Chemical Process Instrumentation
Prof. Debasis Sarkar
Department of Chemical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 41
Flow Measurement

Welcome to lecture 41. So, this is week 9 and we will start today flow measurement. So, in this week, we will talk about measurement of flow measurement of liquid flow or measurement of gas flow is important in many chemical process industries. It is particularly important when you look at operations or manufacturing processes that happen continuously.

For continuous operating processes there will always the flow of raw materials, products, waste utilities, etcetera and it is very important that we will be able to measure as accurately as possible the flow of liquid streams or gas streams in several chemical process industries.

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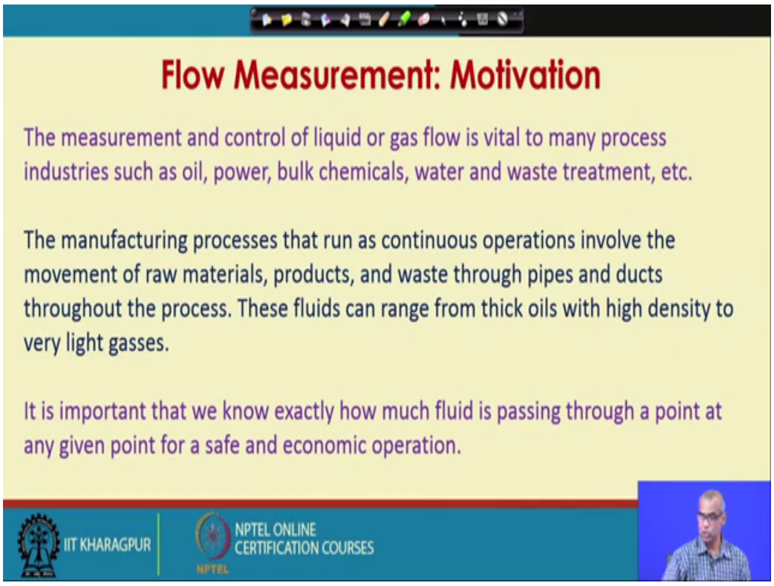

So, the motivations for flow measurement are as follows the measurement and control of liquid or gas flow is vital to many process industries such as oil, power, bulk chemicals, water and waste treatment, etcetera. The manufacturing processes that run as continuous operations involve the movement of raw materials products waste through pipes and ducts throughout the process these fluids can range from thick oils with high density to very light gases. It is important that you know exactly how much fluid is passing through a point at any given point for a safe and economic operation.

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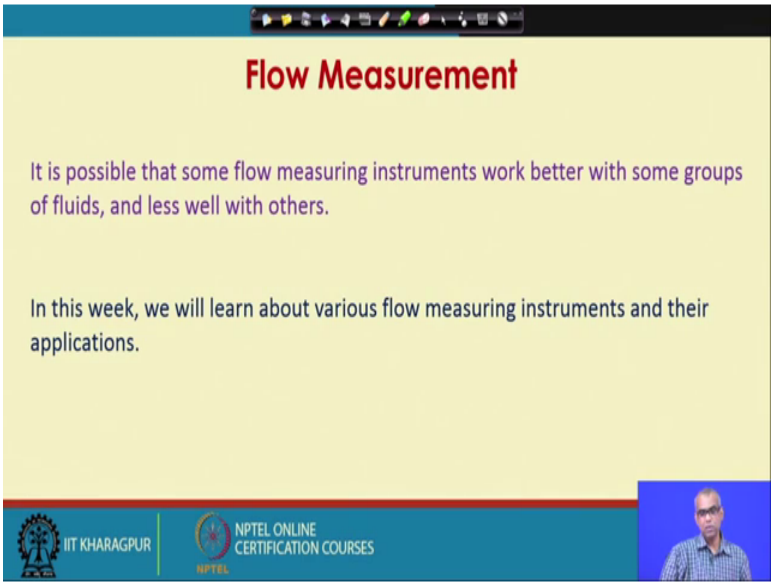

It is possible that some flow measuring instruments work better with some groups of fluids and less well with others, it is obvious because you will be handling fluids which will vary from say very thick to very light. So, there will always be flow measuring instruments which will work better with some group of fluids and less well with others in this week we will learn about various flow measuring instruments and their applications.

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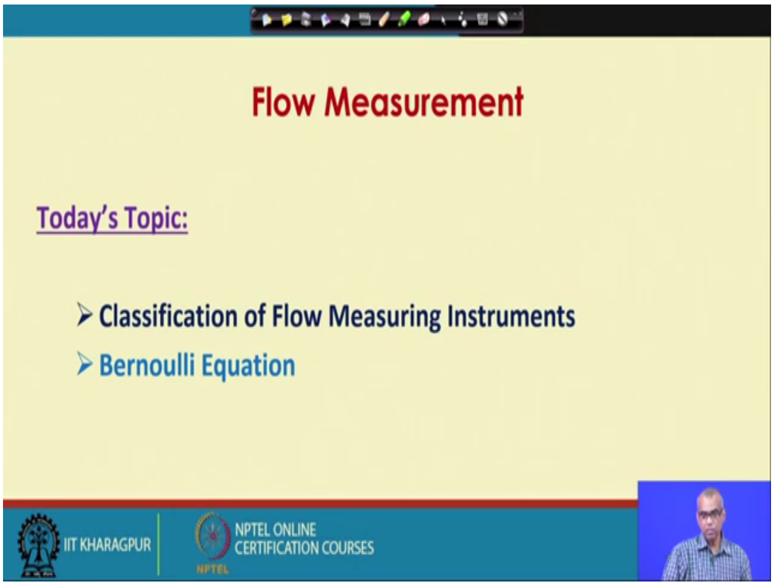

So, today we will classify various flow measuring instruments and then we will talk about an important principle on which a certain class of flow measuring instruments are designed this is known as Bernoulli's principles. So, we will talk about Bernoulli's equation.

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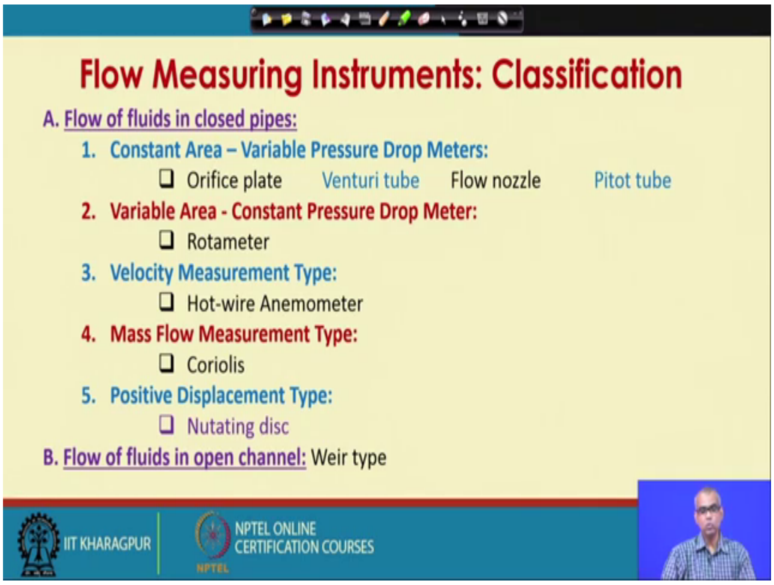

This is how we classify various flow measuring instruments again this is not the only classification that is available, I have been saying this for all measuring instruments because there are various ways of classifying the instruments into different categories and what you see on the screen is one possible way of classifying the flow measuring instruments and we will follow this classification for the purpose of this course, broadly, I classify the flow measuring instruments into two categories one is flow of fluids in closed pipes another the flow of fluids in open channel. Of course, flow of fluids in closed pies finds many more applications and under flow of fluids in closed pipes, we have classified various flow measuring instruments under two different categories.

First constant area variable pressure drop meters under this we will talk about orifice plate Venturi tube, Flow nozzle and Pitot tube, then we have variable area constant pressure drop meter and we will talk about rotameter third velocity measurement type we will talk about hot wire anemometer, then mass flow measurement type we will talk about Coriolis flow meter and then positive displacement type we will talk about Nutating disc.

Under flow of fluids in open channel we will talk about wire types flow meter.

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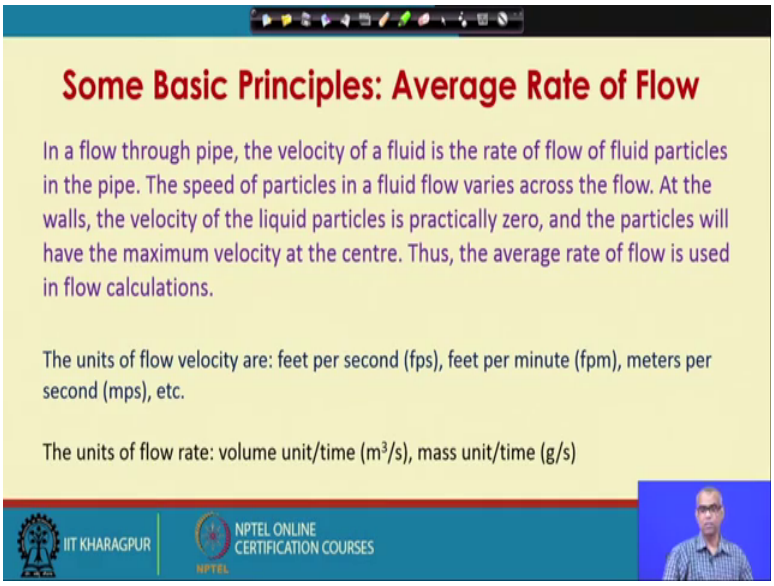

Let us go through some basic principles first average rate of flow in a flow through pipe, the velocity of a fluid is the rate of flow of fluid particles in the pipe. The speed of particles in a fluid flow varies across the flow. At the walls, the velocity of the liquid particles is practically zero, and the particles will have the maximum velocity at the centre. Thus, the average rate of flow is used in flow calculations.

The units of flow velocity are say feet per second or feet per minute meters per seconds etcetera. The units of flow rate if it is volumetric flow rate we will expressed as volume unit per times such as meter cube per second, if it is mass flow rate, we will express in mass unit per time such as gram per second.

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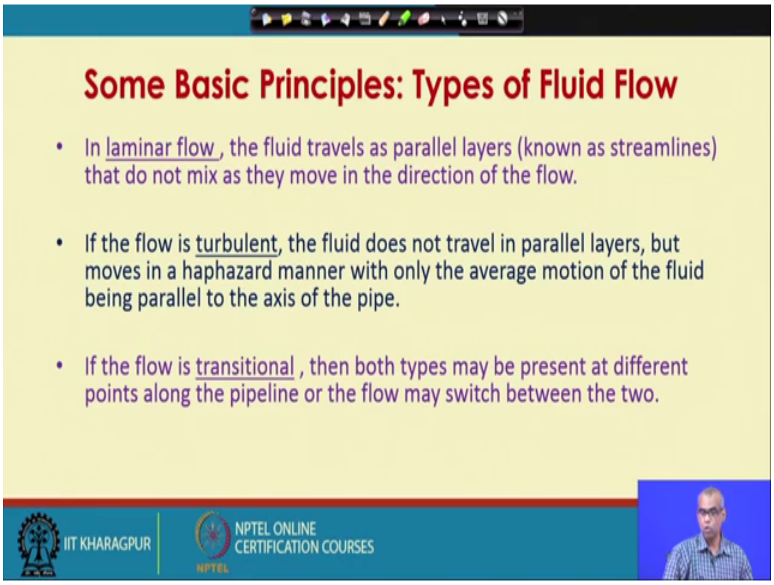

Next we will talk about types of fluid flow in laminar flow the fluid travels as parallel layers known as stream lines that do not mix as they move in the direction of the flow. If the flow is turbulent the fluid does not travel in parallel layers, but most in a haphazard manner with only the average motion of the fluid being parallel to the axis of the pipe. If the flow is transitional, then both types may be present at different points along the pipeline or the flow may switch between the two.

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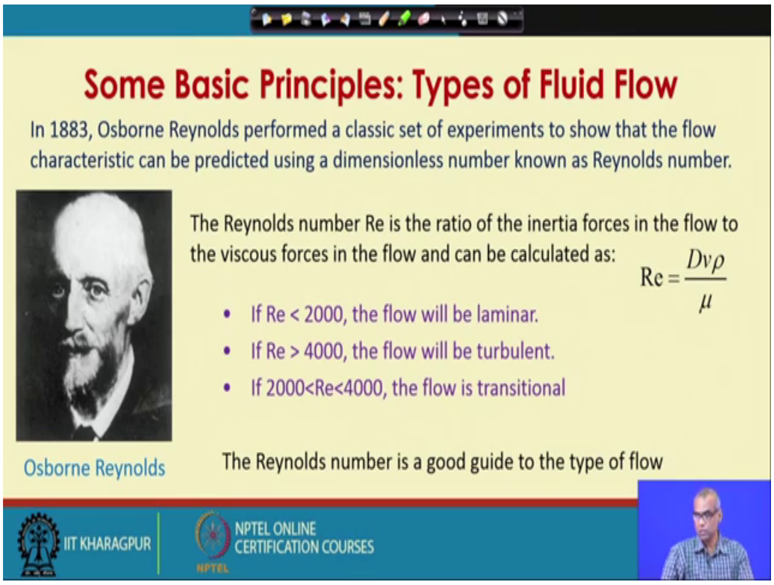

In 1883 Osborne Reynolds performed a classic set of experiments to show that the flow characteristic can be predicted using a dimensionless number known as Reynolds number. The Reynolds number expressed as re is the ratio of the inertia forces in the flow to the viscous forces in the flow and can be calculated as Dv rho divided by mu

Here D is the diameter of the pipe through which flow takes place v is the velocity rho is the density of the fluid and mu is the viscosity if Reynolds number is less than 2000 the flow will be laminar if Reynolds number is greater than 4000, the flow will be turbulent and if the Reynolds number lies in between 2000 and 4000, the flow is transitional thus the Reynold number is a good guide to the type of flow.

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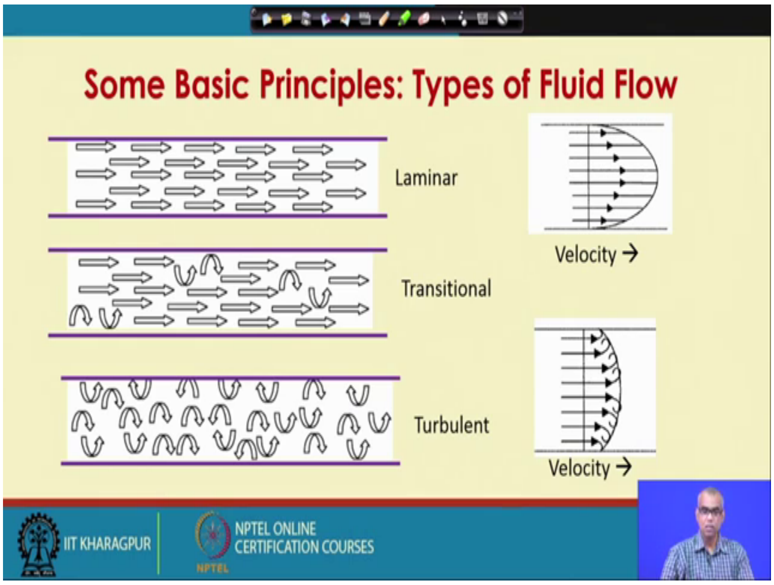

So, this schematically shows laminar flow see how the this fluid particles are moving in parallel with each other this is turbulent flow where it is all haphazard and this is transitional. So, you see a mixture of laminar and turbulent in transitional flow.

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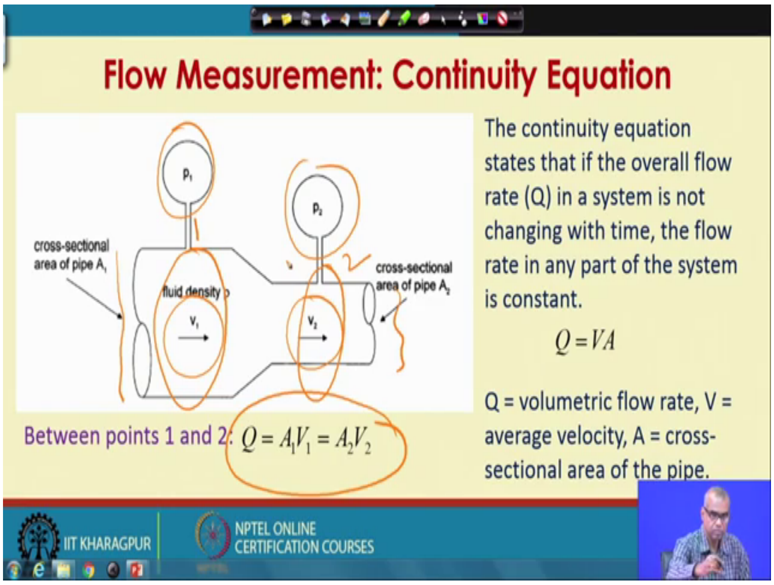

So, these are the velocity profile, now we will talk about continuity equation which plays a very important role in flow measurement. The continuity equation states that if the overall flow rate Q in a system is not changing with time the flow rate in any part of the system is constant. So, consider a flow through a pipe where the cross sectional area is changing from A 1 here to A 2, here the velocity is V 1, here the velocity is V 2, here the pressure is P 1 here the pressure is P 2, here we this is point 1 this is point 2. So, the velocity and pressure at point 1 are different from the velocity and pressure at point 2.

If the overall flow rate in the system is not changing between points 1 and 2 this relationship must hold true; that means, the volumetric flow rate Q is the product of cross sectional area and velocity. So, the volumetric flow rate Q is equal to cross sectional area and velocity product here which is same as the cross sectional area and velocity product here.

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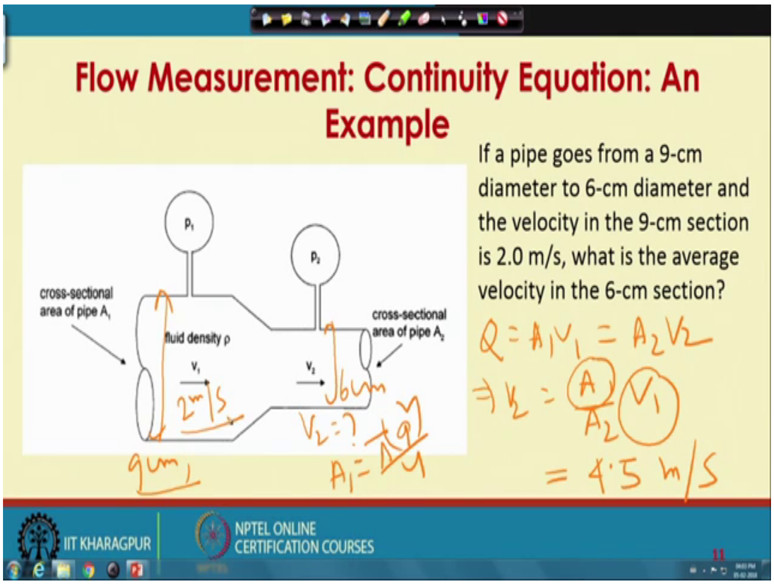

So, Q is A 1 V 1 equal to A 2 V 2 as an example, let us consider the pipe goes from 9 centimeter diameter to 6 centimeter diameter and the velocity in the 9 centimeter section is 2 meter per second what is the average velocity in the 6 centimeter per second.

So, here you have 9 centimeter diameter and the velocity is 2 meter per second here the diameter is 6 centimeter, we have to find out the velocity. So, this is a straightforward application of Q equal to A 1, V 1 equal to A 2 V 2. So, you can find out V 2 as A 1 by A 2 into V 1. So, A 1 is pi d square divided by 4 A 2 is pi d square divided by 4 you can also write pi r one square divided by pi r 2 square into V 1.

So, A 1 can be found out as pi 9 centimeter pi d square by 4 similarly A 2 can be found out as pi 6 square divided by 4 and V is given as 2 meter per second put all these numbers take care of units and you will get V 2 as 4 point 2 meter per second, remember, this is in centimeter, but these are in meter per second. So, you must take care of units.

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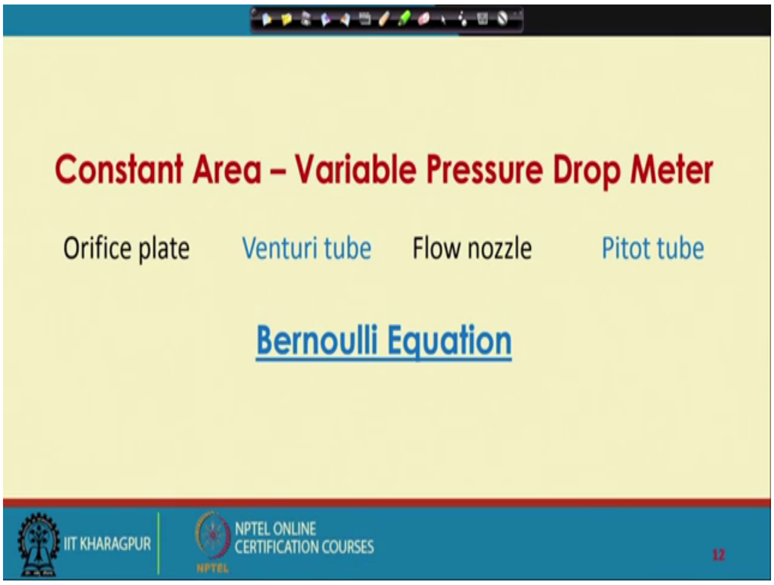

Next, we will start our discussion on constant area variable pressure drop meters under this category. We will talk about orifice plate Venturi tube, Flow nozzle and Pitot tube to understand the working of constant area variable, pressure drop meter; we must talk about Bernoulli's equation first. So, first we talk about Bernoulli's equation or Bernoulli's principle.

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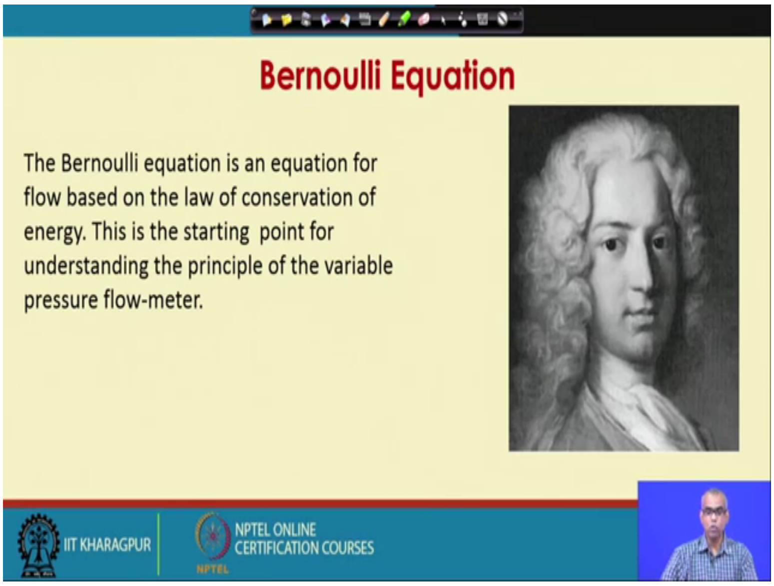

The Bernoulli's equation is an equation for flow based on the law of conservation of energy; this is the starting point for understanding the principles of the variable pressure flow meter. So, Bernoulli's equation is basically a statement of conservation of energy.

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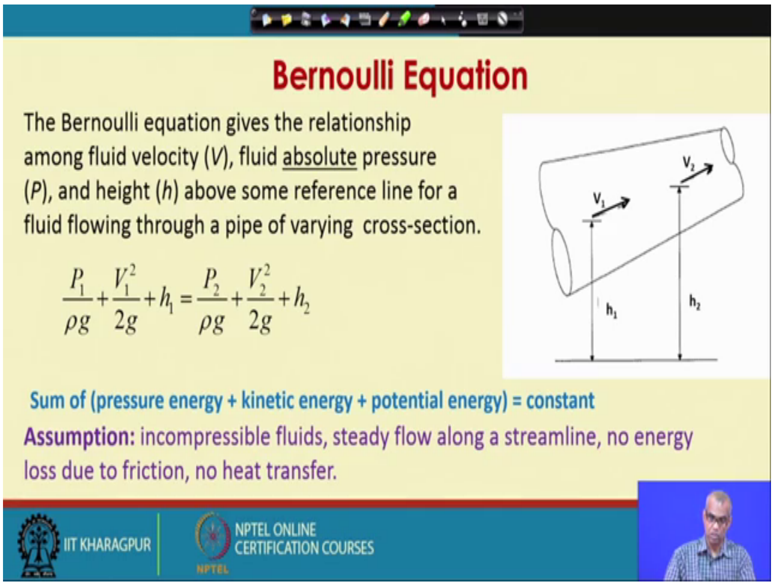

The Bernoulli's equation gives the relationship among fluid velocity fluid absolute pressure and height above some reference line for a fluid flowing through a pipe of varying cross section. So, consider the flow of a liquid through a pipe whose cross section is varying. So, cross section here and cross section here are different.

The height of this pipe is measured from this reference line. So, this point is the height from h 1 from this reference line and this point is at a height of h 2 from this reference line Bernoulli's equation says that between points A 1 points 1 and 2 this is point 1 and this is point 2 the sum of pressure energy kinetic energy and potential energy is constant at point 1 the pressure energy is P 1 by rho g at point 1 the kinetic energy is V 1 square by 2 g and the potential energy can be expressed as potential head h one

So, P 1 by rho g plus V 1 square by 2 g plus h 1 is equal to P 2 by rho g plus V 2 square by 2 g plus h 2. So, sum up pressure energy plus kinetic energy plus potential energy equal to constant here P 1 is absolute pressure V 1 is the fluid velocity rho is the density of the fluid g is acceleration due to gravity and h is height from the reference line this Bernoulli's equation is applicable to incompressible fluids steady flow along a streamline no energy loss due to friction and no heat transfer. So, remember some of pressure energy kinetic energy and potential energy is equal to constant.

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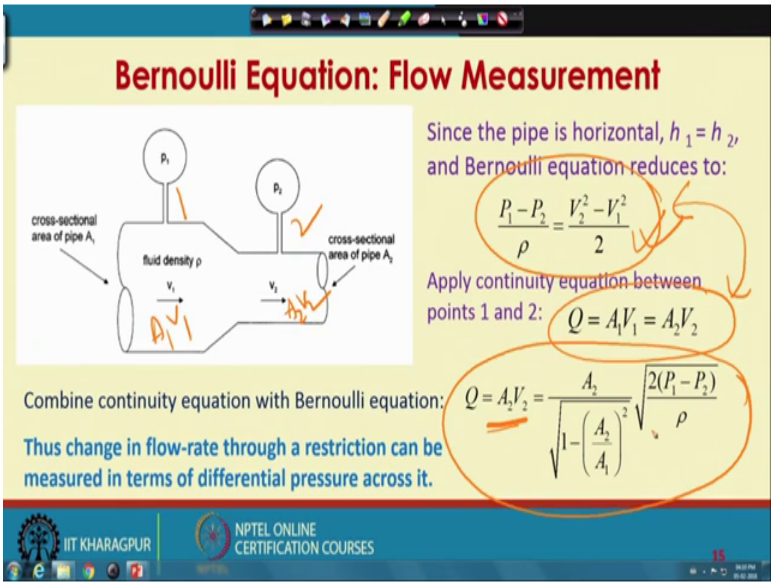

Now, consider the flow through a pipe of varying cross section and the pipe is horizontal at point 1 here at point 2 here. So, since the pipe is horizontal h 1 is equal to h 2 the h 1 and h 2 as we shown in the previous slide. So, they are same. So, then if I apply the Bernoulli's equation; that means, if I apply this equation P 1 by rho g plus V 1 square by 2 g plus h 1 equal to P 2 by rho g plus V 2 square by 2 g plus h 2 between one and 2 and h 1 and h 2 are same what I get is P 1 by rho g plus V 1 square by 2 g equal to P 2 by rho g plus V 2 square by 2 g.

So, if you rearrange this you will get this P 1 by P 2 by rho equal to V 2 square minus V 1 square by 2 if we apply continuity equation between point 1 and point 2, I can write as A 1 V 1 here and A 2 V 2 here they will be same as the volumetric flow rate Q.

Now, if I combine this 2 I can write Q equal to A 2 V 2 and an expression of V 2 can be obtained from this and I will be able to write Q equal to A 2 V 2 equal to A 2 by square root of 1 minus A 2 by one whole square into square root of 2 into P 1 minus P 2 by rho

Thus change in flow rate through a restriction can be measured in terms of differential pressure across it see P 1 minus P 2. So, what I did is I am considering a flow through a horizontal pipe of varying cross section. So, h 1 equal to h 2 apply the Bernoulli's equation between point 1 and point 2 I get this at point 1 and 2 I apply continuity equation I get this I combine these 2 equation and I get this.

And note this equation here on A 2 these are all related to the dimension of the pipe. So, the volumetric flow rate is related to the pressure difference P 1 minus P 2 across the flow restriction note here is a flow restriction because of change in this dimension.

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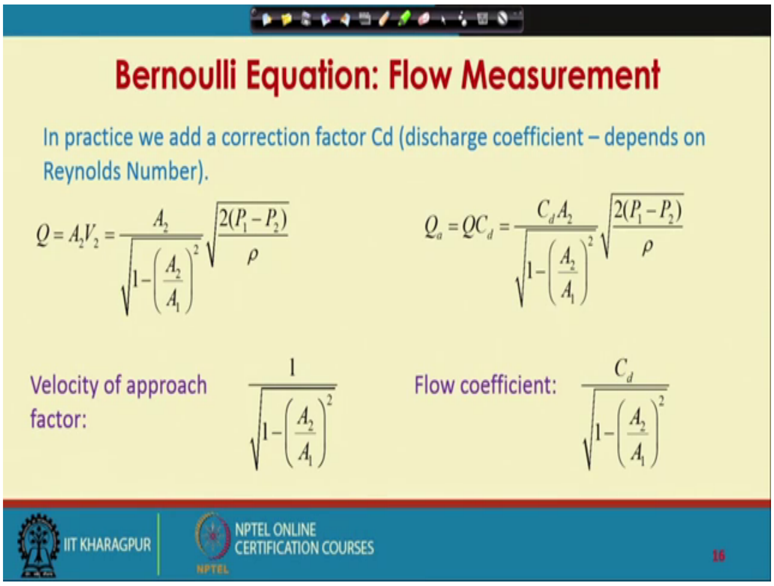

In practice, we had a correction factor cd known as discharge coefficient which depends on Reynolds number.

So, this is the equation you got by combining Bernoulli's equation and the continuity equation. So, this is the idealized volumetric flow rate in practice we will add a correction factor known as C d; we called it stretch coefficient and Q a, Q actual will be this Q multiplied by the discharge coefficient C d. So, this is the expression I get for actual volumetric flow rate through a pipe where we have a flow restriction P 1 minus P 2 is the pressure drop across the flows restriction velocity of approach factor is this term.

So, you look at this. So, velocity approach is one by square root of 1minus A 2 by 1 whole square, similarly the flow coefficient is this term C d by 1 minus A 2 by A 1 whole square; square root for laboratory experiments a u tube manometer may be used to measure the differential pressure head delta h because we know P 1 minus V 2 equal to rho g into delta h.

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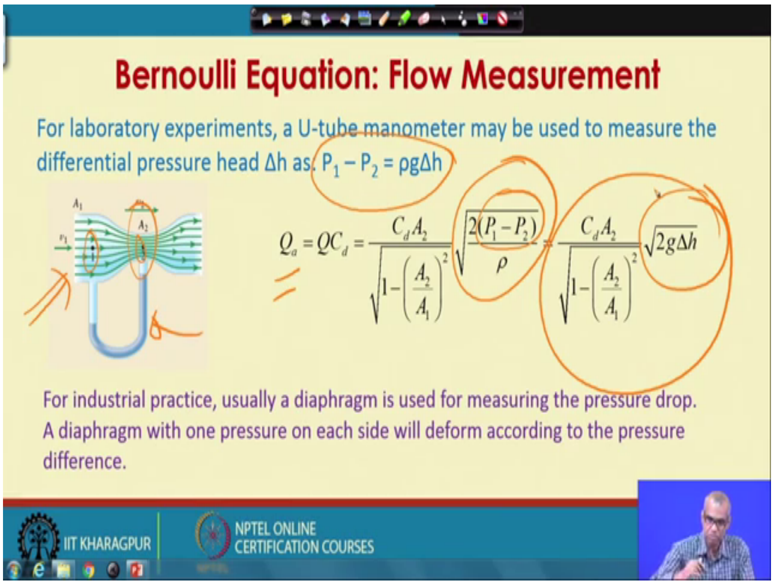

So, this is this is the pipe of varying cross section. So, you have a flow restriction here. So, u tube manometer can be used to determine the differential pressure that happens between point 1 and point 2. So, this P 1 minus P 2 can be replaced as rho g delta h this rho and this rho will get cancelled and what you will get is Q a is this. So, this part will be this part because P 1 minus P 2 equal to rho g h.

However for industrial practice use of a u tube manometer may not be convenient and for industrial practice usually a diaphragm is used for measuring the pressure drop. A diaphragm with one pressure on each side will deform according to the pressure difference, we have talked about diaphragm pressure measuring instrument while discussing pressure measuring instruments.

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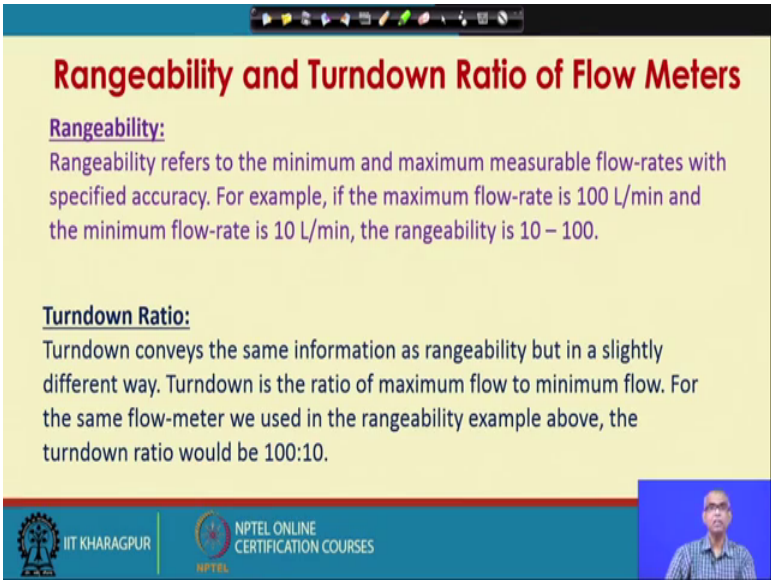

Now, we talk about two important aspects of flow measuring instruments they are known as Rangeability and turn down ratio of flow meters rangeability refers to the minimum and maximum measurable flow rates with specified accuracy. For example, if the maximum flow rate is 100 liter per minute and the minimum flow rate is 10 liter per minute the rangeability 10 to 100 turndown ratio conveys the same information as rangeability, but in a slightly different way turndown is the ratio of maximum flow to minimum flow.

So, basically turn down ratio is maximum flow rate divided by minimum flow rate for the same flow meter we used in the rangeability example above; that means, whose maximum flow is 100 liter per minute and minimum flow rate is 10 liter per minute the turndown ratio will be 100 is 100 is to 10, remember, these minimum and maximum measurable flow rates we are talking about the flow rates which matches with the specified accuracy.

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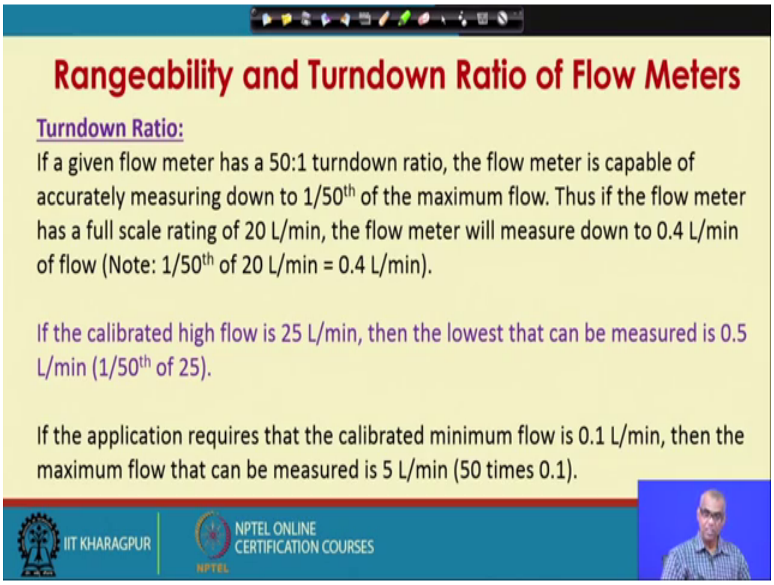

Let us talk about turn down ratio a bit more if a given flow meter has a 50 is to 1, turn down ratio the flow meter is capable of accurately measuring down to 1 by 50th of the maximum flow thus if the flow meter has a full scale rating of 20 liter per minute the flow meter will measure down to 0.4 liter per minute of flow because 1 by 50th of 20 liter per minute is 0.4 liter per minute.

If the calibrated high flow is 25 liter per minute then the lowest that can be measured is 0.5 liter per minute why 0.5 liter per minute because it is 150th of 25 if the application requires that the calibrated minimum flow is point 1 liter per minute then the maximum flow rate that can be measured is 50 times point 1 liter per minute that is 2 liter per minute. So, this is how you can interpret the turndown ratio.

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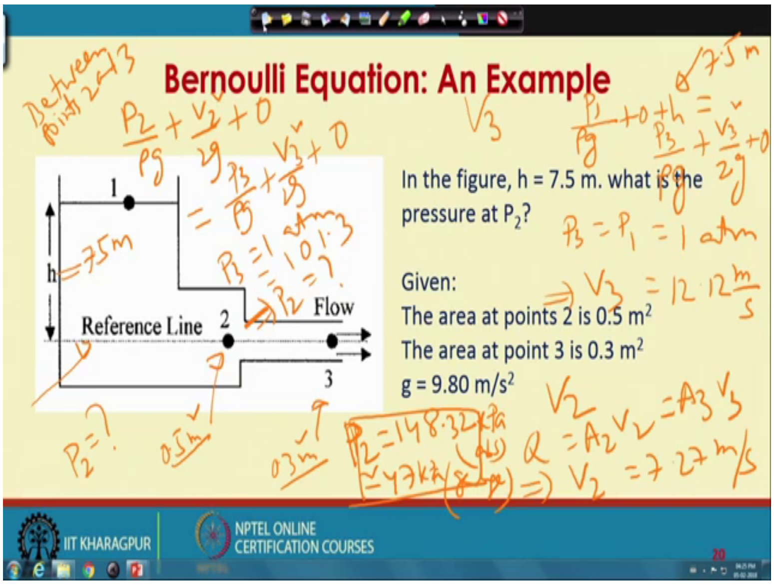

Now, look at the diagram on the screen in this figure this h is equal to 7.2 meter the area at point 2 is 0.2 meter square and the area at point 3 is 0.3 meter square g is given as 9.80 meter per second square, we have to find out the pressure at point 2. So, we have to find out what is P 2. So, I will give you the sketch of the solution procedure.

First what we will do is let us try to find out the velocity at point 3 let us try to find out first at velocity at point 3. So, find out velocity at point 3 what we can do is you can write the Bernoulli's equation between point 1 and point 3 as P 1 by rho g plus 0 plus h equal to P 3 by rho g plus V 3 square by 2 g plus 0 note the reference line.

Note that P 3 P 3 equal to P 1 equal to one atmosphere this equation will allow you to calculate V 3 and V 3 will be able to calculate as 12.12 meter per second note that the value of h is 7.5 meter. So, we have got V 3, once I have got V 3, I will be able to get V 2 by using continuity equation as Q 2 equal to A 2 V 2 equal to A 3 V 3 A 2 A 3 is given. So, this will allow you to compute V 2 as 7.27 meter per second.

So, I have now calculated V 2 I have now calculated V 3, now apply, now apply Bernoulli's equation between point 2 and 3 if I apply Bernoulli's equation between point 2 and 3 I will write P 2 by rho g plus B 2 square by 2 g plus 0 because reference line equal to P 3 by rho g plus V 3 square by 2 g plus 0. So, this is between point 2 and point 3 between points 2 and 3.

So, once you put in all the values you will be able to calculate P 2 because you know P 3 there is one atmosphere. So, P 3 you know is one atmosphere. So, that is equal to 101.3 Pascal; calcula Pascal. So, V 2 V 3 we have found out. So, you will be able to find out P 2.

So, P 2 you can calculate as 148.32 kilo Pascal, but this will be absolute. So, if I am going to find out gauge you have to subtract 101.3 kilo Pascal that most the equation. So, that will be equal to approximately 47 kilo Pascal gauge.

So, this is how you can solve this problem. So, what I what you do is first you basically apply the Bernoulli's equation first between point 1 and point 3 to calculate V 3 once you get V 3 you use continuity equation between point 2 and 3 and calculate V 2. So, at this stage I have P 1, P 3, V 2, V 3; now between point 2 and 3, I use Bernoulli's equation and then calculate P 2.

So, I stopped today here and in the next class we will talk about examples of pressure measuring instruments that make use of Bernoulli's equation such as orifice meter by Venturi tube, etcetera.