Fluid Machines.

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Lecture-19.

Flow and Energy Transfer to Centrifugal Pumps.

Good morning and welcome you all to this session of the course on fluid machines. So we discussed in the earlier class, the general pumping system and the terminologies like net head developed by the pump, head at inlet, head at outlet, the static lift or static head, all these things. Now we will describe how a centrifugal pump looks like. The basic component of centrifugal pump, this is, these are the 2 options, means 2 types of, 2 configurations or 2 types are there.

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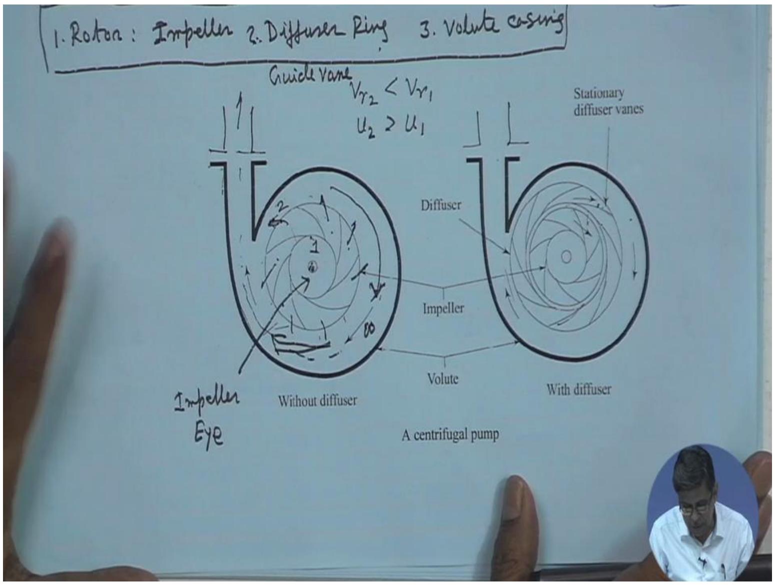

Basic components of a centrifugal pump is rotor which usually is known as impeller, impeller, rotor. And next is diffuser ring, this is number-one, number 2 is the diffuser ring, these are the main components and number 3 is the volute casing. These 3 main components constitute a centrifugal pump. Now a rotor which is known as impeller, this is the terminology used which takes that mechanical energy. You see this is the rotor, this is the shaft, this part is the shaft, rotor is basically 1st a circular disk mounted on the shaft and on this disc, the curved blades like this are mounted.

These are the spread curved blades stand upright on this mounted disk. And this part of the rotor is known as all impeller is known as impeller eye, impeller eye. That means the air, the liquid or water is shucked here and then it flows through this. Now here, this is the rotor blades, sometimes this outlet of the blade, there is another disk used which is known as Shroud, the blades are shrouded to prevent any leakage from one passage to other passage. But in most of the cases, the volute casing itself consists of that partition.

Now this is the volute casing, that things after coming out from the impeller, the fluid is shucked at the impeller eye, this is the impeller eye. That means when this is rotated, for example here, this is the degree of, this is the direction of rotation by an angular, this rotates, the water is 1st shucked, this is a plane, so perpendicular to this plane, if you consider this in the vertical plane, so water is shucked in the horizontal direction by the impeller eye. And then it turns direction and flows in the radial direction through the impeller eye.

And when it enters, it has got radial velocity and also the tangential velocity which is imparted by the rotation of this impeller blades. Now while the, when the water comes out from these impeller blades, what happens, it gains kinetic energy because of the impulse action, the rate of, change of angular momentum because the momentum is being given by the rotating blade and at the same time as already told several times that there is a change in the static pressure because it is a reaction machine while it flows through the impeller blades and it is radially outward flow.

1st is the centrifugal head is increased here, the blade velocity U1 is less, here blade velocity that is U2 is high but at the same time the relative velocity of flow also changes. There is a decrease in relative velocity, you see this gives a diverging passage and the cross-sectional area normal to the flow is increasing in the direction of the flow for each and every blade passages. That means the radius, the relative velocity at the outlet, if it is 2 at the outlet, 1 at the inlet, VR2 is less than VR1, means that the pressure at the outlet is more than that at 1.

And similarly U2 is greater than U1, so therefore centrifugal head which is manifested in terms of this static head is more at the outlet than at the inlet. That means when it comes here, it has both pressure energy or static head because of high pressure and at the same time kinetic energy. Substantial kinetic energy is there because of the velocity which it gets by the impulse action of the impeller blades. Then the function of the volute casing is that then it flows through this volute casing.

It comes like this and the direction of the flow in the, sorry, in the volute casing is like this. This is the volute casing flow is like that, that means the volute casing when it flows, it gets an area diverging. This is also a spiral casing like the turbine, just the reverse, turbine in the direction of the flow the area gets converged, here the area gets diverged. That means the cross-sectional area increases in the direction of flow. That means this volute casing again acts as a diffuser like in the way that kinetic energy which the flow is having at the outlet of the impeller blade is being converted in this volute casing which acts as a diffuser into static pressure head or static head at the outlet.

This is the flange and this is the outlet, here we connect with this plate the delivery line, so this is the final delivery line. This is the overall picture of the impeller, rotor, that is impeller, the volute casing as the diffuser but in some cases depending upon the requirement of static pressure and the flow rate, there is an additional guide vanes type of thing which is, which are attached to the blade, guide vane rings. Diffuser rings or guide vane or sometimes guide vane rings, guide vane rings.

So and this is, the blades are nothing, these are static blades and providing a passage of diverging in nature which gives an increase in cross-sectional area in the direction of the flow which converts the kinetic energy to pressure energy and after this there is a volute casing. That means both the vanes, static vanes as the guide vanes which are attached to the guide vane rings and also the volute casing. So both of these convert the kinetic energy of the fluid coming out from the impeller blade passages into static pressure or static head and this is finally the outlet.

So this is the in brief, the components of a centrifugal pump, all right. And the water at the inlet is shucked in the radial direction, perpendicular direction to this, when it rotates, it shucks and then it turns automatically in this direction and flows through the impeller blade passages. Now with this as the background knowledge, let us see that how the velocity triangle looks like.

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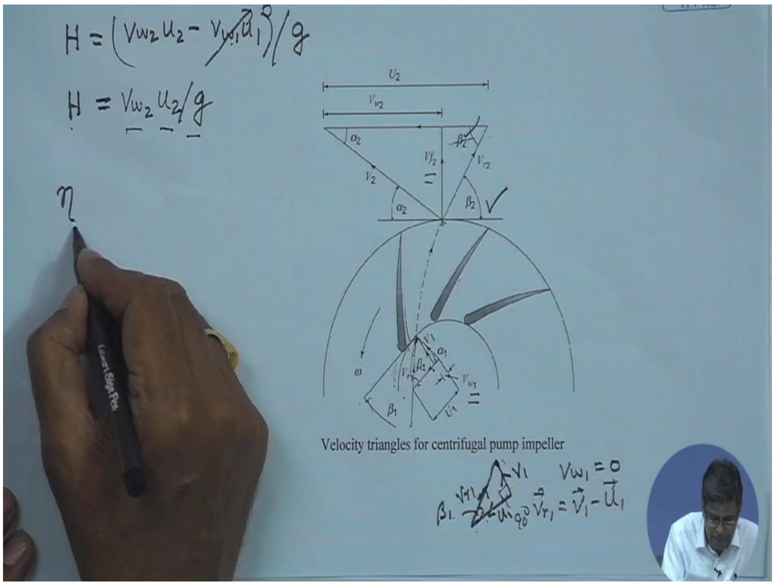

Now I show you a typical section that these are blades, impeller blades, only this part I am showing without any volute casing. We are interested to find out because energy interaction takes place only in the rotor, that means impeller in this case, in the pump it is stored as impeller. It is rotating at a constant angular velocity omega in this direction of rotation. Now 1st thing, we have to understand that the water is shucked off the fluid is shucked axially in the impeller eye and then it moves towards the impeller.

So there is no guide vane at the inlet for which the liquid at the inlet does not have an appreciable swivel component the tangential component of velocity. And the eye is also designed in such a way that at the inlet, the tangential component of velocity is reduced to minimum and ideally should be made 0.

I am telling you why, here you see the design should be such that the inlet velocity triangle if you see here, inlet velocity triangle, here it is the blade velocity U1, here automatically it is drawn, U1 is the blade velocity, here you see, that U1 is the blade velocity, U1 is the blade velocity, this is the relative velocity VR1 and this is the absolute velocity at the inlet which should be perpendicular to this. Without, that means VW 1 is 0. And this is the velocity triangle, VR1 is V1 as I told U1, so this is the velocity triangle.

That VW 1 should be made 0 but in practice and this is beta 1, obviously for smooth entry, actually this has been shown as a broken line in between the 2 blades, in the blade passages as a representative direction of or the flow direction, representative path line of the fluid element. So this point, this is the beta 1, this is actually parallel to this line, that means this is the blade or impeller blade angle at the inlet. That means this is the tangential direction and this is the blade tangent to this point, blade profile, this angle is beta 1, this is beta 1.

So this angle I am showing again is beta 1. But under of design conditions or under different circumstances, so this fluid may not enter so smooth, that is a VR1, that is the relative velocity with respect to the impeller blade may not be making the angle of the blade at the inlet. That means the flow, that the fluid velocity may not glide, the fluid may not glide along the blade at the inlet. So there may be an oblique in transfer for which are inlet, for which there may be a generation of little tangential component of velocity.

So that is why this line is given, this is in practice, the velocity bangle is like that. Nevertheless it should be designed in such a way, even if this V1 is not perpendicular, the direction of fluid velocity is not perpendicular to the rotor velocity U, ideal case, it is 90 degrees. Here also ideal case, this is given by this line but it has a very small component in the tangential direction, it has appreciable component in the radial direction in the flow velocity. Okay.

Now this is done because of the fact that you know that H, that is head which is given to the fluid is VW2 U2 - V W1 U1 by G, that we already developed, Euler’s turbine equation. VW 1 U1 - UW 2 U2 by G is the head delivered by the fluid to the, in case of turbine. But in case of pumps and compressors, this is like this. So it is VW 1 is 0 then the, then this is the maximum. This will be, when this will be 0, so we want to keep it 0 to get the maximum this, head developed by the fluid or head imparted to the fluid by the impeller blade.

Now you see the outlet velocity triangle. Now for this typical blade profile, the outlet triangle is like that, this is a path represented path shown, this is the blade angle VR2 coinciding with that, this is U2, so U2 is this U1 and this is U2, U2 is much larger than U1, this is because R2 is much larger than R1, the radial location at outlet, this is U2 and this is V2. So therefore this is beta-2, that is the angle of the blade at the outlet, this is beta-2, this is beta 2 and this is the flow velocity, that means the velocity in the radial direction, normal direction of the flow.

That is known as, sorry normal, direction of the flow, normal to this cross-sectional area that is VF 2, we already know the nomenclature and this alpha 2 is the angle that the absolute velocity makes with the direction of the tangent. So therefore VW 2 U2 by G is the head that is being given to the fluid or developed by the fluid.

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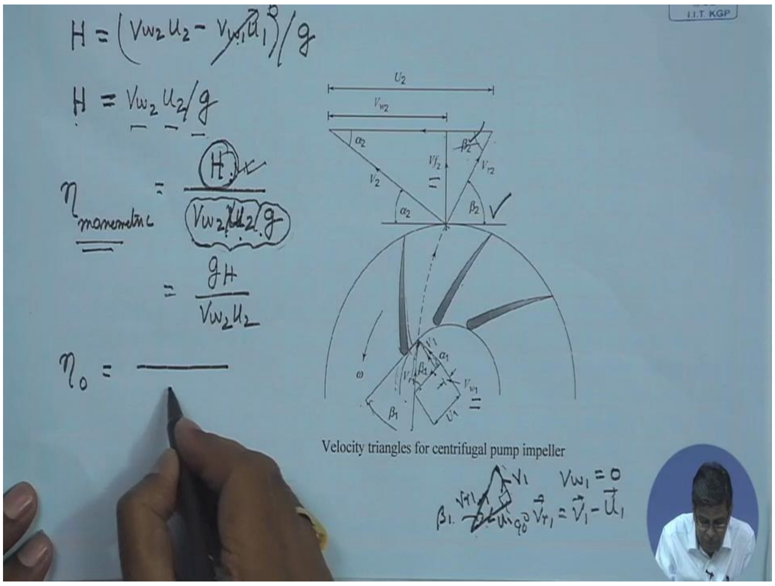

$$H = \left(V_{w_2}U_2 - \cancel{V_{w_1}U_1}\right)/g$$

$$H = V_{w_2}U_2/g$$

$$\eta_{manometric} = \frac{H}{V_{w_2}U_2/g} = \frac{gH}{V_{w_2}U_2}$$

$$\eta_0 = \frac{\quad}{\quad}$$

Velocity triangles for centrifugal pump impeller

$V_{w_1} = 0 \quad \vec{V}_{r_1} = \vec{V}_1 - \vec{U}_1$

Now here manometric efficiency is defined as, this is the terminology, manometric and it is defined as, this head developed by the fluid to the, this is the head or energy per unit weight given to the fluid. But manometric head is defined as head developed by the fluid divided by this.

Sorry, VW2 U2 by G, that means GH by VW2 U2. Now understand what is the difference between these 2. What is the difference between these 2? Yes, it is very important to know. Now this is from Euler’s turbine equation, that is the energy per unit mass, per unit weight VW2 U2 by G, per unit weight given to the fluid by the rotor. That means rotor supplies this much amount of energy per unit weight to the rotor, that means this much amount of head has been transferred to the fluid by the rotor.

This is the net head developed by the fluid which we have found by subtracting the, okay, let us find out that figure by subtracting the, by subtracting the total head at the outlet and inlet. Subtracting the total head at outlet and inlet. So this head, that means the fluid develops the net head this which is different from that and in fact this is less than this, why, this is because of the viscous dissipation in the impeller, impeller of the pump and also in the diffuser.

So because of viscous dissipation in the pump, so this net head developed by the pump which is the difference in the total head at outlet and inlet will be always different from that, the head which has been given by the rotor to the fluid. If we consider the fluid to be inviscid or if we neglect the viscous effects, then these 2 will be equal and manometric efficiency will be

1 or 100 percent. So therefore this manometric efficiency takes into consideration viscous losses, losses due to viscous effect, that is the fluid friction.

This is the discrepancy between the head given to the fluid by the rotor and head developed by the fluid while flowing through the pump, so this is defined as manometric efficiency. Then another efficiency as you know Eta overall, this is defined as, how the overall efficiency is defined, overall efficiency is defined in a way that this is the final energy developed, that is head developed divided by the input, main input to the shaft.

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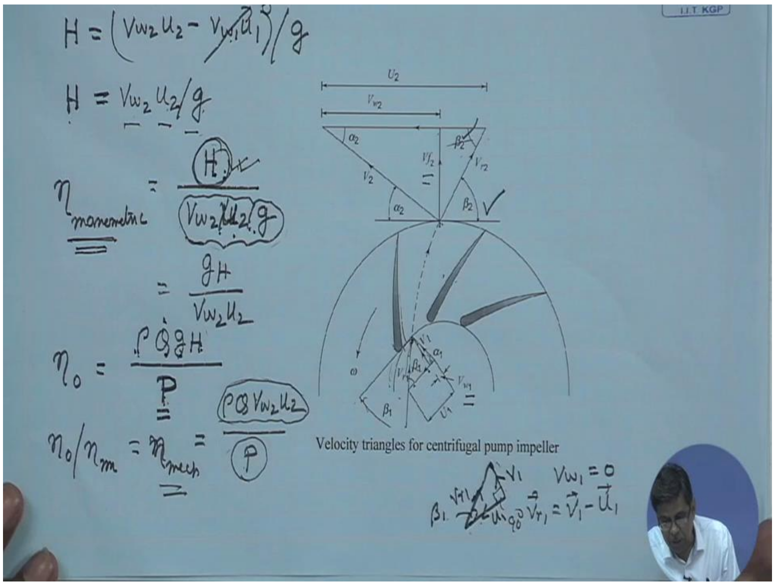

$$H = (V_{w_2} u_2 - \cancel{V_{w_1} u_1})/g$$

$$H = V_{w_2} u_2 / g$$

$$\eta_{manometric} = \frac{\boxed{H}}{\boxed{V_{w_2} u_2 / g}} = \frac{gH}{V_{w_2} u_2}$$

$$\eta_0 = \frac{\rho \dot{Q} g H}{P}$$

$$\eta_0 / \eta_m = \eta_{mech} = \frac{\boxed{\rho Q V_{w_2} u_2}}{\boxed{P}}$$

Velocity triangles for centrifugal pump impeller

$V_{w_1} = 0$

$\vec{V}_{r_1} = \vec{V}_1 - \vec{u}_1$

Now this is the input at the rotor level, rotor gives this input but the actual input given at the shaft or to the shaft at the couplings if we define this as power P which is being given to the shaft that coupling, then this, then what will happen, this is the power. So this is the head developed, so therefore if we have, if we multiplied this, head developed, so per weight flow rate, GH easy energy per unit mass developed, rho into volume flow rate. So therefore this is the energy, that is the total power energy per unit time, this is the total power, you be careful about the unit, this is the total power developed, that is derived from the head developed for unit weight, G per unit mass than the mass flow rate.

This is the developed divided by the gross input. So this and this differs by the frictional losses, mechanical friction at glands, bearings and couplings as I told earlier. So therefore manometric efficiency is similar like hydraulic efficiency of turbine. So overall efficiency is like, so if we divide the overall efficiencies by the manometric efficiency, we get mechanical efficiency, Eta Mechanical, which is if you divide this by this, so you get the mechanical efficiency.

What is mechanical efficiency, that will be rho Q VW2 U2 by P. If you divide this by this, then automatically GH will be cancelled, VW2 U2 will go in the numerator. That means this is the ratio of the work, this is power, rather in terms of power, this is the VW2 U2 by G in terms of head, this is the power given by the rotor blade to the fluid and this is the power given at the input, that means to the shaft at the coupling and this ratio is mechanical efficiency, this is because of the, the discrepancy between these 2 is because of the mechanical friction in glands, bearings and couplings.

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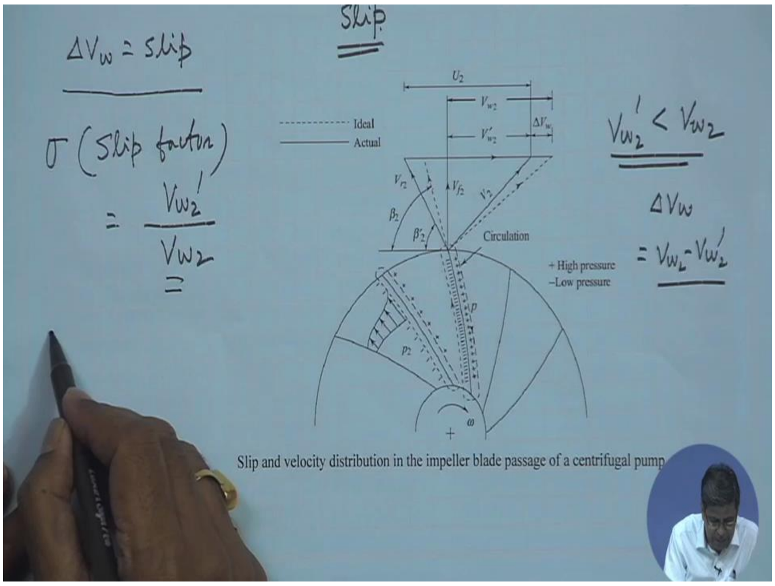

So this way we can define the different efficiency. So therefore this is the typical impeller blades and this is the inlet velocity triangle, this is the outlet velocity triangle and this way we define the manometric efficiency, overall efficiency. Now next I will tell you one very important phenomena of slip, that is known as slip. One very important phenomena that is known as slip in centrifugal pump. The phenomena is like that, before that I tell you, under many circumstances it is found that the velocity of the flow even at the design condition is not matching with that of the blade outlet angle and there is a fall short of that.

As a result of that the tangential component of the absolute velocity of fluid at the outlet is reduced from that which is obtained from an ideal velocity triangle or velocity vector diagram in consideration of the relative velocity or flow velocity with respect to or relative to the impeller blade, okay. This is falling short of that for which the power or the head whatever you call deliver to the fluid is less. Why does it happen? Now here I will show, tell you that this is the fact, before coming to this actual velocity triangle, let us 1st describe the phenomena.

This is the probable cause, we can explain this way for which it happens. Let us consider that this is moving in this direction and this is the impeller blades. Now while the impeller blade rotates and the fluid flows past it, what happens, there is a positive pressure, high pressure rather you can tell a higher pressure on the leading surface and a lower pressure on the trailing surface. And this is because of this curvature of the blade. And this higher pressure and leading pressure is the result of the pressure gradient imposed by this curvature on the leading side and on the trailing side.

So because of this, there is a higher pressure induced on the leading side and lower pressure on the trailing side which induces a circulation like that, there is a circulation like that. The circulation takes place through this part like that, there is a circulation. And finally what happens, this circulation because of this higher and difference in pressure at the leading and at the trailing surfaces, the velocity distribution becomes very much nonuniform. It is true that the velocity variation is not uniform, we are analysing everything in consideration of the uniform velocity distribution.

So at any point we represent the velocity which is the representative of the velocity over the entire periphery. This is not true but this thing makes it much more uniform in a sense that Q distribution is there which makes a higher velocity at the trailing surface and a lower velocity at the leading surface of the next blades. That means in the blade passage, in this blade passages you see, the velocity distribution becomes like this. So this finally results into a velocity distribution which is like this, which is given by the firm line.

The 1st of all we see the lines dotted, that means the triangle with dotted line, so this is the VR2, so this is the VR2 which is, this is, carefully see, this is the VR2 which is being aligned with the blade angle at the outlet, impeller blade angle at the outlet. This is obviously your V2 and this is your U2. But because of this uneven or nonuniform, nonuniform velocity distribution because of the circulation because of the difference in pressure in at both some at leading and trailing surfaces, this is because of the curvature and imposing this type of pressure gradient, this happens so.

So this triangle is being changed like this, this is the, firm line is the actual one. This is V2, so VR2 is not beta-2. This is beta-2 which is the actual, this is you see beta-2, this is beta-2 but here this is beta-2 dash. So this is beta-2 dash, it is lower than this beta-2. So in that case if we draw the velocity triangle, we will see that this tangential component is VW2 dash which is lower than VW2. That means VW2 dash, the tangential velocity component is lower than VW.

And this causes the problem. And this Delta VW is equal to VW2 - VW2 dash, this is different in this. This is known as slip. So therefore you see this work done on the fluid on the energy delivered to the fluid, head delivered to the fluid is changing. This is known as slip and we define a slip factor Sigma, a slip factor which is equal to VW2 dash divided by VW2. This is known as that is the ratio of the tangential component of velocity actually obtained and the ratio of tangential component of velocity that could have been obtained ideally from an ideal velocity triangle with relative velocity making the same angle as that of the impeller blade velocity, blade at the outlet.

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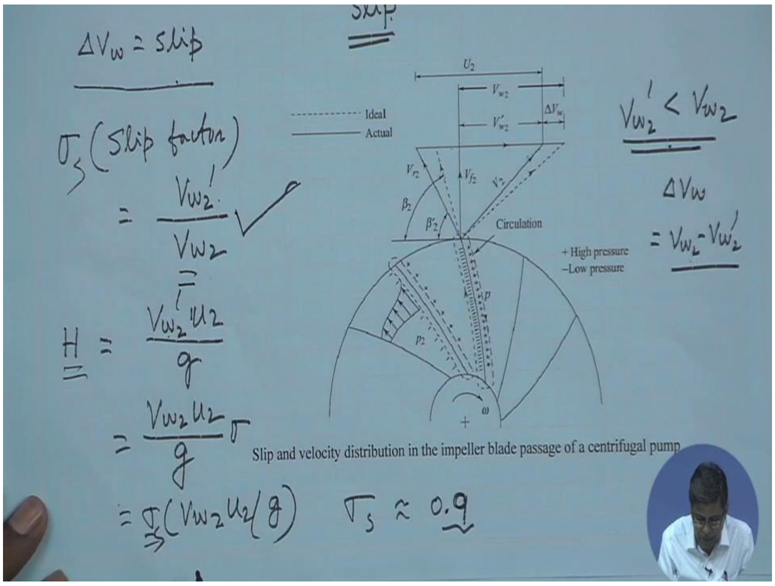

Slip

$\Delta V_w = \text{slip}$

σ_s (slip factor) $= \frac{V_{w_2}'}{V_{w_2}}$

$H = \frac{V_{w_2}' U_2}{g} = \frac{V_{w_2} U_2}{g}\sigma = \sigma_s (V_{w_2} U_2 / g)$ $\quad \sigma_s \approx 0.9$

$V_{w_2}' < V_{w_2}$

$\Delta V_w = V_{w_2} - V_{w_2}'$

Slip and velocity distribution in the impeller blade passage of a centrifugal pump

So therefore one can write the head that is being imparted to the liquid is VW dash U2 by G. It is expressed in terms of its ideal value VW, that means if we calculate using the ideal velocity triangle in our problems to be worked out, we just simply multiply with Sigma because VW dash, that means it is Sigma into VW2 U2 by G. It is reduced by, usually the value of Sigma, this is used as the suffix S, Sigma S is usually lies between is around 0.9, here and there, it is 0.9.

So therefore this is the phenomena of slip, that due to this phenomena and this is an independent phenomena or independent effect as that of the viscous effect. So this has nothing to do directly with the viscous effect in the fluid. This is because of the blade curvature which induces pressure which are different in the leading and trailing faces and creates the circulation for which the velocity distribution becomes nonuniform and makes an alteration in the velocity triangle from that of the ideal one.

Actually velocity triangle we draw makes an alteration means it changes the direction of the relative velocity from that of the actual blade angle for which everything changes. So therefore the component, tangential component of the absolute velocity also changes and it is actually reduced and the reduction is defined as slip for which the energy imparted to the fluid is reduced and this is the definition of the slip factor, the ratio of the tangential component of velocity, actual and ideal and we can express the head developed by the fluid or imparted to the fluid as slip factor Sigma S into this VW2 U2 by G, where VW2 is the tangential component of the fluid velocity at the outlet in consideration of the ideal situation without slip. Okay, so today up to this, thank you.