Introduction to Fluid Machines and Compressible Flow

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Lecture - 04
Residence time distribution: Performance of non-ideal reactors

Good morning, we welcome in to this session, where we will discuss the energy transfer, in continuation of our earlier discussion. And the concept of impulse and reaction machines and the definitions of efficiency of hydraulic or fluid machines.

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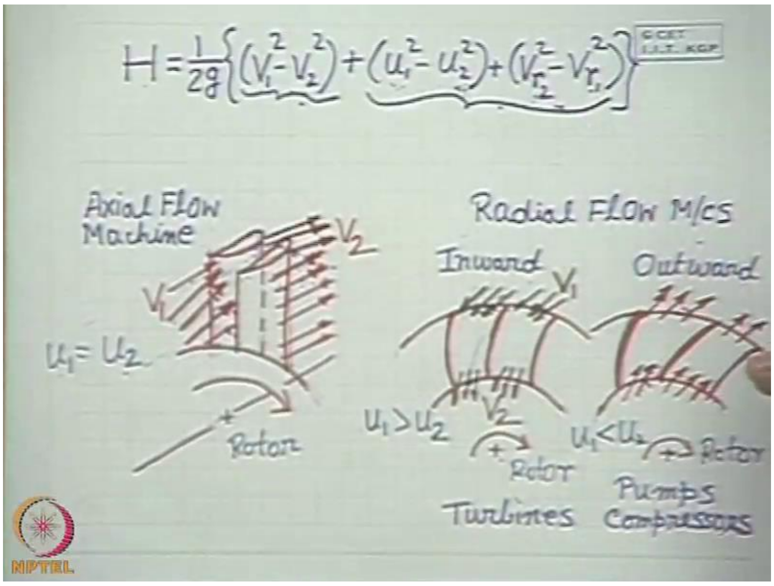

So, let us start from the discussion on energy transfer again which we have already recognized in the earlier class that the head which is being transferred by the fluid to the machine can be written in three distinct components, which we have already seen. One is the change in the dynamic head that is due to the change in the absolute velocity of the fluid. Another component is the change due to the motion of the rotor from one radial location to other radial location. This is usually called as centrifugal head due to change in the centrifugal head for which the static head or the pressure head of the fluid is changed. And another is due to the change of the relative velocity of the fluid with respect to the rotor from its outlet to inlet which is the change also in this static head or the pressure head of the fluid.

Now here with this concept, we can identify different types of fluid machines. One type of fluid is machine is axial flow machine, where the main direction of the fluid flow is in the along the axis of the rotation of the rotor. Just we see here, just if this be the rotor, let us write here, this is be the rotor and if this the axis of rotation if we consider two vanes mounted on the rotator disk then the fluid inlet velocity if it is like this, and the fluid discharges is this direction. Then we see that the inlet and outlet conditions of the fluid are set that the main flow directions is a long the axial direction of the fluid.

The most important thing is that the inlet and outlet of the fluid does not vary in their radial location from the axis of rotation that means, you see that throughout this radius, there is a change in the radius from this point to this point. But throughout there is an inflow and here also throughout there is an out flow that means, we can take a representative point or representative plane of inflow at some radial location, for example, which may be the mean of this height. Similarly, at the exit we can take a representative point or representative section, which is at some means height from the root to the tip of the plane.

So, therefore, the inflow and outflow of the fluid does not vary in their radial locations from the axis of rotations. So, what happens in this case with respect to this equation, we can simply tell that for axial flow machines u 1 is equal to u 2; that means, change of static head due to the change in the rotator velocity, because of a change in the radial location for inlet to outlet does not take place. That means, there is no centrifugal head transfer between the fluid and the rotator in axial flow machines. Now this component if we come whether there will be a change in this static head, due to the change in the relative velocity of fluid from with respect to the rotator between outlet and inlet that depends upon the passage. Here you see that depends upon the area of the passage as fluid flows through this passage.

For example, these two vanes, whether the area is converting or diverting in the direction of flow or not, so that depends upon the setting of the blades. If the blades are set and their curvatures are such that if the passage that is the passage that means, the area normal to the flow is converging one then what will happen that relative velocity it outlet will be more compared to that at the inlet. For which, the pressure at the outlet will be less compared to that at the inlet that means, the fluid will release this pressure that means, the fluid will release this pressure energy, which will be contributed as a positive term to the energy or head transfer to the rotator. That means, here we can conclude that in a turbine the blades are cuffed in such a way and it is placed in such a way that the flow passage in the direction of the flow is a convergent one. In that case, what we get is that v r 2 is more than v r 1, p r 2 is less than p r 1. If v r 2 is more than v r 1 this quantity is positive, because positive sign of each and every quantity replaces the energy transfer to the rotator.

Now we come to another class of machines according to their direction of flow, radial flow machines. Now radial flow machines are machines, where the main direction of the flow is in the radial direction. And here what happens, the radial location of the fluid at inlet and outlet changes. There maybe two possibilities one is the radial inward flow and other is the radial outward flow. In radial inward flow, the fluid flows inward - radially inwards; that means, the inlet of the fluid is at a higher radial location from the access of rotation of the rotor. Let I write this as rotor, and it is discharged at a radial location which is lower than that at the inlet; that means, the main direction of flow is in radially inwards.

Just the opposite one is the radial outward flow where the main direction of flow is radially outwards; that means, the inlet position is at a radial location, which is lower than that at the outlet location from the rotor axis. So, therefore, for radially inward flow, we can write that u 1 is greater than u 2. What is u one u 1 is the rotor velocity at this location that is at inlet; and u 2 is the rotor velocity at this location. So, if you see here, you see that in this case, we get a positive value of this quantity which means this centrifugal head is being released by the fluid, which means the pressure is being released by the fluid. Pressure here is lower pressure here is higher because the centrifugal head which we discussed earlier is higher here, and it is lower here. So, while the fluid flows radially inward, it releases the pressure energy or the centrifugal head and that being transfer to the rotor head.

So, in case of turbine for this reasons the radial flow type in case of radial flow type turbine the flow is radially inward. Similarly in case of radial outward flow, we can write that u 1 is less than u 2, because one is here at this section and outlet section is at a higher radial location. So, therefore, what happens this term is negative; that means, the fluid gains the centrifugal head or fluid gains in static head that is the pressure head. So, this happens in case of pumps of compressors. So, therefore, in pumps of compressors to utilize this centrifugal head in the useful energy, we make the designs such that the fluid flows radially outwards. Pumps and compressors are radially outward flow machines; for turbines, the radially inward flow machines, provided they are radial flow machines nevertheless they are axial flow machines pumps and compressors also.

After this I now come to the definition of impulse and reaction machines. Now if we look to this equation again, we see that there is a distinct difference between the first and other two terms, which we were discuss. The first term is known as the change in the dynamic head; that means, due to the change due to its absolute velocity. And and these two terms represent that change in the static heads; that means, change in the pressure head; one is due to the change in the radial position, and another is due to change in the pressure. Now the proportions of the change in the head due to this dynamic one and this static one is a very important parameter in the design of fluid machines.

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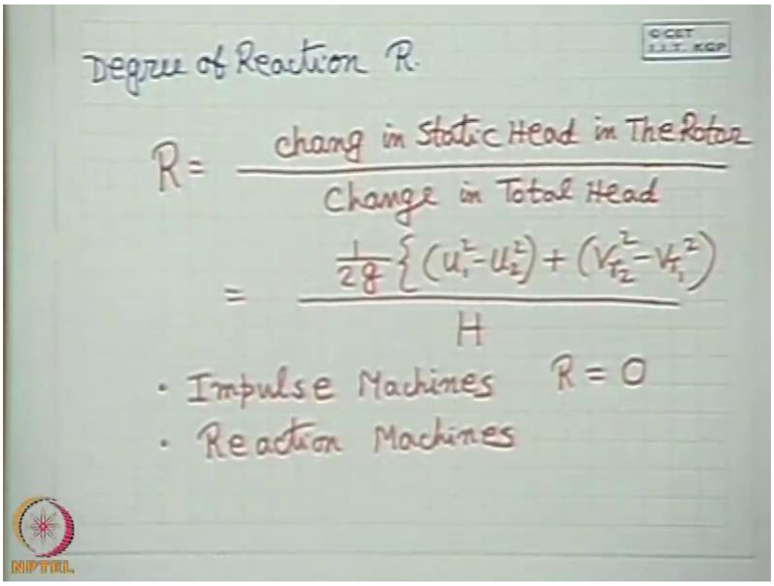

And this relative proportion between the changes in the dynamic and static head is characterize by a very important parameter known as degree of reaction. Let us denote it by a symbol R - degree of reaction. So, degree of reaction is defined as change in static head in the rotor divided by change in total head, which means what fraction of the total head is being changed by the static head. So, if we recall the expression, we can write the change in static head is 1 by 2 g times u 1 square minus u 2 square. This changes I write with the positive sign as that delivered by the fluid with the usual convention and then v r

2 square minus v r 1 square and divided by the h that means, what fraction of h r represents is responsible for the change in the static head. Well with this definition, we can define or we can divide the fluid machines into very two important categories; one is known as impulse machines, another is reaction machines.

Now impulse machines are those machines where the degree of reaction R is zero, which means there is no change in this static head; that means, the change in the total head. That means, the total head transferred between the fluid and the rotor, whether it is transferred by the fluid to the rotor or by the rotor to the fluid is only by the change in the dynamic head, there is no change in this static heads. So, very first consequence of this impulse machine, where R is zero is that if you look back again in this equations, if there is no change in the static head. So, if we consider first the two terms would be independently zero then u 1 has to be u 2; that means, the impulse machine has to be an axial one.

Again there should not be any change in the relative velocity of the fluid which means that an impulse machine, the flow passage should be uniform in construction to the direction of the flow. So, that the flow velocity that means, the relative velocity of the fluid is with respect to the machine should not change, for which the pressure of the fluid will remain constant. And this constant in pressure of the fluid in the rotor makes a simplification for the design of an impulse machine is that the rotor of the impulse machine may be made open, it may not need any case. For example, it may be opened to atmospheric pressure, so that there may be a change in the absolute velocity, but throughout the flow the pressure will be constant at atmospheric pressure, and one of the impulse hydraulic machines rotor is made like that.

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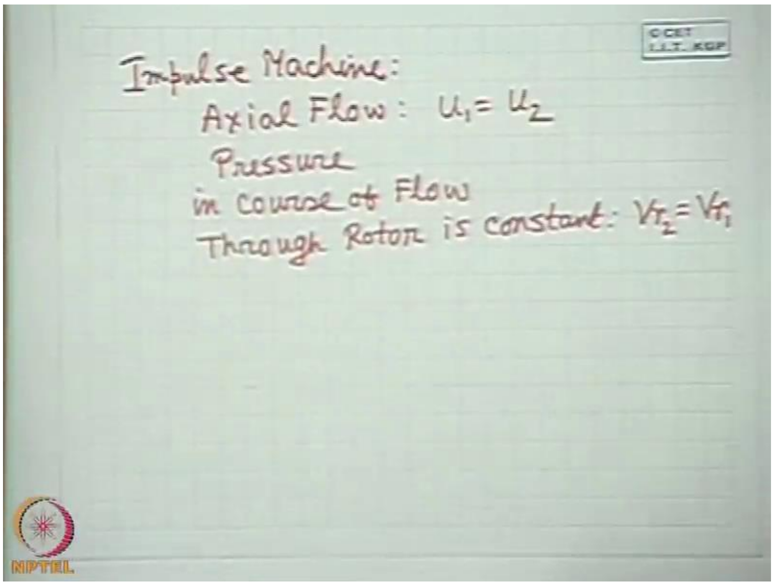

So, therefore, this is a simple design for impulse machine. So, we can write therefore, for impulse machine, the pressure will be constant for impulse machine. We write for impulse machine the outcome is axial flow that means, u 1 is equal to u 2, pressure in course of flow through rotor rotor is constant, which means v r 2 is equal to v r 1. So, therefore, R is zero in this case, since the dynamic change in this static head is zero, but you can argue one thing theoretically, I must tell in many books you will not find this statement that ok… You can tell sir, why independently it will be zero, some of these may be made zero, which an axial flow machine is not immediate outcome of an impulse machine.

Impulse machine may be a reaction type where the two effects may be opposing to each other that means, it may be a radial inward flow, so that the head is released by the fluid and at the same time passage may be made such diverging passage. So, head may be gained by the fluid. So, static head released by the fluid due to the change in the centrifugal head, may be balanced by this static head gain by the fluid due to the change in the pressure to opposing effects by that design is very difficult. So, usually it is not done in practice. Though theoretically one may consider that the two components may give an opposing effect to cancel each other, but according to that the design of a radial flow impulse flow machine is difficult. So, you may note here a very important thing that is why the impulse machine is always an axial flow machine.

So, next we come to the reaction machines, it is very simple that as impulse machine is defined where the degree of reaction is zero that means, the static head change in the rotor is zero. Reactions machines are those machines, where a long with the change in the dynamic head static head of the fluid also changes. That means, there is a profession for the change in the static head either by virtual of the change in the radial location of the fluid in course of its flow from inlet to outlet along with the change in the pressure, because of a change in the relative velocity due to a very near passage of the flow. Why it flow which takes place through the vanes passages or blade passages.

So, therefore, according to this definition we can write reaction machines reaction this R is greater than zero or rather we can write more explicitly zero less than R less than 1, because the maximum value of R will be always less than 1. So, therefore, this is the definition or difference between impulse and reaction machines.

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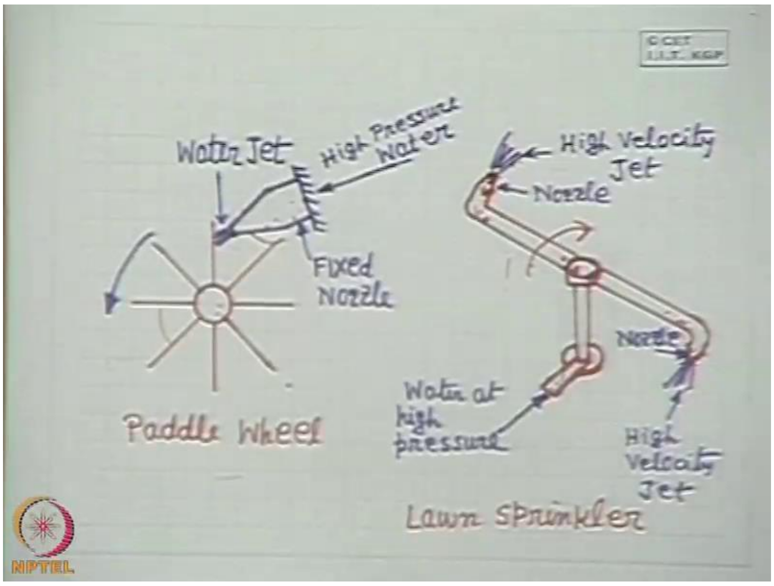

Now the concepts of impulse and reaction machines before coming to the description of axial machines can be well understood by this very interesting, but simple example of two popular fluid systems. You see one here is a paddle wheel as you know, the simple paddle wheel, these are certain straight blades which are being rotated by a flow of water jet which is coming from a fixed nozzle. You see the nozzle is fixed where high pressure water enters into the nozzle, and it flows through a convergent duct which converts the high-pressure low velocity fluid to a low pressure and high velocity fluid. And it comes out with a high velocity fluid jet, so water is used. So, water jet, which makes this wheel to move. This gives a very good example of an impulse machine. So, this nozzle and this wheel can be thought of as a fluid machine.

Here I like to tell you one thing a fluid machine as a whole consists two parts; one is the fixed part known as stator, another is the moving part known as rotor. So as far as the definition of the degree of reaction is that it is the proportion of the energy transfer that takes place rotor, because the energy transfer takes place only in the rotor. Energy transfer means the transfer of stored energy to mechanical energy or mechanical energy to stored energy. So, therefore, here we see if these two positives flow in the fluid machines, so in the rotor the fluid pressure is throughout constant; that means, this is atmospheric pressure. So, the transfer of fluid energy or head to this rotor of the moving part of the fluid machines, which is paddle ring is because only of the change in its absolute velocity, and this is known as the impulse action by which the water jet is capable of rotating the paddle wheel.

This is an example of impulse machine here you notice one thing that the pressure initially in the machine the input is the pressure energy of the water, but this pressure is being totally exploited in terms of the kinetic head or the velocity of the water in the fixed part of the fluid machine. That means, nozzle when it strikes the rotor, the rotor is open. So, its pressure remains same, and there is no change in this static head.

Now, next you see another very interesting example of a reaction machine. If you consider a lawn sprinkler, what is a lawn sprinkler probably you know that it has got two nozzles mounted on two arms of a rotating device. That means, if you make free and if the water at high pressure enters into this system like this, and it flows through this two arms, these are the two pipes and comes out from the two nozzles in the form of high velocity jet then due to the change in the angular momentum. That means, if you can find out the momentum of the fluid here, it is take the moment among this axis and of course, of this makes gives a turning moment for which it rotates. So, if you make it free it will rotate; that means, the energy is being transferred from the fluid to this lawn sprinkler.

So, this will lawn sprinkler can be thought of a fluid machines, where you utilize the high pressure energy of the fluid at the extreme inlet to develop the work output from the lawn sprinkler, which is capable of rotating if you keep it free. Now in this case, you see that this nozzles where the fluid pressure is changed from high pressure to low pressure, it also moves; that means, in the case nozzle was the stationary part, but here nozzle is the part of the rotor. So, therefore, you see while the fluid flows through the rotor both the absolute velocity of the fluid changes, there is an increasing absolute velocity, and at the same time the relative velocity is changed.

How we can realize it, because there is a change in the pressure because pressure here is high pressure here is high pressure here is high only in the nozzle part which is also moving pressure is changed. That means, in the rotor both the absolute velocity and the pressure of the fluid is changed, that means, we get both the change in the dynamic head and the static head in the rotor, why in this case, there is only a change in the dynamic head. So, lawn sprinkler is a very good example of a reaction fluid machines. While your paddle wheel is a very good, but a simple example of a impulse fluid machines.

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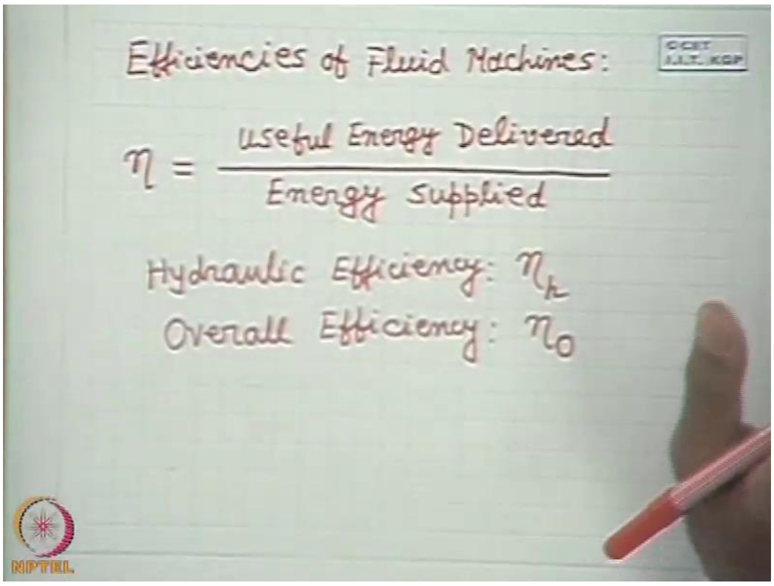

Now, next I come to the definition of efficiencies of fluid machines, eta – efficiency. As you know efficiency of the any system is defined as its output to its input. So, similarly for a fluid machine, the efficiency is defined in a generalized sense at the useful energy delivered, that is the output energy divided by the energy supplied. So, this is the basic definition of efficiency of a fluid machine that is useful energy delivered divided by energy supplied. Now there are two types of efficiencies that are defined in fluid machines; one is hydraulic efficiency, afterwards we will refer it is two types of efficiencies, so you must know the definition at these junctions that one is hydraulic efficiency eta h symbolized as, another is overall efficiency eta o.

Now hydraulic efficiency concerns about the energy transfer between the fluid and the rotor, and overall efficiency concerns about the energy transfer between the fluid and the shaft coupling. The difference between these two is the energy that is being observed by the mechanical system like bearings, glands, coupling; that means, it is the energy, which is lost in the transmission in the mechanical transmission.

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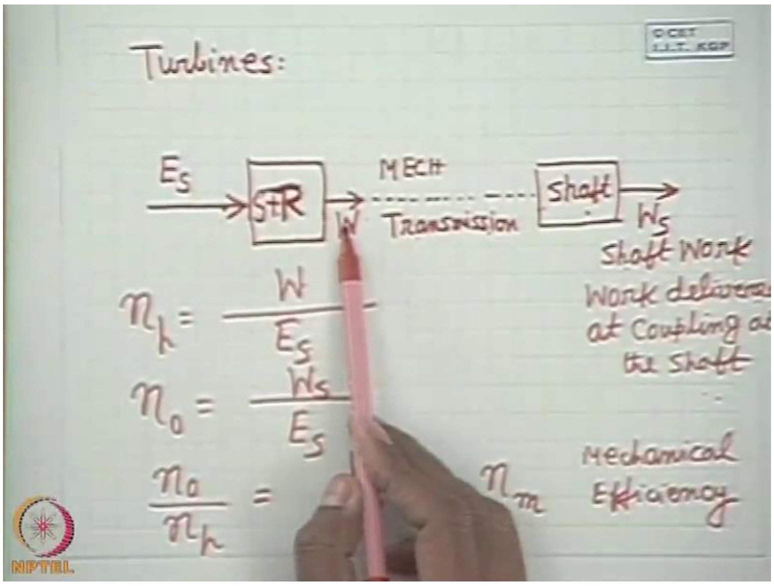

Well we can understand this better if we can think in this way, let us consider turbine in case of turbines. Let us see that let this is the turbine T. You know in case of turbine what is the input energy is the stored energy of the fluid as we recognized earlier that is the store energy of the fluid E s. Now this stored energy of the fluid, here we consider turbine rotor rather, rotor we are doing it for turbines. So, it is the rotor rotor of the turbine rotor of the turbine stator plus rotor you can write S plus R; that means, the stator plus rotor the total machine.

So, it comes to the stator and rotor then what happens just from the rotor we get useful or we get the mechanical energy out that means, the rotor delivers the mechanical energy. To whom, it is delivered to the shaft to a mechanical to a mechanical transmission system, yes that includes everything mechanical transmission, it goes to the shaft. And the shaft gives that the work W s that is the shaft work known as shaft work or this is the work delivered at the shaft coupling, that means, the work delivered at coupling at the shaft. You can very well understand it that rotor due to its motion when the fluid flows to the rotor, the energy is transfer to the rotor and immediately rotor delivers some work. So, hydraulic efficiency concerns with that transfer then that work is being transmitted through mechanical transmission system because the shaft where we get finally, from the shaft as the shaft, work delivered at the coupling at shaft.

So, therefore, hydraulic efficiency according to its definition is W by E s that means, it is dealing with this conversion from the stored energy of the fluid to the mechanical energy or output given by the rotor. Whereas the overall efficiency the input is same E s, but the output is final shaft work; that means, which takes care of the losses in the mechanical transmission system like as bearing, glands, shaft coupling all these things. So, if you see that quantity two what is eta o by eta h eta o by eta h will be W s by W; that means, this is the ration between these two which can be defined as eta m, that is mechanical efficiency. Mechanical is very simple to mechanical engineers that overall efficiency for a work producing device is the hydraulic efficiency into mechanical efficiency, which takes care of the hydraulic losses as its flows through the turbine. For which there is a discriminate between these two quantities and the mechanical loss which takes care of the discriminate between these two things because of the mechanical friction.

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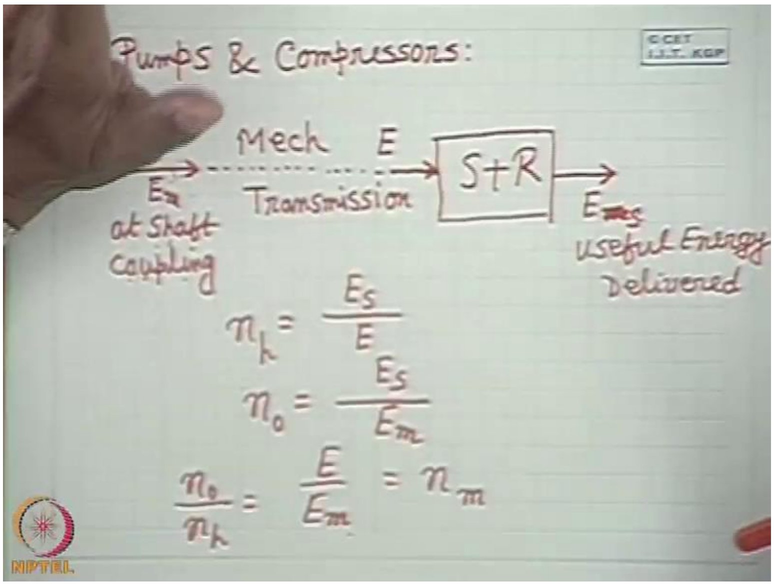

Similarly is the case for pumps and compressor, if you see that pumps and compressors, the concept is same here. What happens the mechanical energy - E m is being first put as the input energy through at shaft coupling that means, the extreme output terminal for the turbines is the extreme input terminal for the pumps and compressor. That means, here also we can consider the mechanical transmission, well after which this mechanical energy goes to the stator plus rotor of the compressor; that means, as a whole the fluid machine the compressors that now. And at the final output point, we get the stored energy of the fluid; that means, this is the useful energy delivered E s useful energy correct useful energy delivered; that means, in case pumps or compressors as we know the useful energy delivered is the stored energy of the fluid.

So, in this case, we see that this mechanical energy is being changed when it comes to stator and rotor due to the mechanical losses, due to friction in this mechanical transmissions system. Let this energy is E. So, therefore, in this case what is hydraulic efficiency, hydraulic efficiency concerns with the energy transfer between the fluid and the rotor. So, therefore, the hydraulic efficiency will be E s that is the stored fluid energy that is the useful energy delivered in this circumferences divided by the energy which is being received by the rotor. Similarly the overall efficiency, which deals with energy transfer between the fluid and the shaft at coupling; that means, the output is the same in both these cases useful energy delivered stored energy in the fluid. Now input will be the extreme at the extreme terminal point, where the input comes initially that is the shaft coupling E m that is the mechanical energy.

So, in the similar fashion we can write that eta o by eta h is e by e n, it remains the same; that means, it is this energy hw is being received by the rotor divided by the energy which is being fed at the shaft coupling which is nothing, but the mechanical efficiency. And takes care of the losses in the mechanical system mechanical transmission system. So, we are now recognize that different efficiencies in a fluid machine is the hydraulic efficiency, which concerns the energy transfer between the fluid and the rotor, and the overall efficacy which concerns the energy transfer between the fluid and the shaft coupling that difference between which is taken care of by the mechanical fiction or the fiction in the mechanical system well.

So, I will stop here. Next class I will discuss the principle of similarity. Now I request to you so if you can you please read and principle of similarity as already we have read earlier make a recapitulation of that. So, I will start from a basic recapitulation of principle of similarity and then I will discuss the application of principle of similarity in fluid machines, which is very important in designing any equipment for our engineering applications, the principle of similarity.

Well thank you.