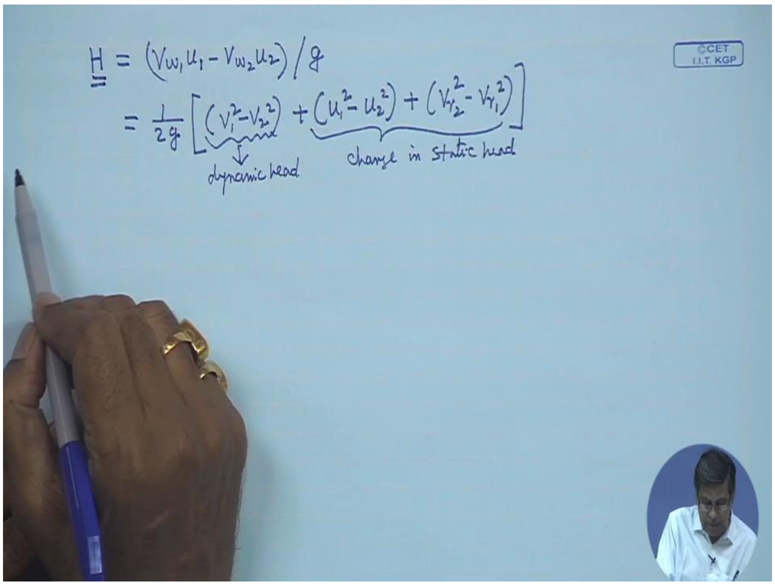
Fluid Machines.
Professor Sankar Kumar Som.
Department Of Mechanical Engineering.
Indian Institute Of Technology Kharagpur.
Lecture-3.
Impulse and Reaction Machines: Introductory Concepts..

(Refer Slide Time: 0:45)



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

$$= \frac{1}{2g}\left[\underbrace{(V_1^2-V_2^2)}_{\text{dynamic head}} + \underbrace{(u_1^2-u_2^2)+(V_{r_2}^2-V_{r_1}^2)}_{\text{change in static head}}\right]$$

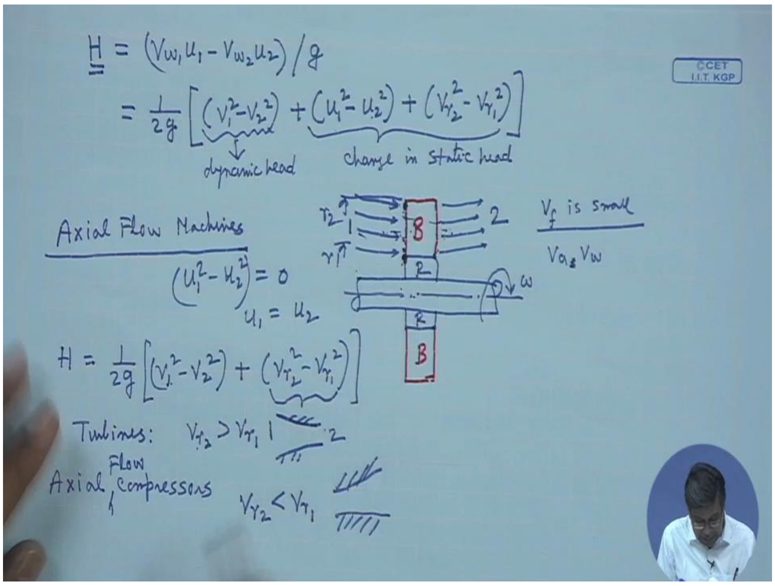
Good morning and welcome you all to this session of the course on fluid machines. In the last class we discussed that the energy per unit mass, that is the head which is delivered by the fluid to a fluid machine is given by this expression. V W1 U1 - VW2 U2 divided by G. While the nomenclature is like this, VW 1 and VW2, I repeat again are the tangential components of the fluid velocity at inlet and outlet of the machine and U1 and U2 are respectively the rotor linear velocity which is the tangential velocity of the rotor because of its rotation, angular motion, U1 and U2 at inlet and outlet.

And this we also showed can be written, same expression in a different fashion by splitting into various components like this. V1 square - V2 square + U1 square - U2 square + VR2 square - VR1 square. By the nomenclatures are V1 and V2 are the absolute velocity of the fluid at inlet and outlet of the machines respectively, with respect to a stationary frame of reference. U1 and U2 as I described the rotor velocities or the blade velocities at inlet and outlet, which is nothing but the radius of rotation times the angular velocity at the inlet and similarly that at the outlet.

And VR2 and VR1 are respectively the velocity of the fluid relative to the rotor blade which is moving with the velocity U1 and U2 at inlet and outlet. So VR2 is the velocity of the fluid at the outlet relative to the rotor and similarly VR1 is the velocity of the fluid at inlet relative to the rotor. And it was also recognised that these 2 terms, 1st of all this term V1 - V1 square - V2 square, this represents the change in the dynamic head because of the change in the absolute velocity of the fluid, that this change in the kinetic energy of the fluid dynamically.

And these 2 terms of the change in the static head, means change in the static or pressure head which is manifested in terms of changing pressure of the fluid which is termed as change in static head or change in the pressure head, that is the flow work, that is pressure energy, sometimes we speak loosely in fluid mechanics, pressure energy, that is per unit mass, per unit weight this is per unit weight, that is change in static head. So this is contributed by the change in the static head, this is contributed by the change in the dynamic head.

(Refer Slide Time: 3:47)



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

$$= \frac{1}{2g}\left[\underbrace{(V_1^2 - V_2^2)}_{\text{dynamic head}} + \underbrace{(u_1^2 - u_2^2) + (V_{r_2}^2 - V_{r_1}^2)}_{\text{change in static head}}\right]$$

Axial Flow Machines

$$(u_1^2 - u_2^2) = 0$$

$$u_1 = u_2$$

$$H = \frac{1}{2g}\left[(V_1^2 - V_2^2) + \underbrace{(V_{r_2}^2 - V_{r_1}^2)}\right]$$

Turbines: $V_{r_2} > V_{r_1}$

Axial Flow compressors $V_{r_2} < V_{r_1}$

V_f is small

V_a, V_w

So the total head delivered by the fluid is given by the change in its dynamic head and change in its static or pressure head, these 2 terms, that already we discussed. Now in relation to this we should now discuss the different types of machines depending upon the direction of flow. One is the axial flow machine. What is this axial flow machine? In axial flow machines, the main or bulk fluid, main direction of flow is in the axial direction where the bulk fluid moves in the axial direction.

There may be components of velocity in the tangential direction and radial direction but the main motion is in the axial direction. Okay. So, these types of machines can be shown like this, axial flow machines, let me draw this here, that let us… This is the rotor, this is the shaft which just… Which is moving, rotating with an angular speed omega, let us, this is a rotor and let us consider, I have, as I have told that rotor is a rotating disk on which the blades are mounted, this is the blade, R is the rotor and this B is the blade, the blades are mounted on it.

And this is also the rotor along with the blade is rotating, they are all mounted on the rotating shaft. Now in an axial flow machine, the flow is in almost the bulk flow is an axial direction like this. The flow takes place like this, that means the main flow is in the axial direction, that is the axial flow machines. Now here what happens, there is a tangential component also because when the fluid flows, so the blade is moving in the tangential direction, it has rotational motion, it has tangential component of velocity, it has mainly the axial component of velocity but the radial component of velocity is very less.

That means earlier it was shown that the radial component is VF is small, is negligibly small compared to the VA and VW, mainly the axial and tangential component velocities, component of velocities are there. Now what happens here you see the inlet and outlet of the fluid do not vary in their radial locations. Because that inlet takes place at all radial locations, the radial location varies, for example this is R1 inlet and this is R2 outlet, that means from the centre of rotations, the inlet, that even the root of this plate and tip of this blade, they vary in their radial location and therefore they vary in the velocity of U.

Here 1 and 2 are inlet and outlet, the nomenclature, now here if we consider this as the inlet 1 and if we give nomenclature 2 out at the outlet, you see at inlet, at 1, the fluid enters from all radial locations, similarly at 2, at outlet, fluid comes out from all radial locations. So therefore you see since the fluid velocity is assumed uniform over the entire blade height, we can say that the effect of U1, that is the effect of U rather than the blade velocity at inlet and outlet is not at all that because at any radius you see that if you follow a particular stream, the inlet and outlet is at the same U velocities because they are at the same radial locations.

So that means the radial locations vary from root to tip and this variation of radial location is same for the inlet and outlet flow which is uniform over the blade height. So therefore we can conclude that in such cases the effect of the change in the rotor velocity is not there. Usually in this, in these cases, the rotor velocity is defined at some mean height of the blade from the central axis, since the rotor velocity is varying from root to tip. So therefore for both inlet and outlet, rotor velocities are specified at a mean height.

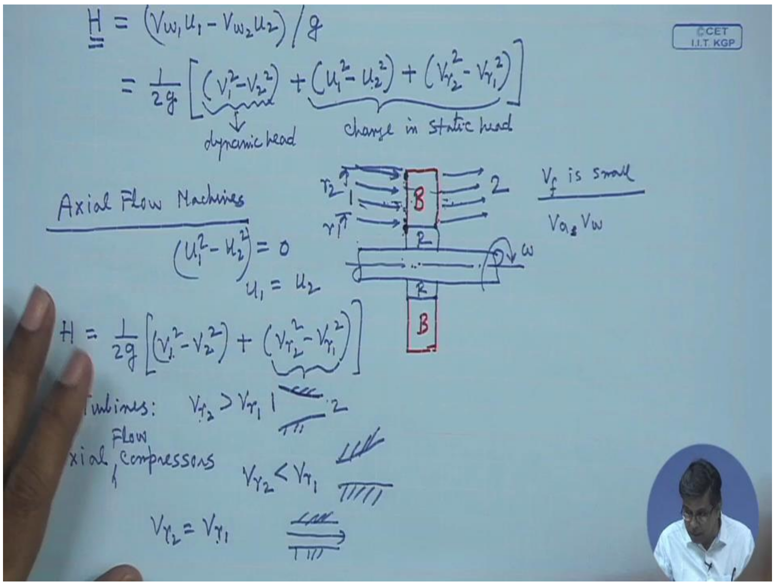
But here my intention of telling that in this case U1 square - U2 square, this term becomes 0. That means U1 equal to U2. If you define U1 at the main velocity and U2 at the main velocity, so therefore this term is 0 in this case. So in this case therefore H equals to, H equals to 1 by 2G V1 square - V2 square + VR2 square - VR1 square. Means that the static head contributed by the change in the rotor velocity is not there but this VR2 and VR1 may change and that change is caused by a change in the area of the flow passage or cross-sectional area of the flow in the axial direction.

Now in case of turbine, for turbine, what happens in case of turbine, this is H, that is the head delivered by the fluid, turbine H is positive, so therefore it turbines V1 is more than V2, that means the inlet fluid velocity is always more than the outlet velocity and to get a positive contribution from this side, that this static head we have to have VR2 greater than VR1. Which means the passage should be, blade pass it should be a converging type. That means it has gone verging passage will make the relative velocity at the outlet more than that at the inlet.

While in case of axial compressors, while in case of axial compressors where H is negative because head or the energy per unit weight is given to the fluid so, in that case this term is negative and in those cases, I mean compressors, the velocity at the inlet is more than the velocity at the outlet, okay. That means the fluid velocity is reduced and to have again a negative term from here to contribute to the head given to the fluid, we must have VR2 less than VR1 so that this term becomes negative.

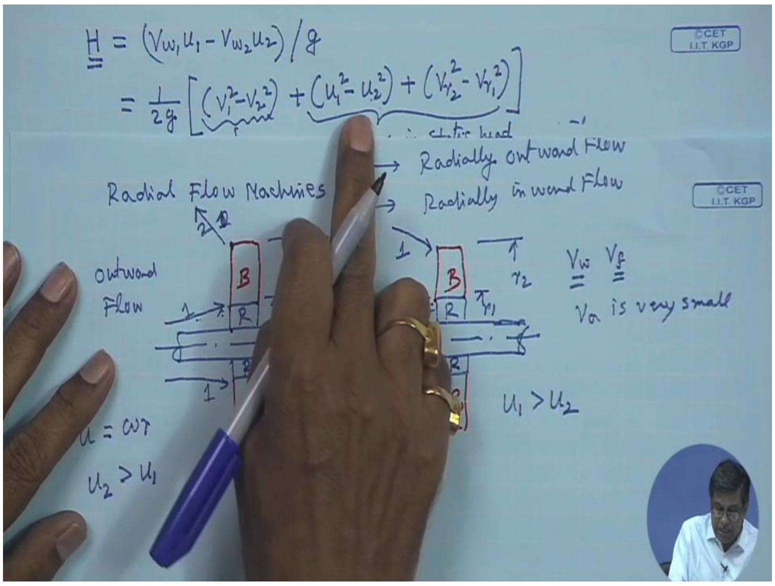
So the passages become divergent, so therefore in an axial flow machine, if we want to have this static head component, the blade passages should be either convergent or divergent. In case of turbine it will be convergent to make VR2 more than VR1 and in case of axial compressors, axial flow compressors, axial flow, it will be axial flow compressors, this will be diverted to make VR2 less than VR1.

(Refer Slide Time: 11:11)



But in a special case VR2 maybe made equal to VR1 which I will discuss after wards where there will be no contribution. That means the passage will be uniform, that means the plate passage, number of blades will be there, so blade passages will have only uniform professional area or flow area so that VR2 equal to VR1 and there will be no contribution from the static head at all. So the head interactions is only because of the change in the dynamic head.

(Refer Slide Time: 11:45)



Now next, another type of machines there which is known as radial flow machines. Now let us consider the radial flow machines. Radial flow machines. Radial flow machines. In radial flow machines the main direction of flow is in the radial direction. It has got very less component of axial flow velocity, radial flow velocity can be represented like that machines, that if this is the shaft, let us have a rotor like this and let us have a blade mounted on it, blade B mounted on it.

Now in a radial flow machine, there are 2 types, one is radially outward flow, radially outward flow machines, another is radially inward flow machine. The name suggests, as we understand that in radially outward flow machines, the flow is radial but it is outward, radially inward flow machines, the flow is radial but inward. Now radially outward flow machines, the inlet is at a lower radius and the outlet, radially outward, the outlet is like this. This is radially outward flow machines, this is outward flow, radially outward flow.

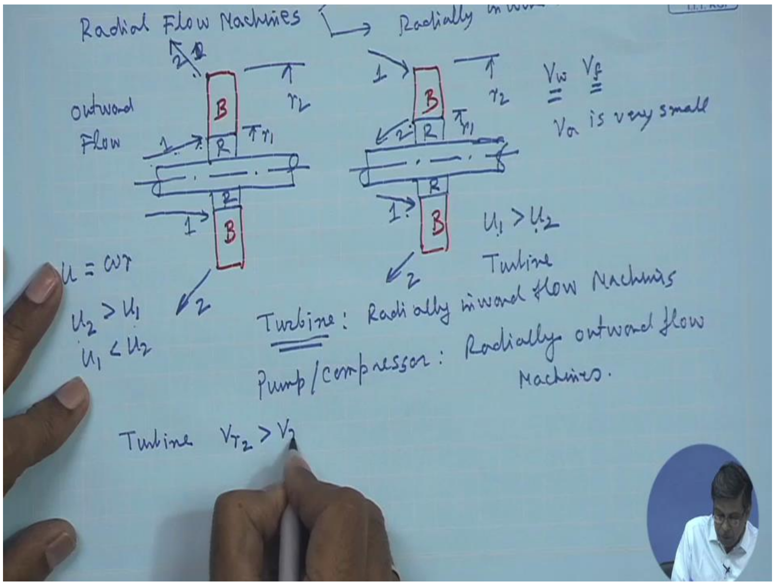
Similarly in a radially inward flow machine, what will be the picture? Radially inward flow machine, if you like to show this or you like to show it radially inward flow machines like this. This is the rotor, this is the rotor, so radially inward flow machine, if it is the blade, this is the blade, then radially inward flow machine, just the opposite, that means the fluid inlet is at a higher radius and comes by a lower radius. That means it is inward, inward and outward means, outward means away from the centre of rotation, inward means towards the centre of rotation.

So for the inward flow machine, the fluid inlet, this is inlet 1, this is, sorry this is inlet 1, this is outlet 2, inlet 1 outlet… Inlet and outlet are given by the suffix 1 and 2, given by the suffix 1 and 2. For inward flow, the inlet is at a higher radius and comes radially inward and goes out at a lower radius. So here what happens, the fluid has substantially VW and VF, that is the flow velocity or the radial component of velocity as I have shown earlier. So here VA is very small, VA is very small.

Now you see in this case what happens, in this case V1 - V2 square by 2, this dynamic head is there, and change in static head, U1 and U2, this component due to change in rotor velocity or blade velocity is very much there because U1 and U2 are varying, U1 and U2 are varying because the inlet and outlet is at a different radial position from the central axis. Now VR2 and VR1, I will come afterwards, that depends upon the change in the cross-sectional area of the flow passage.

Now with respect to U1 and U2, you see for outward flow, U1 is less than U2, this is because, this is that a lower radius of rotation, U is omega into R, so if this is R1 and the tip radius is R2, root radius is R1 and tip radius is R2, so here what happens, the tip velocity is more than the root velocity, so here what happens the U2 is greater than U1. Okay in this case U1 is greater than U2. Now consider a turbine, in case of turbine, consider a case of turbine.

(Refer Slide Time: 16:24)

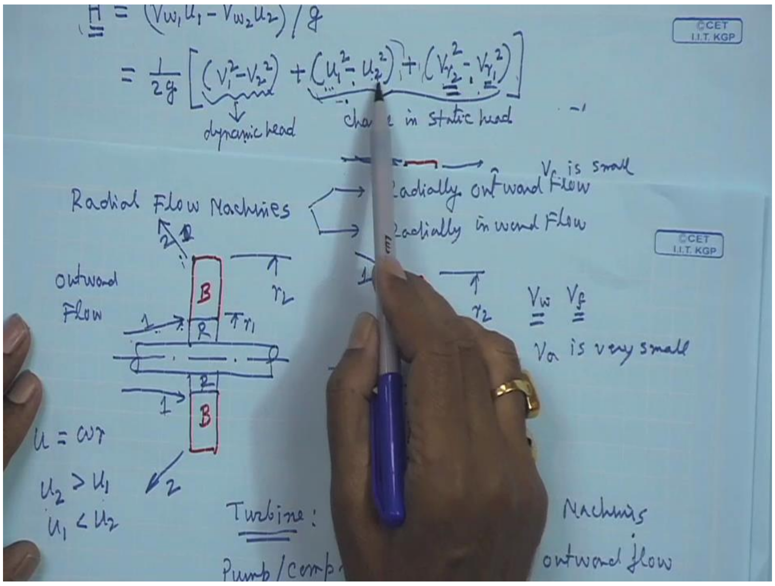


Now in case of turbine, we want this thing to be positive because turbine head is delivered by the fluid and this is the expression for head delivered by the fluid, so this is positive, in case of turbine, V1 is more than V2 as I have told. So if you want a positive value contribution from the centrifugal head which is manifested in terms of static head, U1 has to be more than U2. So therefore for a turbine, this will be radially inward flow, so this is for turbine, this is for turbine.

That means for turbine, it has to be radially, radially inward flow machine. The machine should be radially inward flow machine. Why, because in radially inward flow, it is inlet U1 will be more than the outlet U, that means U2 is less than U1, U1 is greater than U2, so this will be positive. But in case of a pump or compressor, this is the head given to the fluid, so this will be negative, this term will be negative, all the terms will be negative, V1 is less than V2, so that this is negative.

Similarly for a pump or compressor U1 and U2 should be such that this contribution should be negative, that means U1 should be less than U2, so in this case the fluid should throw radially outward so that the inlet U will be lower than the outlet U. That means here you see U2 is greater than U1 or you can write U1 is less than U2, so this is negative. So therefore for a pump or turbine, sorry, for a pump or compressor, sorry for a pump or compressor, the machine should, should be radially outward flow.

(Refer Slide Time: 18:56)



Now it is clear radially, why the turbines are radially outward flow machines and the pumps are made radially inward flow machines. Now along with that the velocity, relative velocity change also if you see, in case of turbine we also want a positive contribution from this, so VR2 has to be more than VR1. So for a turbine, again, for a turbine again, for a turbine again VR2 has to be greater than VR1. Why, because again the same logic that this should be positive, this head, static head should be positive.

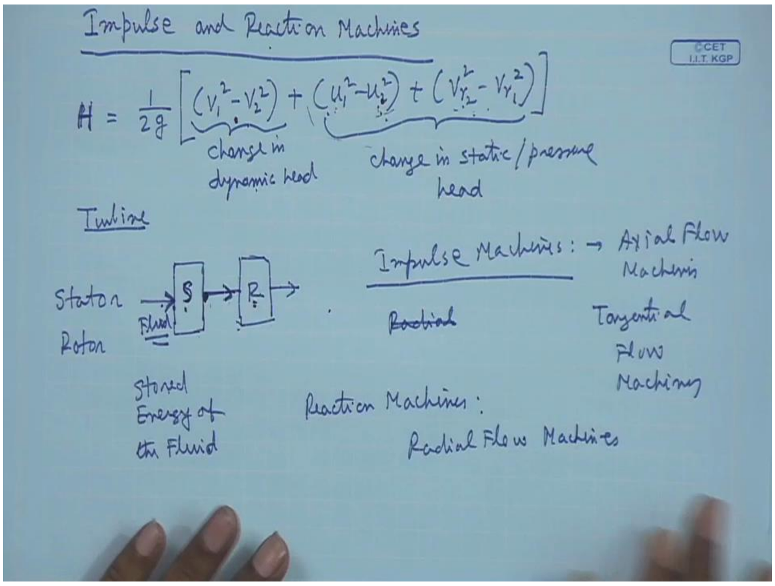
That means the flow passage should be convergent one, that means the blade should give a passage like this, the rotor blade. When for a turbine, this is coming like this, radially inward flow, it should go like that, the converging passage will increase the velocity relative to the blade so that VR2 is greater than VR1. So for a pump or compressor, it is just the reverse, so therefore for a pump or compressor, we want a negative value in this to have a contribution from this, all the terms should be negative so that H will be additive by the 3 terms with a negative sign means that head is giving to the fluid.

So therefore negative this means VR2 will be less than VR1, so VR2 will be less than VR1, in that case the pump, the should be a diverging type. That means the radially outward flow in this case, sorry, this diagram is wrong, so this should be the same diagram but the flow is radially outward. So in the direction of the flow, the passage is diverging, in the direction of the flow, this passage is converging.

So therefore our conclusion is that for its radial flow machine, there will be static head contributed by both the components, the centrifugal component, change in the rotor velocity change in the relative velocity of the fluid along with the change in the dynamic head. And for a turbine this is radially inward flow machine and the flow should be in a convergent passage, the blade passage should be convergent in the direction of flow so that both the terms should be positive.

Similarly in case of forms or compressor is, it will be radially outward flow, that means this term should be negative and at the same time the direction of the flow along the direction of the flow the blade passage should be diverging so that we get this part also negative, so that all the terms are additive and contributing together simultaneously in the head interactions, that means the head given to the fluid or head given by the fluid. So this concludes the discussions on axial flow and radial flow machines.

(Refer Slide Time: 21:26)



Now I will come to a very important thing, impulse and reaction machines. Impulse and reaction machines, reaction machines. Impulse and reaction machines. Now again I will write the same expression that H is 1 by 2G, let us write again this same thing V1 square - V2 square + again U1 square - U2 square + VR2 square - VR1 square with their nomenclature as defined. And this is the change in dynamic head, again I am writing this thing because they formula is very important in understanding all the fluid mechanical principles and these 2 terms together is change in static or pressure head, static or pressure head, static or pressure head.

Okay. Now there are machines where the static or pressure head is 0 while the fluid flows through the rotor and the head delivered by a turbine is giving, if you consider turbine, head delivered by the turbine is given only by the change in the dynamic head. Those machines are known as impulse machines where the change in the static and pressure head is 0, there is no change in the static or pressure head in a fluid machine. Now let us understand this thing in this way, let us consider a turbine.

Now in general a fluid machine, for example turbine consists of a stator S and a rotor R. S stands for stator and R stands for rotor. Now fluid first enters into, stator is a fixed component, rotor is the moving component. Here I am using the block diagram, in sequence of operation to show stator and rotor may not be side-by-side, it depends upon the flow configuration. In an axial flow machine, stator and rotor maybe side-by-side, in a radial flow machine, stator may be radially above or radially below the rotor which is rotating, that depends upon the flow direction, radially inward or radially outward.

In an axial flow machine, it should be side-by-side, but one thing, stator is always fixed, fixed to a casing, fixed casing but rotor is fixed to the shaft or the rotating drum, so rotor is in motion. So fluid 1st enters the stator, consider the turbine, then comes to the rotor, so in that sequence of operations I show this 1st comes to the stator and then to the rotor.

So 1st fluid enters in case of a turbine to the stator, the stored energy of the fluid, stored energy of the fluid which maybe in terms of its pressure, in terms of its thermal energy, in terms of its intermolecular energy because of its temperature, whatever may be the case, that is first being utilised in stator to create a high velocity, kinetic energy of the fluid along with a pressure, along with a high-pressure.

Now here one has to understand that is we want there should be no change in the rotor, if we design a machine where in the rotor there will be no change in static or pressure head, there are 2 ways we can do it. First we can exploit the impaired stored energy of the fluid at the inlet of the stator which comes in the form of fluid pressure or fluid temperature in kinetic energy utilising its entire pressure so that the pressure is to the atmospheric pressure.

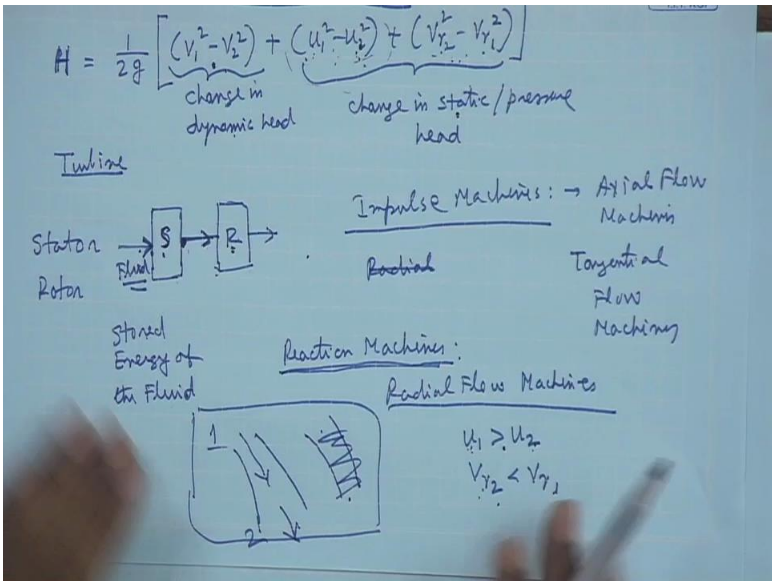
That means we totally expand the fluid up to atmospheric pressure and we make the rotor open so that there is no change in the pressure, the entire pressure is atmospheric pressure. Another way we can do it, that we may not expand it up to atmospheric pressure in the stator to exploit the stored energy of the fluid, in that case we have to make a casing in the rotor since the fluid is at a pressure higher than the atmospheric pressure but the flow passages should be made such that the fluid pressure should not change and it has to be an axial flow machine so that U1 and U2 changes should not be there.

So 2 ways we can think of such an impulse machine but in a reaction machine, both the kinetic energy change or change in dynamic head and the static or pressure head changes in the rotor. That means the stator should not expand up to atmospheric pressure and moreover the flow passages should not be uniform, that means the flow packages should be convergent or divergent to make a change in the relative velocity.

So therefore with this concept we see that impulse machine, impulse machine must have 2 things, that impulse machine, that is the flow areas has to be constant or it should, that means, it should be open if the fluid expanded up to the atmospheric pressure. So that the impulse machine will work on this. But a radial flow machine is always acts as a reaction machine, this is because even if you make the flow area constant in a radial flow machine to make VR2 VR1, but U1 U2, you cannot eliminate.

So therefore this thing is inevitable, the change in the centrifugal area, so therefore all radial flow machines, all impulse machines are usually therefore axial flow machines or there is another machines tangential flow machines, they cannot be radial flow machines, tangential flow machines which I will describe afterwards. But radial, but reaction machines are always radial flow machines, reaction machines are always radial flow machines okay. Reaction machines are always radial flow machines because this is inevitable.

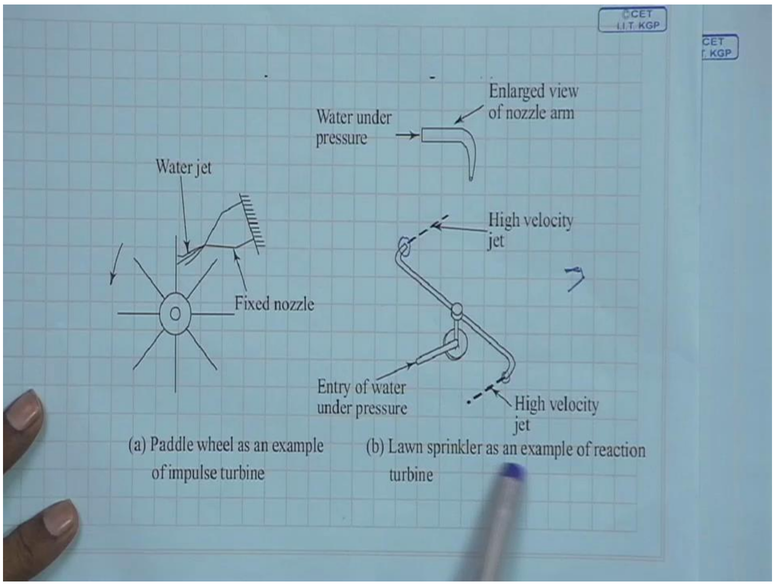
(Refer Slide Time: 28:17)



But nevertheless a theory you can tell that this may be counter way. For example you can make a fluid like this where if we make it like this that this is flowing in such a way that change in the U1 and U2 and VR2 and VR1 counterbalances each other, that means if U1 is greater than U2, that means this is positive and VR2 is less than VR1, that means this is negative, in a way that they balance together, that means what you have to do, U1 is greater than U2 means that your inlet will be at a higher radius than the outlet and VR2 is less than, means not this one, then we have to design like this, a diverging passage and a radially inward flow.

That is 1 and 2, in this case U1 is greater than U2, VR2 is less than VR1 in such a way that the passage will be designed, they counter each other. Or the opposite, U1 is less than U2 and VR2 is greater than VR1, that means the same passage with a opposite direction of flow, radially outward but this thing have never been done in practice, this cannot be done because of this thing independently contributing to the change in static pressure head, all radial machines, all radial flow machines are reaction machines. So that is the difference between impulse machines and reaction machines.

(Refer Slide Time: 29:53)



(a) Paddle wheel as an example of impulse turbine

(b) Lawn sprinkler as an example of reaction turbine

And let me show you an example of a reaction and impulse machine, let me show you an example of reaction and impulse machine. This will be a good example, that you see, this is an example of reaction and impulse machine, you see a paddlewheel which is rotating, this type of paddlewheel, this is rotating shaft and these are the blades of the paddlewheel. A nozzle is fixed by through which a waterjet is directed and is impinged on these blades surfaces.

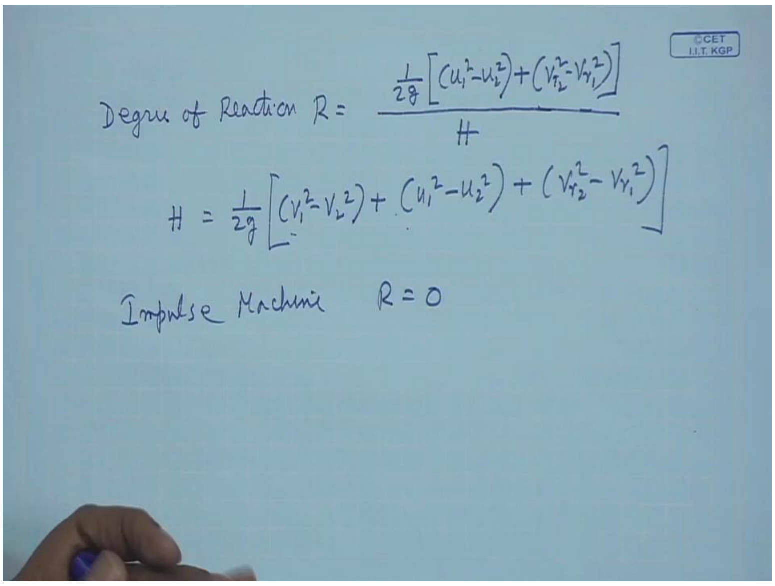
The nozzle is fixed the liquid, for example water enters at higher pressure. What is the function of the nozzle, they convert this pressure into high velocity waterjet and by impinging the jet, the jet impinges and flows along the blade and ultimately comes out with a low velocity and these blades rotate. So here what happens, this is the rotor, the paddlewheel is the rotor and we can consider nozzle as the stator.

So nozzle converts the stored energy of the fluid in terms of pressure at the beginning to a high velocity jet, whereas while it flows through the rotor, the work is done by the rotor or energy is delivered by the fluid to the rotor simply by the changing the dynamic head because there is no question of pressure change, pressure is already atmospheric, that means this has expanded, the nozzle and stator has expanded the fluid up to atmospheric pressure. This is a good example of a impulse machine, paddlewheel is an example of impulse machine.

Similarly on the other hand we see a lawn sprinkler. What happens at the entry of water comes at high-pressure and goes through that to arms, straight arm of the sprinkler at the end of which there is a nozzle which is these nozzles are converging nozzle, this is converging type of area. So the nozzles are converging passages, so what happens when the fluid passes through the nozzle, it changes its pressure to the ambient pressure. Changes its pressure and comes out at high velocity and because of the change in this angular momentum, if you make it free, the long sprinkler will rotate and you will get mechanical power.

So in this case what happens, the entire sprinkler acts as a rotor because this is rotating and developing power and this nozzle being a part and parcel of the rotor changes the fluid pressure, so therefore the both the change in the static head and dynamic head takes place. Why, the fluid is moving through this rotor. So this is an example of reaction turbine, long sprinkler as an example of reaction turbine. Okay.

(Refer Slide Time: 32:28)



Degree of Reaction $R = \dfrac{\frac{1}{2g}\left[(u_1^2-u_2^2)+(V_{r_2}^2-V_{r_1}^2)\right]}{H}$

$H = \frac{1}{2g}\left[(V_1^2-V_2^2)+(u_1^2-u_2^2)+(V_{r_2}^2-V_{r_1}^2)\right]$

Impulse Machine $R = 0$

And at the end I will tell you in a impulse and reaction machine to differentiate these 2, any machine we define a degree of reaction, we define degree of reaction as, degree of reaction R as the ratio of this change in static head. That means 1 by 2G change in the static head U1 square - U2 square + VR2 square - VR1 square divided by the change in the total head. Total head is what? It is 1 by 2G V1 square - V2 square + U1 square - U2 square + VR2 square - VR1 square.

Now for any reaction machine, all these 3 components are there but for an impulse machine, this is not there. That means for an impulse machine, numerator is 0, therefore for an impulse machine, for an impulse machine, the degree of reaction is 0. But for a reaction machine, degree of reaction is not 0 because this part is there. So how much of the total head delivered by the fluid is being contributed by the static head is the definition of degree of reaction. So for an impulse machine the degree of reaction is 0. So for any reaction machine we specify it by the degree of reaction and accordingly we design the stator and rotor blades. Okay. Thank you.