mechanical device, there is a flow of steam and to model the flow we had assumed that the process can be described by an isentropic process. But in reality the frictional effect cannot be ignored and accounting for this frictional effect, we have tried to map the process in the h-s plane. And we have seen that the gain in kinetic energy that is due to the drop in enthalpy, in actual case is always less than that of the ideal case and it is because of this reason we can define one efficiency and that is known as nozzle efficiency and we have mathematically expressed the nozzle efficiency. And we have seen that this is nothing but the square of the velocity coefficient. So with this I stop here today and in the next class we shall solve one numerical problem. And we shall see the several factors that affect the nozzle efficiency. Thank you.