

Hydraulic Engineering
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Lecture – 09
Basics of fluid mechanics-II (contd.)

Welcome back in this lecture we are going to start elementary fluid dynamics or more commonly Bernoulli's equation. So, we are going to cover some basic derivation in this regard and then we proceed further to some of the solved examples.

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Bernoulli Along a Streamline

$-\nabla p = \rho a + \rho g \hat{k}$

$-\frac{\partial p}{\partial s} = \rho a_s + \rho g \frac{dz}{ds}$

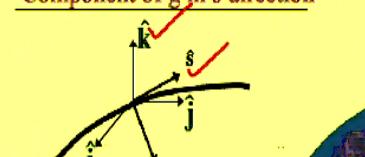
Separate acceleration due to gravity. Coordinate system may be in any orientation!

\hat{k} is vertical, s is in direction of flow, \hat{n} is normal.

Component of g in s direction

Note: No shear forces!
Therefore flow must be frictionless.

Steady state (no change in p wrt time)




So, we are going to see the Bernoulli along a stream line. So, if you remember this equation we had got from the in the last weeks lecture that is on fluid statics. So, if you I am just going to, you know, draw a stream line this is i direction, this is j direction and this is k direction, it is better to take away all the ink I should and this is the s direction is the streamline, I mean, the direction of the streamline and this is normal to the stream line.

So, we have to separate the acceleration due to gravity and coordinate axis here can be in any orientation. This is quite important to understand, k is vertical, s is in the direction of the flow and is normal to the flow that is our standard assumption that we have been taking. So, this equation when we start writing down, you know, in the component form, so, Δp in the s

$$-\frac{\partial p}{\partial s} = \rho a_s + \rho g \frac{dz}{ds}$$

direction will be

So, that is the component of g in s direction. So, we have to note that there is no shear forces there the flow must be frictionless. This is also a steady state so, there is no change in p with respect to time, p is pressure.

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Bernoulli Along a Streamline

$$-\frac{\partial p}{\partial s} = \rho a_s + \gamma \frac{dz}{ds}$$
 Can we eliminate the partial derivative?

$$a_s = \frac{dV}{dt} = \frac{\partial V}{\partial s} \frac{ds}{dt} = \frac{\partial V}{\partial s} V$$
 Write acceleration as derivative wrt s

$$dp = \frac{\partial p}{\partial s} ds + \frac{\partial p}{\partial n} dn$$
 (n is constant along streamline, $dn=0$)

$$\therefore \frac{\partial p}{\partial s} = \frac{\partial p}{\partial s}$$
 and $\frac{dV}{ds} = \frac{\partial V}{\partial s}$

$$-\frac{\partial p}{\partial s} = \rho V \frac{dV}{ds} + \gamma \frac{dz}{ds}$$

So, the equation that we have obtained

$$-\frac{\partial p}{\partial s} = \rho a_s + \gamma \frac{dz}{ds}$$

or

$$-\frac{dp}{ds} = \rho V \frac{dV}{ds} + \gamma \frac{dz}{ds}$$

And this is obtained through this way of doing this, you know, this differentiation is called the chain rule, write acceleration as a derivative with respect to s . So, the total change in pressure can be written as dp is $\delta p / \delta s$ into ds + $\delta p / \delta n$ into dn . So, n is constant along the stream line so, $dn = 0$. Therefore, this term goes so, dp / ds can be written as $\delta p / \delta s$, you see. Now, this is the total and this is the partial that is why we are able to write this and dv / ds is written $\delta v / \delta s$.

So, this equation turns out to be $-dp / ds$ because this is what we have proved from here, and dv / ds as $\delta v / \delta s$ or the opposite. So, we can write $\rho V dv / ds + \gamma dz / ds$, a_s is $V \delta v / \delta s$ and instead of $\delta v / \delta s$ we can write dv / ds . So, this is the equation.

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Integrate F=ma Along a Streamline

$$-\frac{dp}{ds} = \rho V \frac{dV}{ds} + \gamma \frac{dz}{ds} \quad \text{Eliminate } ds$$

$$dp + \rho V dV + \gamma dz = 0 \quad \text{Now let's integrate...}$$

$$\int \left(\frac{dp}{\rho} + \int V dV + g \int dz \right) = 0 \quad \text{But density is a function of } \underline{\text{pressure}}.$$

$$\int \frac{dp}{\rho} + \frac{1}{2} V^2 + gz = C_p \quad \text{If density is constant...}$$

$$p + \frac{1}{2} \rho V^2 + \gamma z = C_p$$

Bernoulli Equation along a Streamline



Now, we have to use force is equal to mass into acceleration along a streamline and integrate it. So, this is the equation that we have, so, what do we do? We integrate it, first eliminate ds because it is common so, we can write $dp + \rho V dv$, because dp will come this side + $\gamma dz = 0$ and if we integrate, this will become dp . So, what we do is we divide by, you know, ρ so that this γ becomes z it will become $dp / \rho + V dv + g \int dz = 0$.

Here, the density is a function of pressure so, we have to keep it inside so, we write integral $dp / \rho + V^2 / 2 + gz = \text{constant}$. If density is constant we can write

$$p + \frac{1}{2} \rho V^2 + \gamma z = C_p$$

So, what we have done so, we have written the equation along the stream line, applied force is equal to mass into acceleration along the streamline integrated it and we have obtained Bernoulli's equation along a stream line. This is one of the ways of the derivation.

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Bernoulli Equation

- Assumptions needed for Bernoulli Equation
 - Frictionless ✓
 - Steady ✓
 - Constant density (incompressible) ✓
 - Along a streamline ✓
- Eliminate the constant in the Bernoulli equation?
 - Apply at two points along a streamline.
- Bernoulli equation does not include
 - Mechanical energy to thermal energy ✓
 - Heat transfer, Shaft Work



Now, the Bernoulli equation, the assumptions that are needed for Bernoulli's equation, what have we assumed, the flow was frictionless, the flow was steady, the final equation that we have derived we have assumed, constant density that means the flow was incompressible and we have done it for along a streamline. Now, can we eliminate the constant in Bernoulli's equation? Yes, if we apply the Bernoulli's equation at 2 points along a streamline, this is important so, the streamline should be the same and if we apply this equation along two streamline, I mean, to 2 points along a streamline the constant would be the same and therefore, it can be eliminated. Bernoulli equation does not include mechanical energy to thermal energy conversation, heat transfer or shaft work. So, this is some general information about the Bernoulli equation that you might be aware of from before.

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Bernoulli Equation

The Bernoulli Equation is a statement of the conservation of Mechanical Energy

$$\frac{p}{\rho} + gz + \frac{1}{2}V^2 = C_p$$

p.e. k.e.

$$\frac{p}{\gamma} + z + \frac{V^2}{2g} = C_p$$

Pressure head Hydraulic Grade Line ✓ HGL
Elevation head Piezometric head ✓ EGL
Velocity head Energy Grade Line ✓ EGL
 $\frac{V^2}{2g} = \frac{p}{\gamma} + z = \frac{p}{\rho} + gz + \frac{V^2}{2g} = \frac{C_p}{\rho}$ Total head ✓



Now, the Bernoulli equation is a statement of conservation of mechanical energy. So, you see

$$\frac{p}{\rho} + gz + \frac{1}{2}V^2 = C_p$$

So this is potential energy. So, let me take the eraser. And this is let it this is kinetic energy. I will take down the ink again. So, $P / \rho + z + V^2 / 2g = C_p$, where P / ρ is the pressure head, z is the elevation head and $V^2 / 2g$ is the velocity head. We can also say that $P / \rho + z$ is hydraulic grade line HGL, very common concept in your fluid mechanics class, or piezometric head, whereas, $P / \rho + z + V^2 / 2g$ is called energy grade line EGL or total head. This is something that you can be asked, you know, by anyone whether you are giving, I mean, a gate exam or an interview sitting for a company which works in hydraulics. So, you must be remembering what hydraulic grade line is, what is energy grade line, what is piezometric head, what is total head.

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Bernoulli Equation: Simple Case ($V=0$)

- Reservoir ($V=0$)
 - Put one point on the surface, one point anywhere else

$$\frac{p}{\rho} + z + \frac{V^2}{2g} = C_p$$

$$\frac{p}{\rho} + z_1 = \frac{p_2}{\rho} + z_2$$

$$z_1 - z_2 = \frac{p_2}{\rho}$$

We didn't cross any streamlines so this analysis is okay!
Same as we found using statics

So, now, proceeding forward first simple case, very simple case, where $V = 0$. So, there is point 1 and there is point 2, z direction is shown as above, you know, this is pressure datum and this is elevation datum. Reservoir means $V = 0$. So, now, as I said this point 1 has been put on surface and we can put point 2 anywhere we have decided to put at this random point, point 2, point number 2.

So, we apply the Bernoulli equation between these 2 points. So, in the reservoir the velocity is 0. So, $V^2 / 2g$ is going to be eliminated here. So, the between these 2 points we can write $P_1 / \rho + z_1 = P_2 / \rho + z_2$, whatever it is going to be, we also know

that p_1 is a gauge pressure and this is a pressure datum atmospheric pressure, so, p_1 will be 0. In our second case, so, we can write $z_1 - z_2 = P_2 / \gamma$.

Because elevation datum is here, so, 2 is anywhere. Here, we did not cross any stream line so this analysis is okay. If we keep crossing the stream lines, then what happens is this equation is valid for 2 points on the same stream lines; you cannot cross the stream lines. So, this analysis $z_1 - z_2 = P_2 / \gamma$. This is exactly the same analysis, which we have found using the statics lecture, if you remember from last week.

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Bernoulli Equation: Simple Case ($p = 0$ or constant)

- What is an example of a fluid experiencing a change in elevation, but remaining at a constant pressure? Free jet

$$\cancel{\frac{p}{\gamma}} + z_1 + \frac{V_1^2}{2g} = \cancel{\frac{p}{\gamma}} + z_2 + \frac{V_2^2}{2g}$$

$$z_1 + \frac{V_1^2}{2g} = z_2 + \frac{V_2^2}{2g}$$

$$V_2 = \sqrt{2g(z_1 - z_2) + V_1^2}$$



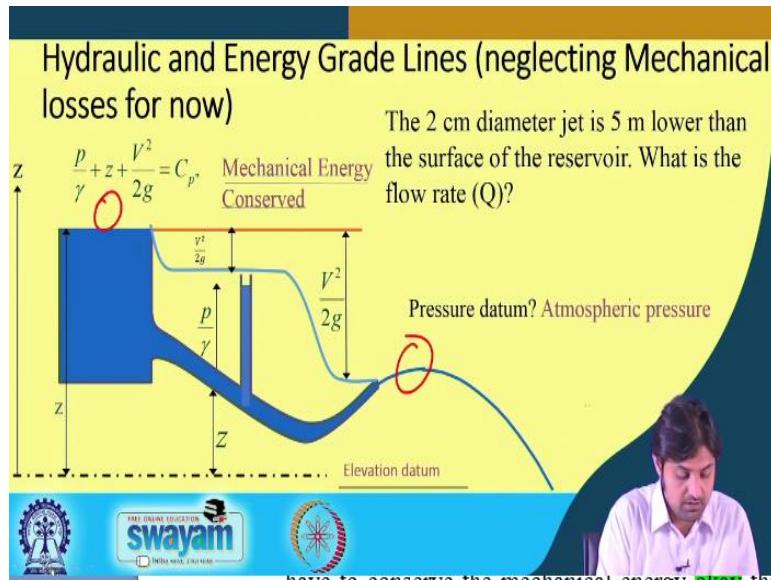
So, proceeding forward, so, we take another simple case, where pressure is 0 or constant. What is an example of fluid experiencing a change in elevation but remaining at a constant pressure? It is an example is a free jet. What is a free jet? This can be taken as a free jet, you fill a bottle with water or any fluid and make many holes, we saw similar type of figure last week as well and you see there are, you know, jets of, I mean, the free jets, this one, this one, this one, this one as well. I will delete that.

So, the equation, Bernoulli's equation along 1 streamline will be $p_1 / \gamma + z_1 + V_1^2 / 2g$ will be = at any point two same, $p_2 / \gamma + z_2 + V_2^2 / 2g$. Because this is atmospheric pressure at 0.1, we assume, the 0.1 to be the free surface there. So, pressure at 0.1 will be atmospheric therefore, 0. Similarly, if we consider any point along the stream line what is going to happen is p_2 also exposed to atmosphere and that is also 0.

So, we can write $z_1 + V_1^2/2g = z_2 + V_2^2/2g$ and therefore, the velocity at point 2 will be $V_2 = \sqrt{2g(z_1 - z_2) + V_1^2}$

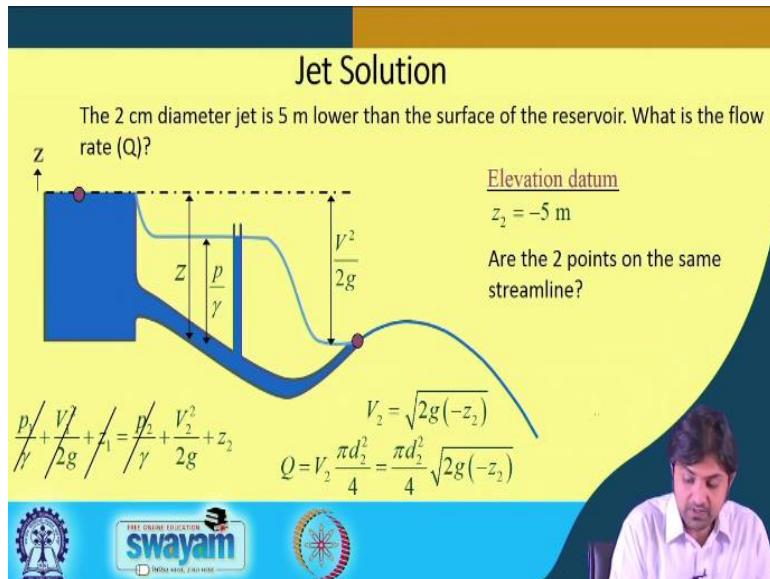
where V_1 can be the velocity for velocity of the surface.

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So, we talked about but if we talk about hydraulic and energy grade lines, the question is the 2 centimeter diameter jet is 5 meter lower than the surface of the reservoir, what is the flow rate Q ? Let us draw a figure like this. So, this is the elevation datum here. So, the equation Bernoulli equation is $p/\gamma + z + V^2/2g = \text{constant}$. We this is we have to conserve the mechanical energy that is the energy conservation. So, to make this less cluttered will delete these annotations. So, pressure datum is atmospheric pressure, very simple, both at the out at here or here.

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So, the jet solution, so, the question again coming back to the question, the 2 centimeter diameter jet is 5 meter lower than the surface of the reservoir. What is the flow rate Q? Again drawing the same figure, this is the elevation datum, therefore, z_2 is 5 meter below that is what it says, 5 meter lower are the 2 points on the stream streamline? Yes. So, we can write $p_1 / \gamma + V_1^2 / 2g + z_1 = p_2 / \gamma + V_2^2 / 2g + z_2$ so, these are the 2 points just that if you are confused.

So, $p_1 / \gamma + V_1^2 / 2g + z_1 = p_2 / \gamma + V_2^2 / 2g + z_2$, p_1 / γ will be 0, there is no velocity and, I mean, this is at rest. So, the velocity is also 0 and then the datum is also 0 because we have set the elevation datum here. The pressure at 2 will also be 0 atmospheric pressure, now, there will be a velocity and because there is z_2 , so V_2 will be $\sqrt{2g - z_2}$ and the discharge will be $\pi d_2^2 / 4$, if d is the diameter 2 centimeter diameter jet it says, $\sqrt{2g - z_2}$ very simple applications, but it is important to, you know, apply to these cases.

So, this is our 2 results, you know, V_2 and z_2 is -5 , so, you can obtain the, it will be approximately 10 meters per second. For example, if you assume g as, if you take 10 meters per second square, V_2 will be $\sqrt{2 \times 10 \times -5}$, so, that means, $+5 \times 10$. So, V will come out to be 10 meters per second.

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Bernoulli Equation Application: Stagnation Tube

- What happens when the water starts flowing in the channel?
- Does the orientation of the tube matter? Yes!
- How high does the water rise in the stagnation tube?
- How do we choose the points on the streamline?

$$\frac{p}{\gamma} + z + \frac{V^2}{2g} = C_p$$

Stagnation point

So, one of the other applications of Bernoulli equation is the stagnation tube. What happens when the water starts flowing in the channel? For example, this and so, the equation along the stream line by Bernoulli equation will be given as $p / \gamma + z + V^2 / 2g = \text{constant}$. Here, the orientation of the tube is like this, but does the orientation of the tube matter? Yes, because it can either lower up, I mean, it can change the different value of z so, yes. How does high does the water rise in this stagnation tube that we have to calculate. How do we choose the points on this timeline, another important question that we will solve?

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Bernoulli Equation Application: Stagnation Tube

- 1a-2a $V = f(\Delta p)$
 - Same streamline
- 1b-2a $V = f(\Delta p)$
 - Crosses || streamlines
- 1a-2b $V = f(z_2)$
 - Doesn't cross streamlines

$$\frac{p}{\gamma} + z + \frac{V^2}{2g} = C_p$$

1a 2a 1b 2b

$\frac{p}{\gamma} + z + \frac{V^2}{2g} = C_p$

In all cases we don't know p_1

$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g}$$

$$\frac{V_1^2}{2g} = z_2$$

$$V_1 = \sqrt{2gz_2}$$

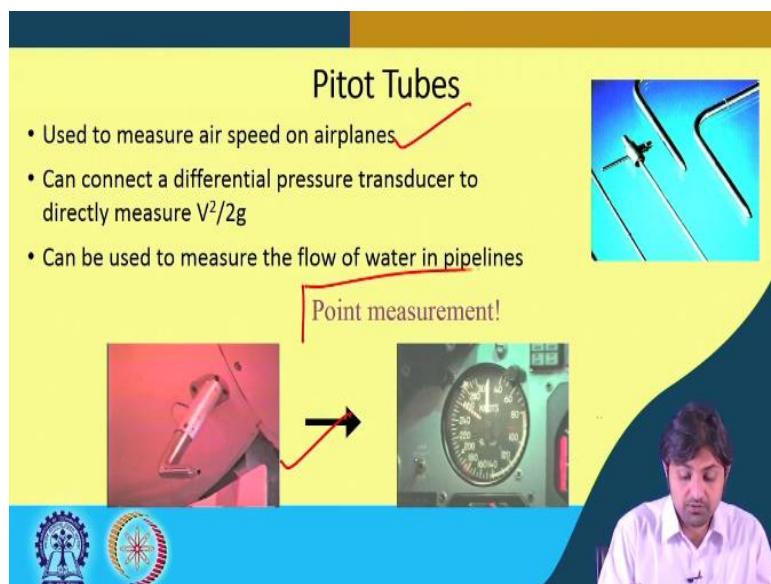
So, we assume, points 1a, 2a, 1b and 2b like this, this point, this point, this point and this point. The equation, Bernoulli equation will be the same $p / \gamma + z + V^2 / 2g = \text{constant}$. So, if you go from 1a to 2a, velocity will be a function of pressure, it is the same stream line; 1a is going to 1a to 2a, if you go from 1b to 2a it crosses perpendicular stream

lines. If you go from 1a to 2b, it does not cross the stream lines, going from 1a to 2a does not cross the stream line.

In all cases, what we do not know is p_1 . So, the equation, Bernoulli equation $p_1 / \gamma + z_1 + V_1^2 / 2g$ is constant. So, $p_1 / \gamma + z_1$ is going to be, we can set it as 0 at 0.1 and because this is exposed to atmosphere we can assume to be 0 and because this has reached at the top what happens is, there will be no velocity because the water will have high rise until the maximum, you know, that it can and there the velocity will be 0.

So, we can simply write, $V_1^2 / 2g$, so, the velocity that is there will be $= 2g z_2$ or $V_1 = 2g z_2$. So, this is the velocity or if we know the velocity there we can estimate z_2 that is how the water is going to rise in the stagnation tube.

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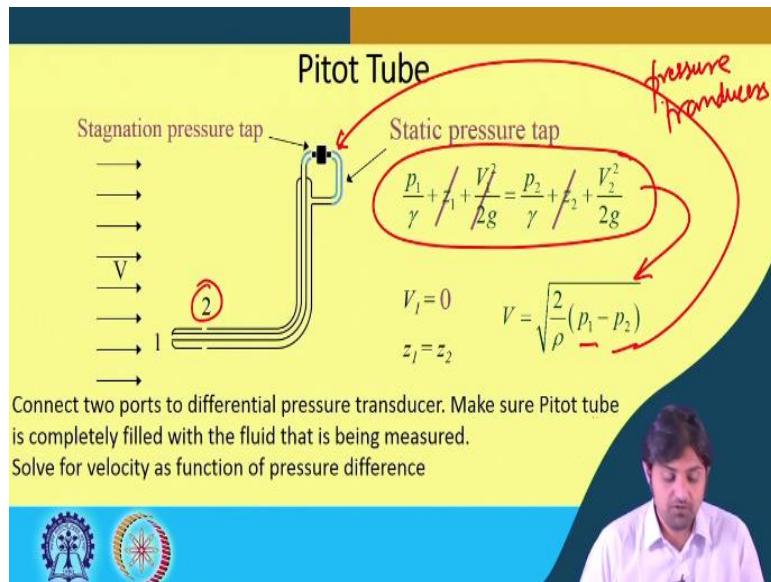


Now, there is another thing pitot tube, which is used to measure the flow velocities in an aero plane as well. So, this is how a pitot tube looks like. It is used to measure air speed on aero planes. It is very old technique but still very successfully this is used for measuring the air speed on an airplane. It can connect differential pressure transducers to measure the $V^2 / 2g$ because Bernoulli equation has $V^2 / 2g$. So, what it does is measures $V^2 / 2g$ and therefore tells the airspeed.

It can be used to measure the flow of water in pipelines also pitot tube. So, this is something like this, it looks something like this, in an aero plane, so this is fixed in the aeroplane. So, this is, it shows this how many knots are there, I mean, the typical panel of the aero plane

speed. An important thing to note is, this is a point measurement because Bernoulli principle is applied at different points along a stream line this is important to note.

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So, pitot tube, so, there is a velocity V , there is 0.1 here and 0.2 here. So, connect 2 ports to a differential pressure transducers. Make sure that the pitot tube is completely filled with the fluid that is being measured. Solve for velocity as a function of pressure difference. This is stagnation pressure tap, this is static pressure tap. So, what it does is it measures pressure at 0.1 at 0.2. And so, the Bernoulli equation says $p_1 / \gamma + z_1 + V_1^2 / 2g$ is constant. So, here, z_1 is, you know, is 0 at 0.1.

We assume, that is the datum and because it is a stagnation point, the velocity at 1 will also be = 0. Because this is also at the point 2 is also here, where datum is 0, that z_2 is also = 0. So, V_1 is 0 and $z_1 = z_2$ that is why we have done this. So, V that is measured here is a difference of pressure and is equal to V is equal to using this equation we get this and p_1 and p_2 are measured using this pressure transducers. So, this is how the pitot tube works or functions.

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Relaxed Assumptions for Bernoulli Equation

- Frictionless (velocity not influenced by viscosity)
Small energy loss (accelerating flow, short distances) ✓
- Steady
Or gradually varying ✓
- Constant density (incompressible)
Small changes in density ✓
- Along a streamline
Don't cross streamlines *cross a streamline
constant C*

So, there, I mean, there are some relaxed assumptions for Bernoulli equation, I mean, ideally but Bernoulli equation should be applied for the assumptions that we had discussed a couple of slides ago. But there could be some relaxed assumptions for Bernoulli equation. For example, frictionless, that the velocity is not influenced by viscosity, so, there is if the flow is not frictionless there will be some energy loss accelerating flow.

For example, at short distances there we can apply a steady flow or we can also use gradually varying flow. Constant density incompressible, so, if we have very small changes in density then also we can apply Bernoulli's equation, it will not be the exact, but approximately equal and we have to use it along a stream line and but this cannot be relaxed, we cannot cross a stream line because the constant C will change and therefore, Bernoulli's equation will no longer be valid.

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Bernoulli Normal to the Streamlines

$$-\frac{\partial p}{\partial n} = \rho a_n + \rho g \frac{dz}{dn}$$

$$a_n = \frac{V^2}{R}$$

R is local radius of curvature
n is toward the center of the radius of curvature

0 (s is constant normal to streamline)

$$dp = \frac{\partial p}{\partial s} ds + \frac{\partial p}{\partial n} dn$$

$$-\frac{dp}{dn} = \rho \frac{V^2}{R} + \rho g \frac{dz}{dn}$$

$$\therefore dp/dn = \partial p / \partial n$$



So, another concept is Bernoulli's equation normal to the stream lines. We have seen along the streamline, now the other is normal to the stream line. So, we have seen this in the previous, you know, when we are dealing with the Bernoulli's equation along the stream line. So, similarly, we can write minus the force equation we can write, $-\Delta p / \Delta n + \rho a_n + \rho g dz / dn$. Here, a_n is V^2 / R , where, R is the local radius of curvature, n is towards the center of the radius of curvature and this is equal to 0, s is constant along the stream line.

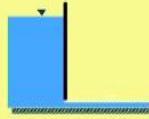
So, therefore, proceeding in a similar way, we obtain $dp = \partial p / \partial s \cdot ds + \partial p / \partial n \cdot dn$, you remember, we had the same along the stream line $ds = 0$ because and we can write $dp / dn = \partial p / \partial n$. So, what happens is we get $-\Delta p / \Delta n = \rho V^2 / R + \rho g dz / dn$ because we can write $\partial p / \partial n$ is equal to and we obtained this from this, so, this equation becomes this, the same procedure, no changes whatsoever.

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Bernoulli Equation Applications

- Stagnation tube
- Pitot tube
- Free Jets
- Orifice
- Venturi
- Sluice gate
- Sharp-crested weir

Applicable to contracting streamlines ([accelerating](#) flow).



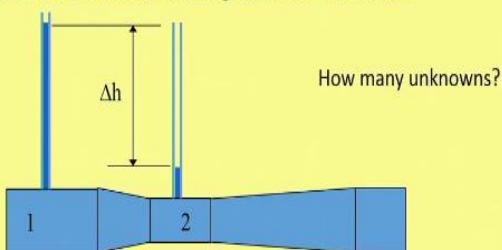
So, this is the equation we are not going into too much detail about this, but this is how you can have the Bernoulli equation normal to the streamlined. So, you see when you integrate this, this will have a different consequence. So, now the Bernoulli's equation applications; 1 is stagnation tube that you have already seen, the other was pitot tube which we discussed, the free jets equation we have seen.

We have not seen orifice, but orifice is one of the other areas where Bernoulli's equation is there. Venturi meter, the Bernoulli's equation is applied across sluice gate and sharp crested weir, this is how a Venturi meter looks like, this is how a sluice gate. So, these actually are all, you know, practical places where Bernoulli's equation can be applied. So, I will take this one and these are applicable to the contracting streamlines accelerating flow.

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Example: Venturi

How would you find the flow (Q) given the pressure drop between point 1 and 2 and the diameters of the two sections? You may assume the head loss is negligible. Draw the EGL and the HGL over the contracting section of the Venturi.



One of the examples as I said, we had not seen was venturi meter, how would you find the flow Q given the pressure drop between point 1 and 2 and the diameter of the 2 section? You may assume the head loss is negligible. Draw the EGL and the HGL over the contracting section of the venturi metre? So, this is the venturi meter, the water will rise depending upon the pressure. How many unknowns what equations are you going to use? Those are the questions.

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Example Venturi

$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g}$$

$$\frac{p_1 - p_2}{\gamma} = \frac{V_2^2 - V_1^2}{2g}$$

$$\frac{p_1 - p_2}{\gamma} = \frac{V_2^2}{2g} \left[1 - \left(\frac{d_2}{d_1} \right)^4 \right]$$

$$V_2 = \sqrt{\frac{2g(p_1 - p_2)}{\gamma \left[1 - \left(\frac{d_2}{d_1} \right)^4 \right]}}$$

$$Q = C_d A_2 \sqrt{\frac{2g(p_1 - p_2)}{\gamma \left[1 - \left(\frac{d_2}{d_1} \right)^4 \right]}}$$

$$Q = C_d A_2 \sqrt{\frac{2g(p_1 - p_2)}{\gamma \left[1 - \left(\frac{d_2}{d_1} \right)^4 \right]}}$$

$$V_1 A_1 = V_2 A_2$$

$$V_1 A_1 = V_2 A_2$$

$$V_1 \frac{\pi d_1^2}{4} = V_2 \frac{\pi d_2^2}{4}$$

$$V_1 d_1^2 = V_2 d_2^2$$

$$V_1 = V_2 \frac{d_2^2}{d_1^2}$$

for practical problems

So, the first thing that we can do is, we apply at points at 2 points we apply the Bernoulli's equation. So, we take the pressure p_1 p_2 on one side $z_1 = z_2$, so, that will be $p_1 / \gamma - p_2 / \gamma = V_2^2 / 2g - V_1^2 / 2g$. As you see the point 1 and 2 the datum is same that is why we were able to cancel this 1 out and $Q = \text{velocity into area } V_1 A_1 = V_2 A_2$. So, $V_1 \pi d_1^2 / 4 = V_2 \pi d_2^2 / 4$. So, $V_1 d_1^2 = V_2 d_2^2$ just continuing with this thing, so, $V_1 = V_2 d_2^2 / d_1^2$.

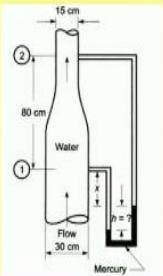
Normally, we know d_1 and d_2 . So, there is a relationship obtained between V_1 and V_2 . So, putting V_1 in terms of V_2 , so, we can instead of V_1 obtained from here, we can put here and therefore, we can get this equation here, you know. Therefore, on writing V_2 we can get $2g p_1 - p_2 \gamma 1 - d_2^2 / d_1^2$ to the power 4 and Q simply we multiply this with $V_1 A_1$.

We have this account this term C_d , that is, for, you know, practical problems and I know practical problems. There is a coefficient that you determine in experiments but anyways this is the theoretically this is the main method p_1 and p_2 you can obtain from how much the pressure water has risen into the.

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Practice Problem

Water flows up a tapered pipe as shown in Fig. below. Find the magnitude and direction of the deflection h of the differential mercury manometer corresponding to a discharge of 120 L/s. The friction in the pipe can be completely neglected.



So, this is the question, water flows up a tapered pipe as shown in figure below. Find the magnitude and direction of the deflection h of the differential mercury manometer comprising to a discharge of 120 liters per second. The friction in the pipe can be completely neglected. I think we should stop the class for today now, and resume our next class by solving this practice problem. Thank you so much. See you in the next class.