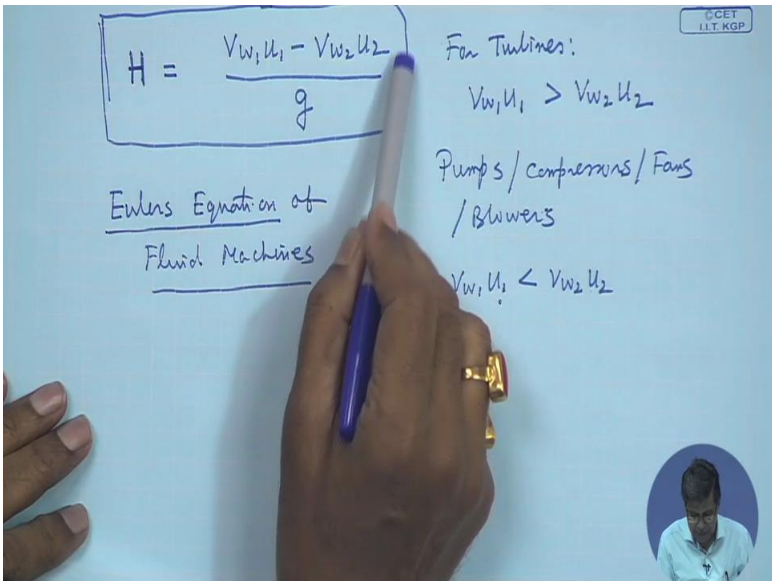
Fluid Machines.

Professor Sankar Kumar Som.
Department Of Mechanical Engineering.
Indian Institute Of Technology Kharagpur.

Lecture-2.

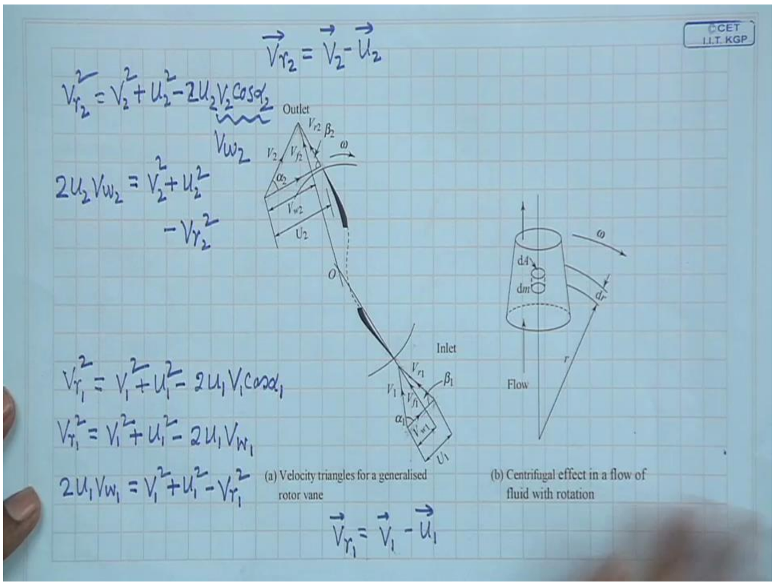
Definition Of Fluid Machines and Energy Transfer in Fluid Machines Part II.

(Refer Slide Time: 0:32)



Good morning and welcome you all to a session of fluid machines. Now in the last class we derived this expression that this H represents the head or energy for unit weight that is being delivered by the fluid to the rotor is given by this expression. And this nomenclature again I repeat that VW1 and VW 2 are the tangential component of fluid velocities at inlet and outlet of the rotor respectively and U1 and U2 are the linear velocities of the rotor at the inlet and outlet.

(Refer Slide Time: 1:50)



Now as I have told that rotor consists of a number of blades, moving blades, moving rows of blades, more rows of blades and each row has number of blades which constitutes number of blade passages, so therefore here is we will show a typical section of a rotor with blades. Now the blade is shown like this with a broken path to show the inlet and outlet portion. So we will concentrate our attention at the inlet and outlet. Now here what we will do, the velocity of the fluid at both inlet and outlet will be, will be shown with a vector diagram.

Now what is that, at the inlet if we show the vector diagram which is known as velocity triangle, you see that V1 is the fluid velocity, absolute velocity of the fluid. Now let U1 is the linear velocity of the blade which is tangential at this point, tangential means this is perpendicular to the radial direction, so this is a vector diagram where this is V R1 is a relative velocity of the fluid with respect to the blade at this point, at the point of inlet.

That means one can write, one can show that VR 1, the relative velocity is V1 - U1. That means this is the absolute velocity of the fluid and this is the velocity, this U1 is the direction of the velocity, blade velocity here which is U1 and if we draw it in sketch, then if we complete this triangle, this will be the direction of the relative velocity, that is the velocity with which fluid is entering the rotor blade or entering the rotor blade at the at the inlet of the rotor blade with respect to the rotor.

That means this is the velocity with respect to the rotor. To show this relative velocity, we draw this velocity triangle which is the velocity vector vector triangle. So here also vector diagram, V2 is the absolute velocity of the fluid and you see that the V2 is the absolute velocity, here also if we write VR 2, that is the relative velocity of the fluid at the outlet of the blade with respect to the blade will be nothing but it is absolute velocity - the blade velocity.

And blade velocity, we will be having in the tangential direction, that is omega R2, this is this one, so if this is the blade velocity and this is the outlet velocity, if you complete this vector triangle, so this will be VR2. So this way we will always draw the velocity triangle which is a vector triangle, always be will write this and this is one be simple to understand, if you take U2 here, VR2 + U2 will be V2. You see in that triangle, V R2 + U2, here you see this is V R2, this is U2, that means U2 V R2 is in the same direction.

If they are added we get V2 in the opposite direction as the resultant velocity. That way you can understand this vector triangle. Here also V R1 + U1 is V1, so if you take this one, in this case also you see this is V R1 and this is U1, so U1 added with V R1 in the same direction gives the value of V1 which is in opposite direction, this is V1. This way one can understand by vector diagram at the 1st level which is known as velocity triangle.

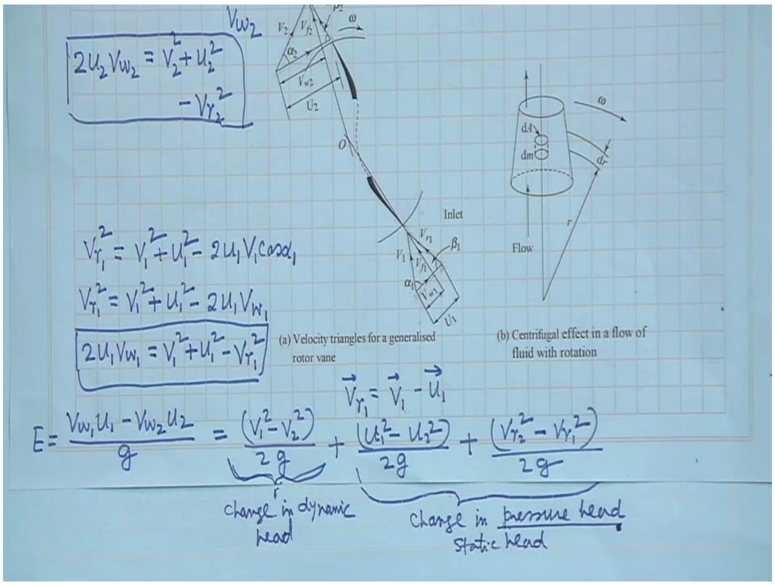
Now if we write this from the velocity triangle, we do that trigonometric thing. What is this, if we denote this alpha 1 as the angle made by the absolute velocity with the tangential direction, this is the tangential direction, that direction along with the blade speed is, the direction of the blade speed, this is the tangential direction. And beta 1 is the angle made by the relative velocity with the tangential direction at inlet. Similarly Alpha 2 is the angle made by the absolute velocity at the outlet with the tangential direction and beta 2 is the angle made by the relative velocity at the outlet with the tangential direction.

Now let us write here for the inlet one you see we get, we can write, with this triangle, V R1 square, taking this triangle into consideration, trigonometric relation V1 square, that means square of 2 sides + U1 square and this angle is acute - twice U1, this is U1 into the perpendicular link, that is V1, the projection of V1 on U1 cos Alpha 1. VR 1 square is equal to V1 square + U1 square - twice U1 into V1 cos Alpha 1.

This can written as V R1 square is equal to V1 square + U1 square - twice U1 and this V1 cos Alpha which is given here, this projection of V1, that is a component of V1 in the tangential direction, that is nothing but I was tangential component of absolute velocity of the fluid at inlet which already we defined, twice U1 V1 or one can write U1 VW1 is equal to V1 square + U1 square - V R1 square. Okay.

Now similarly if you write it here at the outlet, we will get, what we will get, VR2 square, that is the square of this side is equal to square of this side + square of this side, that means V2 square + U2 square, + U2 square, - twice U2, this is U2 into V2 cos Alpha 2, - U2 twice U2 into V2 cos Alpha 2. Well, at this V2 cos Alpha 2 again is VW. See, this is VW 2, that means the tangential component of velocity, absolute velocity of the fluid at outlet.

(Refer Slide Time: 8:48)



So one can also write here twice, twice U1 V W1, twice U2 VW 2 equals to V2 square + U2 square - V R2 square. Well now if we subtract this one from this, we get a very important relation. What is this, this one is like this that we can write V W1, this way U1 - VW 2 U2 by G which we already know as E, the energy per unit mass given by the fluid, now can be written from these 2 expressions, this one okay and this one, these 2 expressions as V1 square - V2 square by 2G, from these 2 expressions now I am writing, + U1 square - U2 square by 2G + V R2 square - V R1 square by 2G.

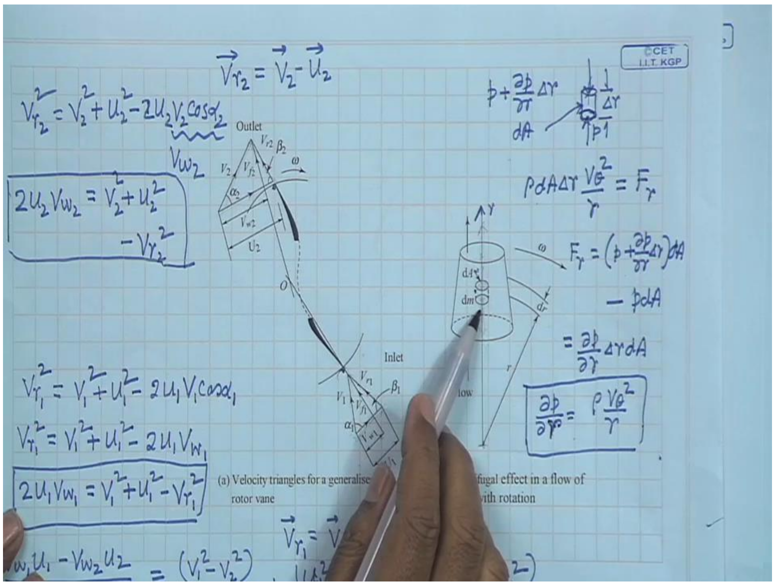
So what I have done now, this expression was proved earlier, deduced earlier, not proved, deduced earlier as the energy per unit mass that is being delivered by the fluid to the rotor which can be split into 3 components like these with the help of the trigonometric relations of the velocity triangles at inlet and outlet. Velocity triangles at inlet and outlet are nothing but the velocity vector diagram at the inlet and outlet with the help of the simple trigonometric relation we have got this.

Now here, absolutely we see one thing is apparent that the net energy exchange or the net energy delivered by the fluid depends, I have got 3 components, one is the change in its kinetic energy, this is purely change in its kinetic energy, change in the absolute velocity. And this part, so this is known as change in dynamic head, change in kinetic or dynamic head, head is again the energy per unit mass, this is known as change in dynamic head and these 2 parts corresponds to the change in pressure head, change in pressure head or it is known as static head.

This is the loose come actually pressure head, actually these 2 things are responsible for change in the fluid pressure and in a very strict sense, they represent the change in the flow work of the fluid which loosely sometimes we tell the pressure head, the pressure energy per unit mass which is manifested in terms of the change in the pressure. So therefore when the fluid delivers energy, it is dynamically changes, it changes its kinetic energy, at the same time it changes the pressure, pressure is also reduced.

Kinetic energy is reduced, this part is positive, V1 is greater than V 2 and this part is also positive, so that the change in the pressure at pressure head or static head is such that the fluid reduced, fluid releases the pressure. Again in the other way when the fluid games them, this is negative, that means when the fluid gains energy, fluid gains energy in the form of its dynamic head and also in the form of its pressure, pressure or static head. Now an understanding, for a physical understanding that how does it work as a change in the pressure head, we can think a simple system like this.

(Refer Slide Time: 12:58)



Consider how a fluid when it gets displaced in the field of rotation, that means when there is the tangential velocity of the fluid which is imparted by the rotating rotor, then if a fluid changes its position from one radial location to other radial location, how the pressure changes is being determined by this quantity. This can be explained very simply, probably you people know at this point that let us consider a container like that which is filled with fluid and which this container is rotated with an angular velocity in this vertical plane about a horizontal axis.

This way the container is being rotated. So with this rotation, let us consider the fluid has a slow motion in the radial direction. Fluid moves radially from one radial location fluid moves to others radio location, this is the central point, that means this is the axis of rotation. From the axis of rotation fluid changes its radial position from one position to another. So in that case if we consider a fluid mass like this, a simple fluid mass, a small elemental fluid mass, let us show it here, elemental fluid mask like this.

And here in this case what happens when the fluid moves with a tangential velocity here, because of the rotation of these with an angular speed omega of this container, what happens, the fluid as the centrifugal force and the centripetal force, that means any fluid mass is being balanced at a location by virtue of both the forces, one is centrifugal force, which is away from this in the radial direction, away from the central axis and another is the centripetal force which is inward radial force and this inward radial force that the centripetal force and the outward radial force, the centrifugal force, both of them balance each other to make the fluid in position to rotate.

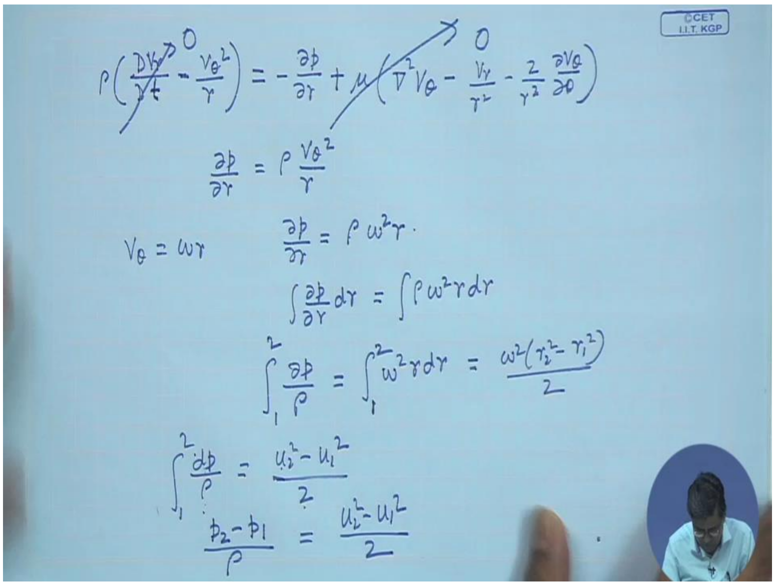
Nowadays neither going out or neither coming in, it slowly moves in the radial direction, that is why it has to be moved along the, according to the flow field. So this centripetal force causes causes a radial pressure field here, that means a radial pressure field is generated, so this radial pressure field actually exerts a pressure force on this fluid element in the radial direction. If we understand this in a very simple case.

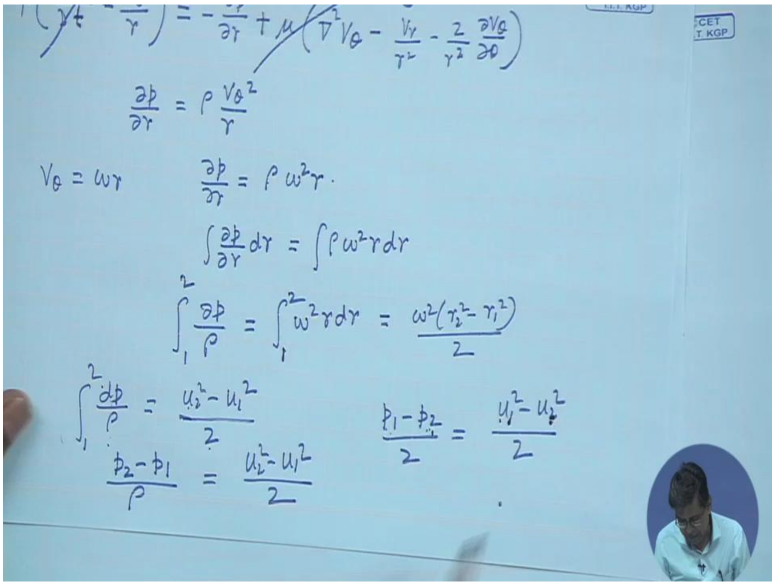
You will see that if we consider this as the R direction, now let us consider the pressure here at P and let us, if we think that this is small radial lines or height D R, then the pressure here can be written as P + Dell P Dell R, Dell R by neglecting the higher-order terms in the Taylor's series expansion. And if we consider the cross-sectional area, this area as DA, then we can write the centrifugal force equals to the centripetal force which is nothing but the pressure force in this fluid element.

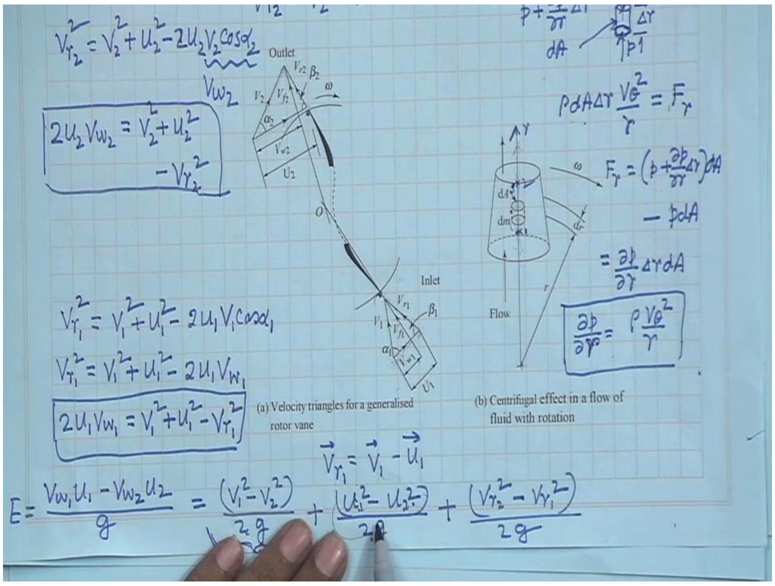
Now what is the centrifugal force? So centrifugal force is rho times the volume, that is mass, that is DA into delta, that is the volume of the fluid element into density, mass into V Theta, if this is the tangential component of velocity of the fluid V Theta square by R. This equals to the centripetal force, that is the inward radial force FR. This FR is what? This FR is given by in word radial force which is P + Dell P Dell R Dell R into DA - from this side P into BA.

This becomes equal to Dell P Dell R Dell R DA. Now if you put FR there, DA Dell R DA Dell R cancels, we simply get an expression that Dell P Dell R is rho V Theta square by R. You see this rotational velocity is responsible for a radial pressure gradient to be set in here. Radial pressure field rather, radial pressure field or radial pressure gradient to be filled in air, so that from one point to other point there is a change in the pressure. And that is why the fluid changes its pressure if it moves from one radial point to another radial points.

(Refer Slide Time: 18:18)







Now the same thing you can get if you, if you write the Naviar-Stokes equation in general, in a cylindrical coordinate system in R direction. If you recall the Naviar-Stokes equation in a cylindrical, polar coordinate system, you will see in R direction, the Naviar-Stokes equation is like that. This is for your knowledge, for your information I am telling you, probably you know these things, this is the Naviar-Stokes equation in the left-hand side inertial term.

This is the DV DT, the substantial derivative, change of radial velocity with T, this is the radial acceleration - V Theta by R equals to - Dell P Dell R + mu into, it is the Laplacian, I am not writing this full, I am not repeating this, this you will get from any fluid mechanics course, - VR by R square -2 by R square Dell V Theta Dell…

Now here I will tell you that is while deducing these expressions, what we 1st did, we considered the radial flow is so small or radial acceleration is so small that this is neglected because whenever we write that the centrifugal force is equal to this centripetal force, that means this is the mass times V Theta square by R, it is the only centrifugal acceleration.

Okay, and this is equal to the net inward radial pressure force. So here we neglected the radial acceleration and at the same time we neglect any viscous force acting on this element. That means if you neglect the viscous force, the entire thing 0 and if we neglect the radial acceleration, you get this same thing that Dell P Dell R is rho V Theta square by R. Okay, now here if you consider the rotation of this container, if you consider V Theta as omega R, then you can write Delta P Dell R is equal to rho omega square R square, that means omega square R.

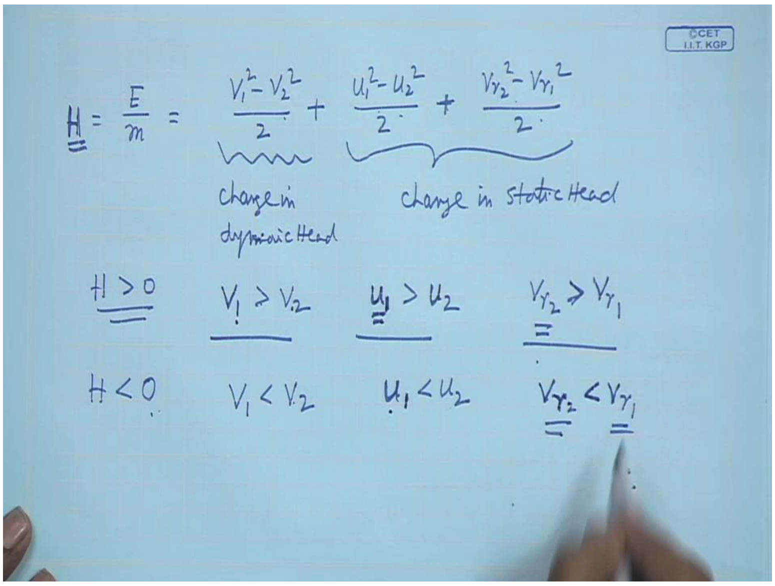
So if you integrate this Dell P dell R DR and here we consider P is a function of R, not as a function of Theta, then we can write DP DR is equal to rho omega square R DR. Well, so we can write this by taking rho here at integration of Dell P by rho or we can write this Dell P by rho 1 upon rho here is equal to integration of omega square R DR. If we integrate from 1 to 2 where 1 is a point at initial point, 2 is the final point, that means if particle moves from the, mass move from a location 1 to 2, that means from inlet to outlet, this can be written as omega square R2 square - R1 square by 2.

So therefore you see we can write now DP considering P as a function of the radial location only for your understanding, this is U2 square - U1 square by 2. That means this is the flow work delivered by the fluid which is U2 square - U1 square by 2. You see here also, this is the flow work given to the fluid, I am sorry, here it is delivered by the fluid, U1 square - U2 square by 2G, that is per unit weight. So from here you get a concept that the flow was, that means that is the change in the pressure, that if you integrate for an incompressible flow, it will be giving 2 - P1 by rho is equal to U2 square - U1 square by 2. Okay.

That means one can write that P1 - P 2 by 2 is equal to U1 square - U2 square by 2. So therefore it is clearly seen that since U2, let us consider an incompressible flow, this will easy to, it is easy to understand. If U2, if U1 is the inlet and U2 is the outlet, so if U2 is at a higher radial location then U2 is more than U1, so therefore this is negative, so P 1 - P2 will be negative, that means P2 will be higher than P1. So if U2 is at the higher radial location but U2 is the lower radial location, then U2 will be lower, that is 2 is that a lower radial location, U2 will be lower than U1, then it is positive, then P1 - P2 is positive and in that case P1 is higher than P2.

There will be reduction in pressure. So therefore we see that this term U1 square - U 2 square represents a static as we already shown earlier in this that this represents a change in the pressure of static head. Similarly it is there for the relative velocity.

(Refer Slide Time: 23:52)



Again I write it to explain you after this understanding that I show you that finally what we get H is equal to E by M is equal to V1 square - V2 square by 2+ U1 square - U2 square by 2+ VR2 square - VR1 square by 2. Now let us understand 1st then how this term is the change in the pressure. This term is the change in dynamic head, change in dynamic head that is energy per unit mass, this term is the change in static head, change in static head. And here we have understood this that for the displacement of the fluid particles from one radial location 1 to another radial location 1, there is a change in the static head.

Similarly if there is a change in the relative velocity, there will be also a change in the pressure. This is very simple to understand that if we consider the entire rotor is fixed, that means there will be opposite direction rotation that makes the rotor fixed, then the fluid will pass through the blade passages with a velocity which is nothing but the relative velocity. So it is change will take place provided the cross-sectional area of flow passage changes. And with that change the flow velocity will change and the change in the flow velocity will be directly related to the change in pressure.

Simple Bernoulli's question, if you discard the viscous effect, it will give simply the Delta P by rho is equal to the difference between the square of the velocity V2 square - V1 square by 2. So therefore the change in the velocity with respect to the rotor when the rotor is fixed will depend on the cross-sectional area of the rotor passage will indicate or imply a change in the static pressure. So this will you see this is the change in the static head or pressure head.

So therefore this is clear now for turbines where H is positive, H positive, that means H greater than 0 by convention, that means the energy is delivered by the fluid. And if we have the individual components all to be additive, then what will happen, V1 is always greater than V2, so in turbines the inlet velocity of the fluid is always greater than that of the outlet velocity. U1 has to be the U2, that means inlet radial position, if it is a radial flow machine, that means if the flow takes place in bulk in the radial direction, then the inlet radial location has to be at a higher, the inlet to the blade is to be at a higher radial location than the outlet.

And VR2 - VR1 has to be positive, that means VR2 has to be greater than VR1. That means the outlet relative velocity has to be greater than the inlet relative velocity, okay. So outlet relative velocity greater means that the cross-sectional passage of the blade in the direction of the flow has to be the convergent one, so has to be the converging, cross-sectional passages have to be converging. So all the 3 are maintained in case of turbine so that we get additive effect.

All the individual terms are positive and they are added and they give the things that the energy delivered by the fluid. While in pumps, compressors, the energy is absorbed by the fluid, that means energy is taken by the fluid, by convention it is negative, in that case V1 will be greater than, now less than V2, that means inlet velocity is higher than the outlet velocity and U1 is less than U2, that means the inlet will be at a lower radial location than the outlet so that U1 is less than U2 and VR2 is less than VR1.

That means the outlet radial, outlet velocity, relative velocity of the fluid will be less than the inlet relative velocity. That means the flow passages will be diverging one. The flow passages will be diverging one so that the outlet velocity relative to the fluid will be less than that at the inlet. So that all the terms will be negative and will be additive in nature so that we get the total energy gained by the fluid. So this way we can understand the different components of this energy interactions as a change in dynamic head and change in static head. Okay. Thank you.