Principles of Mechanical Measurement

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Module – 09
Flow Measurement
Lecture – 3
Mass flowmeters & velocity probes

Hello friends. So, today we are going to start the 3rd lecture on our module number 9 where we are talking about the Flow Measurement. Now over the previous 2 lectures we have discussed about quite a few very common options of measuring the flow like we have discussed exclusively about the obstruction based flow meters where, we have a several examples like the orifice meter, flow nozzle venturi meter. In the previous lecture we have talked about laminar flow meter and also something known as the target flow meter or drag for base flow meter.

And then we went on to the discussion of so called volume flow meters where we are actually going to get the entire volume flow rate as of as output of the measurement. And there we have discussed about two very accurate and common options of high precision based flow measurement like the turbine flow meter and also the electromagnetic flow meter. So, today we have several things in our plate. Let me see how much I can go for because, I would like to finish the discussion on this particular topic through this lecture itself. Now, in the last class we have finished our discussion on electromagnetic flow meter.

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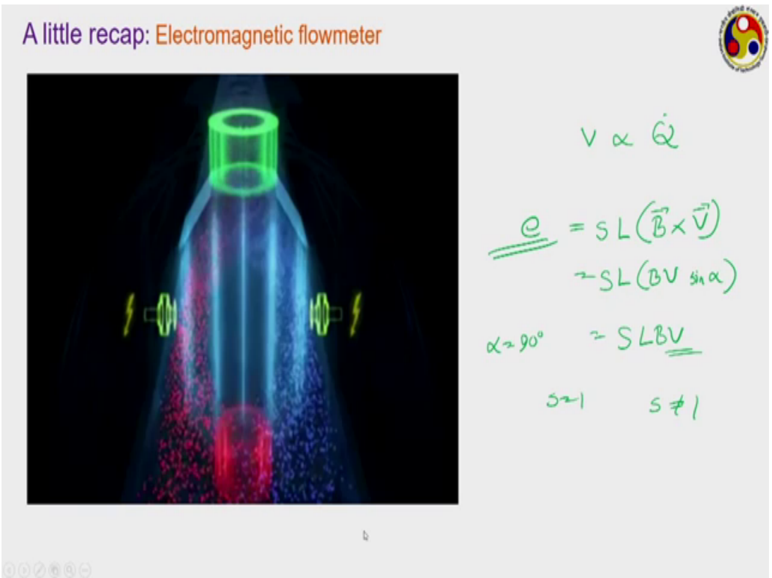

Today for this one and also for several other topics; I have made my job simple I have several animation or animated videos to show the working principle. And the first one is related to the electromagnetic flow meter. All these videos are taken from YouTube only. So, if you are interested you can go for this, but if I just go it back go back a bit you can see the one of video here on the pipeline we have put 2 magnetic poles or basically the magnet which are shown. There by these red and green refers to the two different poles and this is creating the magnetic field. And the fluid which is coming in a direction perpendicular to this on the other 2 arms of this we have put couple of electrodes.

So, when the fluid is flowing through this if the fluid has some kind of electrical conductivity, then the one that is just shown that is the test section which is basically the flow meter itself. And now you can see the fluid has been shown to comprise of red and blue particles. So, which basically represents the two different kinds of charges, let us say red is the positive one and blue is the negative one. Now whenever the fluid is having some kind of electrical conductivity and that is flowing through this magnetic field, then the charges will align like just like this the positive charges will go to one side the negative charges will go to the other side.

And as we have the electrodes positioned on the adjacent walls then we shall be able to get the sense this EMF the potential difference between this. And this EMF will if we can measure the t m f using some processing circuitry, then we can get a direct measure of this volume flow rate. Because the EMF that is being generated, like if V refers to the voltage that is being generated that voltage has been found to be directly proportional to q dot. And if we follow the faradays law of electromagnetic induction then the force that is being generated or I should say the electrical charge that is being generated that is generally found to be l into B cross V.

Where, L refers to the length of the conductor, B is the magnetic flux intensity or magnetic flux density and V is a velocity both B and V are vectors and it is a cross product. So, we can also write them as L into B V sin alpha. Here alpha refers to the angle between them. Commonly we have alpha equal to 90 degree thereby, it is given as L B into V. Generally, we also have to add coefficient S to this which is some kind of meter based constant which depends on the configuration of the meter. And if we are using a uniform magnetic field and uniform velocity in that case S is equal to 1, but practically that is not the situation.

So, we generally have S not equal to 1 for all the practical situations, but that generally comes has a specific part of the meter specification. So, once we know the magnitude of this B then we can get from just from the knowledge of this electric charge or total current that is flowing through we can get a measure of this velocity of fluid. Or, we can directly get this one to the Q dot. Just explained yesterday this is just an animated V of that. Let us move to the next kind of meter to talk about.

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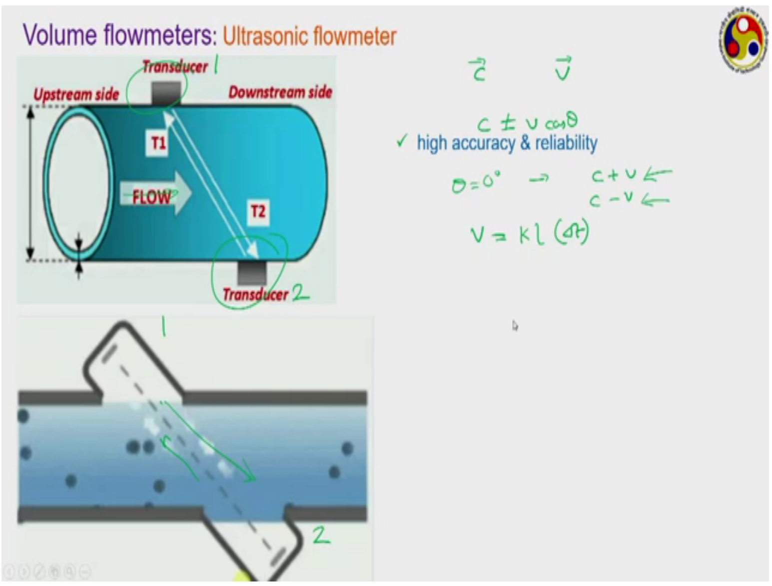

And that is known as the ultrasonic flow meter. It is another kind of non-intrusive measurement where we are using ultrasound or sound waves for the measurement. Just see how the configuration is shown here. On 2 opposite walls of the flow section we put couple of transducers, like this is one transducer this is the other transducer. And both act as simultaneously as receiver and detector. Now, if we put certain kind of sound wave from one transducers towards the other transducer and let us say fluid is flowing the flow direction is shown here.

So, this is the flow direction. Then if suppose C is the velocity of the sound then and V is the velocity of the flow, then the time that is required or I should say the actual velocity of the wave that is traveling from one transducer to the other transducer will be equal to C plus minus V cos theta. Where theta definitely this theta depends on the orientation; that means, the fluid the wave which is moving in the towards the downstream direction is velocity will be higher. The fluid wave which is moving towards the upstream direction that is opposite to the flow is velocity will be lower.

If we are talking about a theta equal to 0 degree in that case one wave the one that is moving in the upstream sorry moving towards the downstream side that is in the direction of the flow it is effective velocity will be C plus V and the one which is moving towards upstream the effective velocity will be C minus V. So, the time taken by the wave to move from one transducer to the other that will be different like the one which is moving from let us say this is transducer 1 and this is transducer 2. So, the one that is moving from transducer 1 to transducer 2, that is actually moving in the direction of the flow.

So, is velocity will be increased effective velocity will be C plus V. And the time taken for this one to reach from transducer one to transducer 2 will be lesser. Whereas, the wave which starts from 2 and goes to 1 that is this one 8 C it is moving opposite to the flow. So, it is effective velocity will be C minus V. And so, it will take more time to reach the other transducer. And from there we can get a measure of the effective velocity.

Practically the velocity is related as K into l into delta t, where K is some kind of coefficient related to the meter, l is the distance between the 2 transducers that is the path that the wave has to travel and delta t is the time difference between these two waves going from one transducer. To the other to make it effective both transducers intermittently works as receiver and I should say a source that is at one instant ordinary act as a source in the next instant of time it acts as a detector. So, that we can get a measurement of this delta t from both from the two combining the two transducers.

So, this is the principle of ultrasonic flow meter; again a very effective instrument for measurement of fluid velocities and also a non-inclusive one. Actually ultrasonic flow meter can be of 2 types depending upon their working principle or I should say the ultrasound based flow measurement can be accomplished in 2 waves. The one that we are showing here that is known as transit time flow meters because, here we are looking for the time difference required by these two waves to reach from one end to the other.

And there is another one which is based upon the Doppler shift principle, but that is generally more used for the velocity measurement as. So, we shall be talking about that later in today's lecture. Because in the Doppler shift principle we get flow velocity not the flow rate whereas, in this case we are getting the flow rate. Ultrasonic flow meter has several advantages like the if I erase these things to make some space. So, there high reliable and very high accuracy we can get from them comparable the electromagnetic flow meter.

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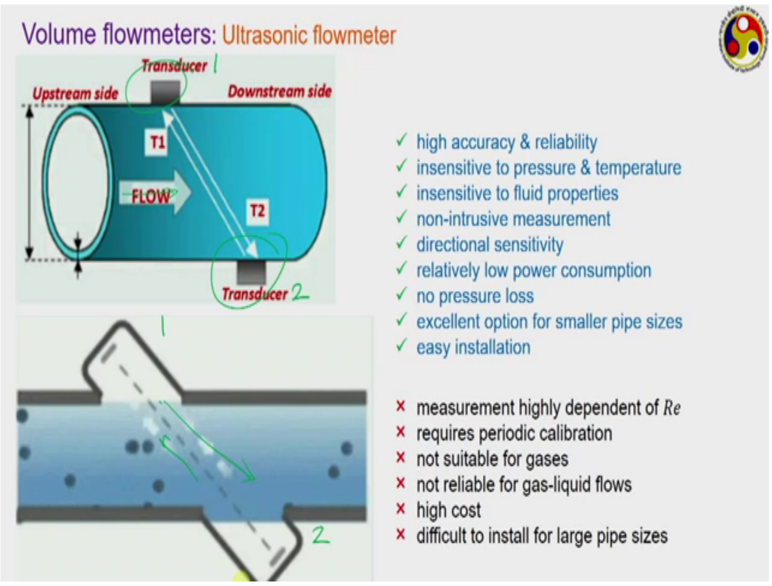

Insensitive to the pressure and temperature; so, we can easily use them for very high pressure situation very high temperature flows just like the flow of steam or in the power plant turbine or maybe the flow of hot combustion gases inside an ISO engine they can always be used for. Their insensitive to fluid properties because we are just sensing the velocity of or rather time taken by the wave to reach from one transducer to the other and that does not depend upon any thermo physical properties like density or viscosity of the fluid. Non-intrusive measurement; so, it takes into account all the advantages of non-intrusive measurement hardly any obstruction in the flow no additional pressure losses it does not distort the flow itself. It can sense the direction. Clearly if we do not have any idea of which direction the fluid is flowing still we can get it from the measurement.

Because as we know that wave traveling in the downstream direction will move faster, the one moving in the upstream direction will move slower accordingly we can easily identify just from this 2 time measurement we can easily identify which one is the upstream direction. And which one is the downstream direction they does not require too much power for their operation.

Because they just have to produce the ultrasonic sound wave and that can be a very low power wave. No pressure losses because of the non intrusive nature and they are excellent option particularly when you are dealing with smaller pipe sizes. Like options like electromagnetic flow meters etcetera can be more potent in larger pipe sizes, but this one is excellent for smaller pipe sizes. And very easy to install we just have to mount the 2 transducers in suitable location and mostly that is it we can go start the measurement immediately.

But there are problems like the velocity as the time required or the change in time required for the 2 waves to travel is dependent on the fluid velocity. So, the entire dependent entire measurement is based upon the flow velocity or the Reynolds number. In fact, it is not a linear relationship that we are going to get from this it is somewhat non-linear depending upon the Reynolds number. Periodic calibrations are required. And they are not at all suitable for gases because in gases our sonic velocity will be quite small and may become quite difficult to distinguish with that from the gas velocity.

Or, I should say it may become quite difficult to sense the time difference, but for liquid where the sonic velocity itself is much larger they are much better option, but even when this liquid flow if there is some gas bubbles present. Similar problem may appear that is the ultrasound which is traveling through the 2 phase mixture if it strikes some bubble it may get reflected back and thereby not able to reach the other end of the transducer or the transducer at the other end. So, they are not suitable for gas liquid flows or even particulate flows fluid flows which are having solid suspensions etcetera. They are costly very costly like the electromagnetic flow meter.

For difficult the large pipe sizes they may be difficult to install particularly how to orient the 2 transducers; so, that we can get a decent travel path for that may be quite difficult. So, this is the ultrasonic flow meter which is again a quite common option. All these 3 that we have talked about electromagnetic turbine and ultrasonic based flow meters all are very standard equipments easily available from several vendors or manufacturers. And extensive database is available about their performance characteristics you can easily. Go you can easily look into internet and find a supplier to purchase any of these 3 kinds of meters of the desired specification. So, there despite certain disadvantages for each they are quite potent option and common options for flow measurement.

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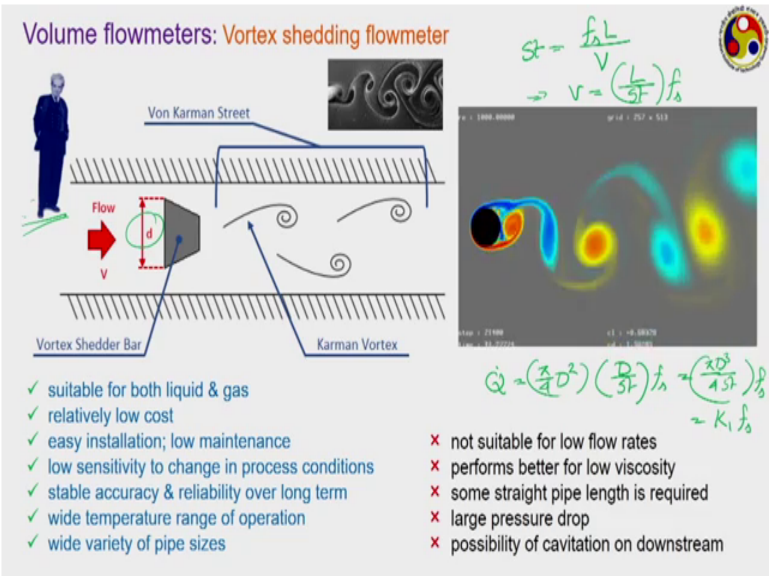

But the next one is a quite innovative one, which is called the vortex shedding flow meter. Now what do we mean by vortex shedding that is whenever we are putting a block body that is a block like this inside a flow stream, then the fluid has to find a way pass to this one that is a flow which is may be the this if we draw the streamlines which are initially just horizontal lines. They have to find a way around this one some of them or rather one of them may reaches a stagnation point.

Other has to find a wave parallel to this thereby, for forming compressed zone of streamlines on either side of the block bodies and when they reach the other side the downstream side of a blob body there may be flow separation accordingly the development of recirculation zone and subsequently the formation of vortex. This vortex are known as the von Karman vortex based upon the legionary scientist von Karman who was the first person to properly identify them.

This is just an example of how they may look like. On the downstream side with increasing initially we may have 4 small Reynolds number we may have a recirculation zone created. However, if you are dealing with a high Reynolds number flow like in up to this case we are only a vague recirculation zone and then steady flow; however, if we are dealing with a turbulent flow situation high Reynolds number flow then we shall be having this vortex formation.

And it has been identified that the frequency of this vortex can give a measurement of the flow velocity. Here the parameter that is of our interest is known as the Strouhal number, ST the Strouhal number is defined as f s into l by V. Where f s is the frequency of this vortex shedding l is the characteristic length of this vortex shedding bar like in this case the D can be the characteristic length when you are dealing with a spherical object like this. It is very easy the diameter itself is the characteristic length and V is the velocity.

Now, by proper design it has been found that for several block bodies the value of Strouhal number can be maintained to be constant over a wide range of Reynolds number. And once Strouhal number is a constant then the velocity V becomes just l by Strouhal number into the frequency. So, if we can says the frequency then it can give a linear relationship to measure the flow velocity and correspondingly the value of the flow rate.

Like if we are interested in the flow rate q dot will be the cross section area flow into the velocity itself. And if we represent the velocity with corresponding expression for Strouhal number and take D is the object or sorry the diameter of the object the characteristic length, then it becomes pi D cube by 4 into Strouhal number into f s that is Strouhal number is constant K one into f s.

So, this K one generally for a given energy of Reynolds number with a constant velocity Strouhal number K one is known. And so, just from the measurement of this frequency, we can get a measurement of the flow rate. There suitable for both liquid and gas kind of flow situations relatively low cost because you just have the block body to be placed and subsequently you have to say is the frequency that is all we do not need to produce any magnetic field or any kind of ultrasonic arrangement.

That is why their cost are not that important. Easy to install mean to hardly any maintenance required over long term operation. Low sensitivity change in the process condition that is if there is a change in the process flow temperature or pressure they are generally not that much sensitive. Stable accuracy and reliability over long terms wide temperature range of operation just mentioned 2 points back and wide for they can be used for wide variety of pipe sizes.

So, we can change depending on the size of the pipe we can select different kinds of vortex shedding bar and get the similar kind of representation, but they are not suitable for low flow rates as I have mentioned when the flow rate is low then you will be getting like if I go back to the this particular situation up to the loading or somewhere you are getting only recirculation zone no vortex. Only at high Reynolds number and the flow becomes turbulent you are getting this vortex.

And that is why they are suited not suitable for low velocity measurement only suitable for reasonably high Reynolds number; again performed better for low viscosity because if viscosity is low Reynolds number will be high. Some straight pipe length is required to form the vortex. So, that you can have a descent upstream portion of uniform flow then the positioning of the vortex shedding bar and then a subsequent or I should say sufficient length of the downstream section to visualize the vortex and measure the corresponding frequencies.

So, quite significant for straight line passage is required; a large pressure drop you can understand because of the formation of the recirculation zone all the eddies and vortices, that are appearing there will be significant pressure drop. And that is why again they are not suitable for low pressure drops situation. Where we cannot afford large pressure drop they are not suitable. Possibility of cavitation on the downstream because of the large pressure drop we may reach a pressure on the round stream side which is lower than the corresponding vacuum pressure, which will lead to the problem of cavitation. Any flow scenario where we are having a large pressure drop corresponding to the measuring instrument we may reach a situation of cavitation and that is particularly relevant in kind in this kind of vortex shedding flow meter.

So, vortex shedding flow meter is for high velocities it is a very good option to have definitely not as common as the previous 3, but is an interesting one. And it is also commercially available. Next we have another very important device that is called the positive displacement flow meter extremely common one has wide kind of applications because of the white kind of varieties that we can have.

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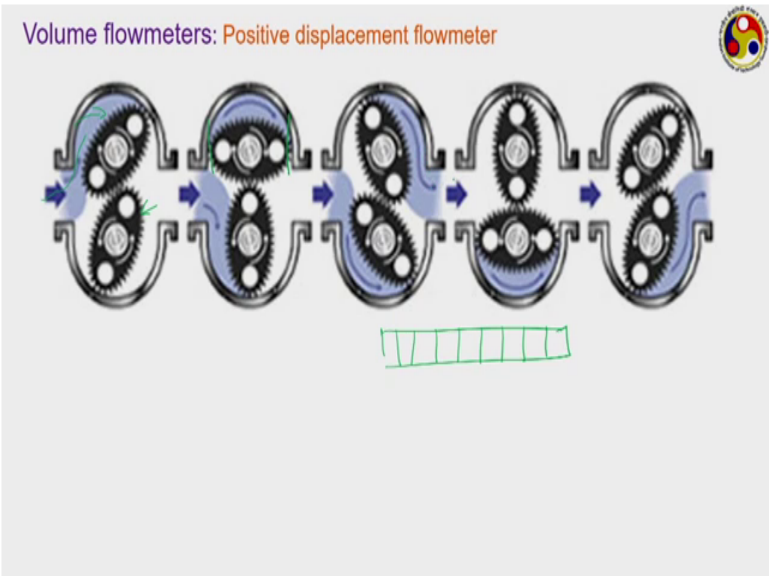

Here the idea is the in entire flow is generally divided into several small components. The components are selected such that each of them has a fixed volume then just by counting the number of components we can calculate the total volume flow rate like. Let us suppose this is the fluid volume that is flowing through.

Now, we are dividing into several equal components of this. And measuring the time required for these components to pass through or consequently we are measuring the number of component that is passing through over a given period of time. So, let us say over a given period of time, over once again only 4 components has passed through. Then the volume of one component multiplied by 4 divided by the time average this passage taken place is definitely the flow rate, that is the idea of a positive displacement flow meter. Just like shown here a positive displacement flow meter can have different categories we shall be seeing a few examples.

The one that is shown here is a gear type. As you can see there are 2 gears in the first figure when the fluid flows through it is there is no passage towards the lower side so it flows in the upward direction over the gear, but as the gear is rotating when it is striking the gear in this portion it makes the gear rotate. And because of the rotation of this stop gear the bottom one that is this one also starts to rotate in the well the top one both top one is moving in the clockwise direction. Now the bottom one is moving in the anti clockwise direction because of their arrangement.

Now, as the top gear moves a bit then look at the second situation here, there is hardly any gap left on either side. And so, a fixed volume of fluid has got trapped on top of this first top gear. And there is fluid flow now allowed towards the lower side and. As it keeps on moving or as both the gears keeps on moving then after some time the top gear releases the fluid towards the ground seems right the bottom gear keeps on rotating. And in the 4th scenario we have reached a situation where there is a volume of fluid being trapped below the bottom gear. And subsequently that is again released to the surrounding.

So, in one rotation of both the gears then we can see twice we are collecting a fixed volume of fluid and then discharging that to the downstream side. And now if we know this particular volume of fluid then we know how much volume we have discharged during one particular movement of this gear. And how many such movements are taking place that will give you the idea about the total volume that has been supplied. So, that is the way we use a positive displacement.

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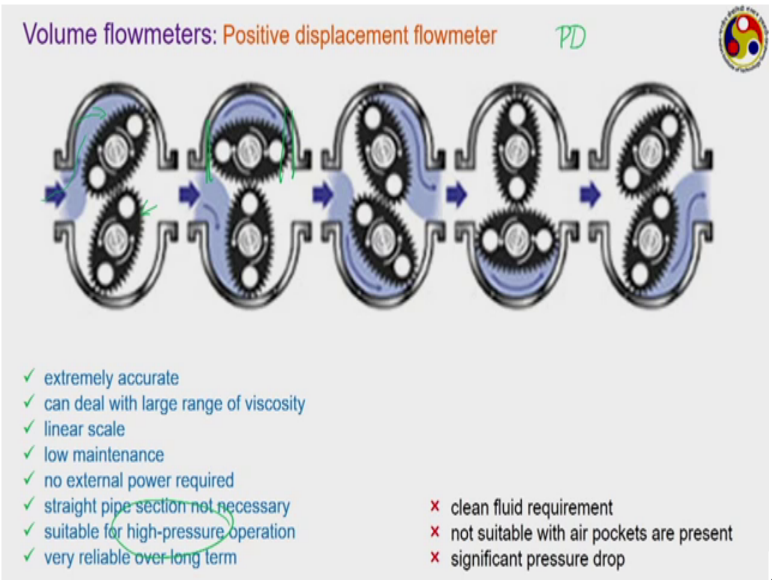

Flow meter they are extremely accurate only where there can be loss is through the small gap which maybe there left in these in between these portions general they are quite tight fit well sealed through the use of lubricating oils, but there may be small amount of slippage otherwise they are very accurate, can deal with large range of viscosities. In fact, they are more suitable for high viscosity fluid because higher the viscosity lesser is the chance of slippage through that gap.

So, they are more suited for high viscous fluid, but for common fluids or low viscous fluids also they can give quite good performance. Linear scale because very easy measurement we know we are just counting the number of such discharges and the volume corresponding to each discharge is given. So, it is a the final volume flow rate is just a linear function of the number of components that a number of such collections and discharge combination has taken place.

Not too many you maintain requirement because you can see the one shown here is a simple gear arrangement. So, you hardly need any maintenance. No external power required because the movement of the gear is because of the inertia imparted by the fluid motion itself. So, we do not need to import any additional motion to the gears only as the fluid strikes the gears or whatever may be the corresponding arrangement they start to rotate in the corresponding their respective directions and thereby necessitate the measurement of the flow.

Straight pipe section is not necessary you can put it anywhere even in the vertical channels also and there suitable for high pressure operation. At high pressure we do not have to make any separate arrangement of course, the slippage maybe is an issue at higher pressures. But, again we present mechanisms or present day industry has sufficient technology to take care of such kind of slippage and finally, if they are very reliable over long term.

So, this reliability over long term low maintenance requirement linear scale etcetera make them very suitable for long term use in different industries particularly when we are dealing with high viscosity fluids, but they can have a few limitations like clean fluid is required. If the fluid has certain kind of darts or dust particles or maybe some kind of solid suspensions, then that may block the passage. Like some if there is some kind of sand particles or stone pieces have represent that may go in into these gear teeth and can block the corresponding passage.

So, we need clean fluid clean fluid. Not suitable when air packets are present or air pockets are present because if air pockets are there that will give an erroneous reading to the volume. Actual volume will be less than the volume corresponding to the component itself corresponding to each component. And there can be significant pressure drop in the flow; so, there again more suitable for this high pressure operation because of the significant pressure drop to give to be overcome over during the operation.

Now, positive displacement machines can be of different kinds depending upon the orientation of this like the 2 gear shown here. This is called a gear based positive displacement flow meter. Quite often they are also called p D meter or p D flow meter. Here these 2 gears are looking like ovals. So, they are also called the oval gears.

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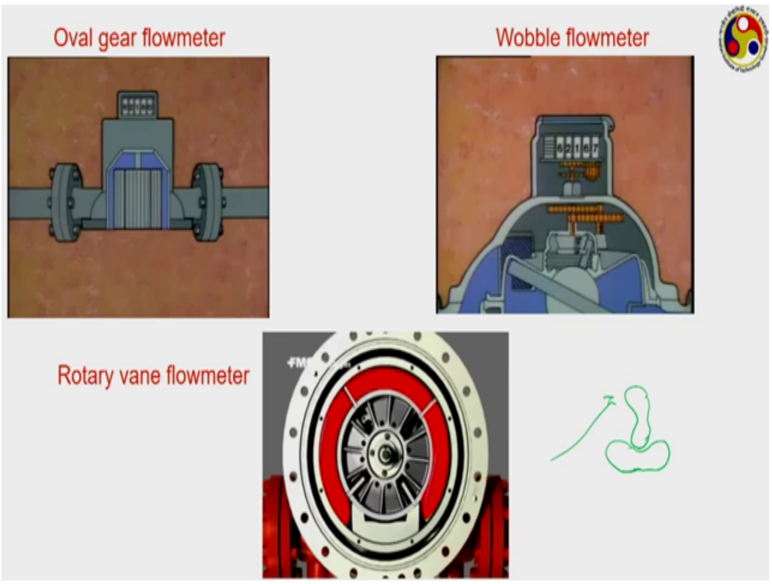

And I have a few animations for this is us for the same scenario that is oval gear flow meter. The 2 gears you can see the gears are connected to each other through the teeth. And as the fluid is flowing the gears rotate in opposite directions and allow the fluid to flow through. During each motion you can see a fixed volume of fluid is allowed to pass through a fixed volume of fluid is connect up or collected and then discharged to the to the outlet side.

At the flow velocity increases you can see the gears are rotating with a higher velocity, but. So, there are mod number of rotations or more number of this collision and discharge, but the volume corresponding to is discharged remains the same. And then there is a counter which counts the number of rotation corresponding to each gear. So, if we count the number of rotation for one gear then multiply by 2 we will get the total number of components discharged. And that multiplied by the volume corresponding to each discharge divided by the time of measurement gives you the volume flow rate.

So, this is an oval gear flow meter or just oval gear p D meter. This is another interesting one this oval gear flow meter is generally more used in the lubricating pump of the automobiles. The wobble flow meter actually is more common in case of the fuel stations the gasoline stations you can see this kind of flow meter commonly. Here instead of any gears you have a large plate just like shown here you can see this large plate. This plate is mounted on the base on certain kind of hinge such that they are able to oscillate in their own position depending upon the direction of the flow. And you can see on one in one case it is allowing a volume of fluid to move on the top side in the next case it is allowing a fixed volume of fluid on the bottom side. Again depending upon the flow velocity it is movement can increase or decrease, but every time it is allowing the same volume of fluid to pass through.

And now, counting the number of components using a suitable counter which can be a digital one; just like what you can find in a petrol pump. There we can get a measurement of the fluid volume. Another variation that we can have is the rotary vane flow meter. Here we have vanes we do not have gears or plate rather you can see vanes. There are several veins you can find there are 4 veins in the one that is shown here. And as the fluid is passing through you can see this is one particular vanes and this is the other vane. So, a fixed volume of fluid gets trapped in these 2 vanes. This is the portion which is separating the inlet and outlet to the flow meter and now, the volume corresponding to one pair of vanes that gets discharged. So, how many number of rotations that has taken place from there we can calculate the total volume that has been discharged.

So, these are called positive displacement flow meter we can have a few other variations also like something coming to my mind is called the low flow meter, where we have 2 lobes of this kind of shape some would like a dumbbell shape 2 lobes of this particular shape. And as a fluid flows through this, then the lobes form a mechanism quite similar to the gears. So, this positive displacement flow meter have found extensive application particularly in conjunction with long term industries or long term operation dealing with high viscosity fluids. That takes us to the end of volume s flow meters.

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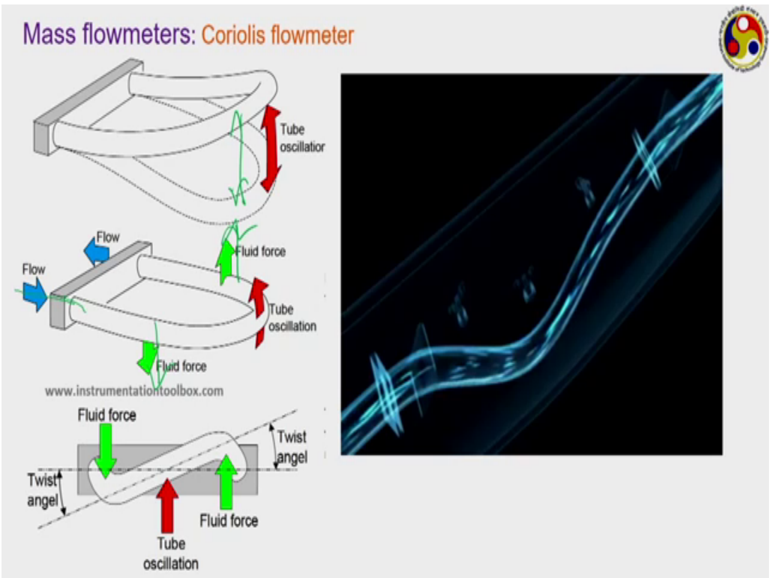

Next we are going to discuss about couple of options for dhe measuring the mass flow. Now you may be arguing that if we know the volume flow rate you also know the mass flow, but problem is mass flow rate m dot is given as rho into q dot that is density into volume flow rate. So, you need to know the value of the density. And if you do not know the density properly then the mass flow rate that you are going to calculate using the volume fluid will be erroneous. And there are several situations we have we may have non uniform distribution of densities. So, we have to be very careful. And there these mass flow meters can be very effective where you are directly going to get the mass flow rate as the output.

One example is this Coriolis mass flow meter. In case in case of the Coriolis mass flow meter we have an u kind of flow section just like shown here. You can see as the fluid enters from one side of this u and goes out to the other side of the u. It the tube is subjected to certain kind of oscillation. The tube oscillates in a direction perpendicular to the flow. And now because of the Coriolis section I am sure you have heard about the Coriolis section.

Like very common example can be the atmospheric or the ocean movement because of the rotation of earth. As the earth is rotated the air that is traveling on the northern hemisphere and on the southern hemisphere they take a different turn in different direction depending on the rotation of art same happens to the waves and which is called the Coriolis action. The same action is used here the tube is oscillating in direction perpendicular to the flow. Now, as long as there is no fluid flowing through the u tube the oscillation is there. Oscillation will take go on, but when the fluid starts flowing through this the force imparted by the fluid on the tube itself that tube tries to twist. The and the magnitude of the twist if we know the magnitude of the magnitude of the twist that or the twist angle that depends on the oscillation and also the fluid velocity.

Now, the oscillation generally is fixed because that is something that we are controlling from it is outside. So, this twist angle then becomes only a function of this fluid velocity. This twist, why this twist is coming into picture because the direction of this fluid force are different like shown here. It is acting in this direction here it is acting in the other direction. So, accordingly they are trying to twist the tube in opposite direction or move the tube in opposite direction leading to this twist just shown in this animation of for the same thing. You consider as a you kind of configuration where. Firstly, you have one exciter which is exciting the flow exciting this tube. As the or making the tube to oscillate. And now as the fluid is allowed to flow through this, there are these are the couple of detectors which detects if there is any twist at all or not.

Now, initially when there is no flow there was no twist, but at the fluid starts to flow through this portion starts to twist because the flow the force that is acting in this portion and the force is acting in this portion they are acting in opposite direction. So, they are trying to twist the tube and from there we can get a measure about the flow velocities. So, this is the detector which continuously detects the distance of the tube from it is location or the variation of the distance of the tube from it is initial location. And as both we combine the measurement from both the both the detectors we can get an idea about the corresponding twist angle.

As the flow velocity increases the magnitude of twist also keeps on increasing. In fact, Coriolis mass flow meter can also give you an idea about the density of the fluid. If we know the velocity, then we can calculate the density from this like. If the fluid density is higher the magnitude of twist also will be lesser. If we compare the performance of say oil and some much high density fluid then the high density fluid when this flowing through that will definitely try to dampen the motion a bit more resulting in lesser amount of twist.

So, thereby we can get a measurement of the fluid density as well. So, Coriolis flow meters can also be used for measurement of fluid densities.

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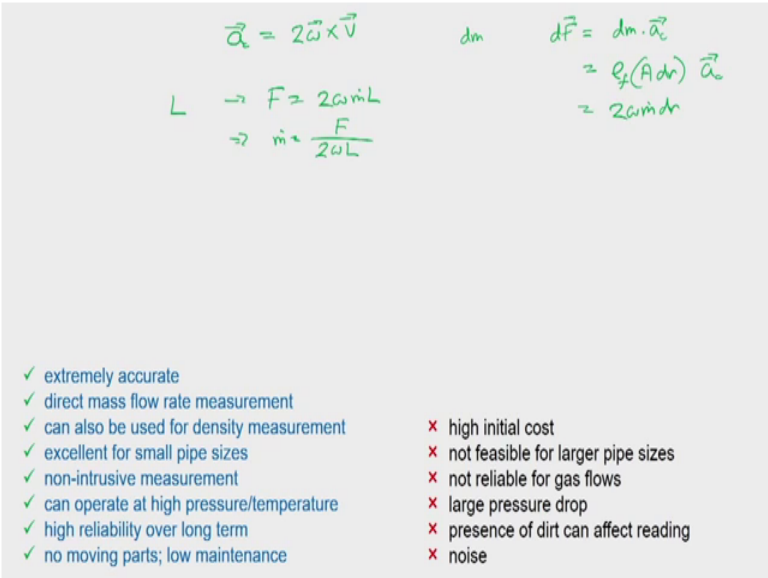

If we just quickly check the mathematical part; when the fluid is flowing through because of the oscillations that you are putting in and also the fluid velocity the acceleration of the tube can be written as 2 omega cross V, where V is the fluid velocity and omega is the acceleration. Then if suppose we are having an (Refer Time: 34:29) small element tube element of mass D m, then the differential force D f that is acting on this is definitely dm into the this particular Coriolis acceleration a C.

Now, how much can be the mass? If say the rho f is the density of the fluid then the mass of this corresponding fluid element which is present in this small dm, dm amount of mass is equal to a into d R where R is a flow section. So, if 2 omega m dot d R now if total length of the tube is l then total force that is acting on this will become 2 omega m dot l giving m dot is equal to f y 2 omega l. So, from there we can get a measure about the total mass flow rate. Coriolis mass flow meters are again extremely accurate instrument for mass flow rate measurement we are getting a direct mass flow rate measurement, which was not possible at any of the earlier instruments.

We can also measure density as I have mentioned excellent for small pipe sizes; however, they may not be very good option for large pipe sizes. Because for large pipes the twist may lead to the breakage of the pipe, but for small pipes we can make them very flexible; so, that we can have reasonable degree of twist. Non-intrusive measurement. So, nothing going inside the flow stream; however, actually we are modifying the flow conduit. So, we are not at all going to get all the advantages of non-intrusive measurement, but still we are not including anything into the flow stream at least. They can easily operate at very high pressures.

So, temperatures highly reliable over long term and no moving part reading low maintenance operation, but problem is their initial cost they are much costlier compared to the venturi meter kind of instruments. They are not feasible for large pipe sizes as I have just mentioned because the twisting may lead to the failure of the pipe or rupture of the pipe in if the pipe dimension is large or pipe diameter is large. They are not reliable for gas flows because if we are talking about flow of gas then the density is much lower. So, the force that is created may be quite small, which is not the case with liquids are having higher densities. So, leads to reasonable degree of twist.

So, they are more use for liquid measurement theoretically they can still be used for gas flow measurement, but the low density of gas necessity rates a lower sensitivity of the output. Large pressure drop despite the non-intrusive measure nature of the measurement we are having a large pressure drop because we are making the fluid to flow through an oscillating u tube thereby actually taking it out of it is own flow path and then sending it back to the flow path after that oscillating u tube junction. And so, there can be significant pressure drop. Presence of dirt can affect the reading and because they can clog the small dimension tube and also there can be significant amount of noise. So, the signal processing is very important in this Coriolis mass flow meter. The other mass flow meter we can have is the thermal mass flow meter.

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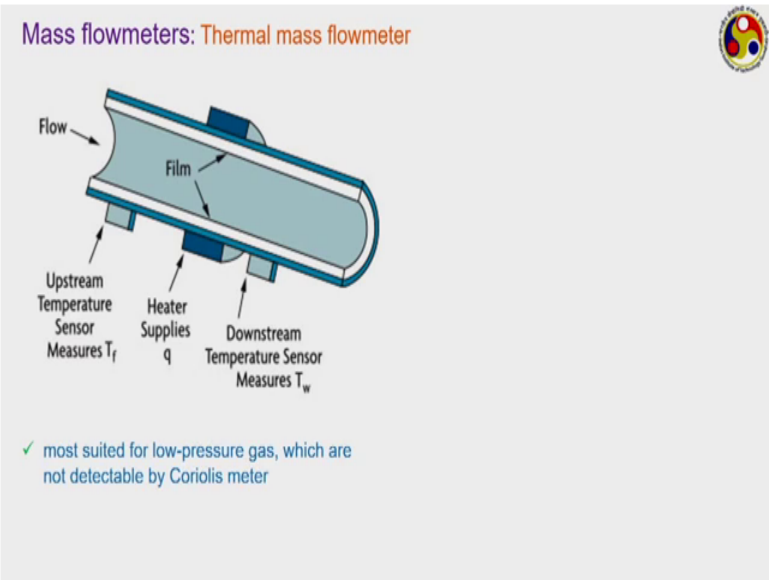

Thermal mass flow meters can have very interesting operating principle here what we are doing is that we are aligning some fluid to flow through a duct.

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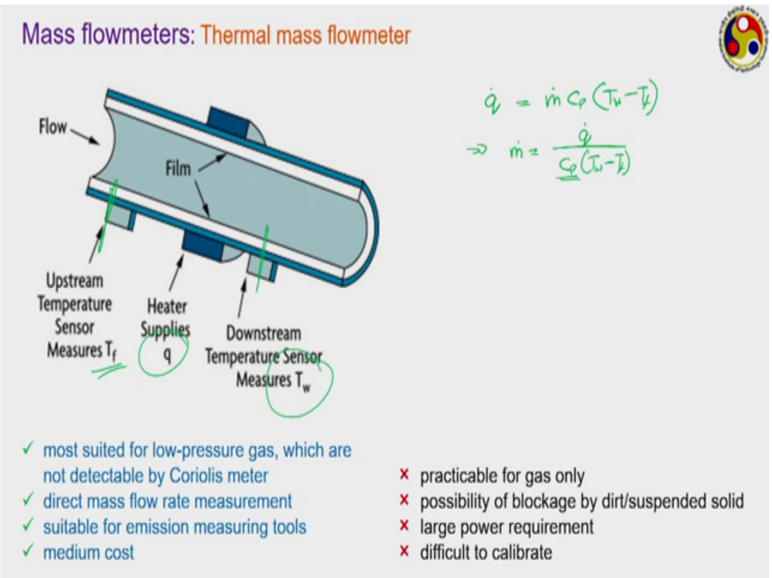

At this particular section we are measuring the temperature given by T f at this particular section we are again measuring that temperature T w and within this portion a supplying a fixed quantity of heat q. Then this rate of heat transfer q dot can be written as m dot mass flow rate into C p into the change in temperature. That is T w minus T f or I can write m dot is equal to q dot by C p into T w minus T f. Now if we can give a constant value of this q dot, and now measure these 2 temperatures Tw and Tf we can get a measurement of the mass flow rate.

So, that is exactly what that is done in a thermal mass flow meter fluid is allowed to flow through these measurement section and we supply a fixed quantity of power to get an reading about the and take the reading at the of temperature at the inlet section and outlet section and combining we get the measurement of the mass flow rate. Truly speaking thermal mass flow meter can operate in two modes one is a constant heat flux mode just like shown here. Here we supply a fixed quantity of heat flux or power in the form of q dot and measure the change in temperature. The other one can be a constant temperature mode where we control the temperature rise or for a given T f we can to control the outlet temperature T w and then using some feedback control we adjust q such that we can maintain a constant value of this T w.

And that again in a way gives a measurement of this mass flow rate. Thermal mass flow rate is a very suitable for low pressure gases which are not detectable for Coriolis meter. For Coriolis meter as we have just seen they are more suitable for liquids not for gases. And also for only for high pressure gases we may use a Coriolis mass flow meter whether density becomes higher, but thermal mass flow meter particularly suitable for gases. One problem of course, there is a C p generally we take as constant, but C p may vary the temperature rise is significant then C p can also vary. So, if this temperature rise between Tf and Tw is very significant, then we also have to take some corrective factor into equation because of the C p variation.

Now, we are again getting a direct mass flow rate variation they are particularly suitable in emission measuring tools like pollution emission measuring or car pollution waste measurement etcetera. And they are medium cost less costlier compared to the Coriolis mass flow meter, but they are practical only for gas flows for not for liquid force because for liquid generate specific it is much larger and we if we want to have a detectable value of delta t then q need to be much larger. There can be possibility of blockage by dot or suspended solid because, these channel generally have much smaller dimension large power requirement can be there and they can be difficult to calibrate.

Still thermal mass flow meter because of their relative use relative ease particularly the gas flow are quite well used a variation of the thermal mass flow meter we shall be discussing very shortly regarding the velocity measurement which is called the anemometer, which uses the same principle, but gives a measure of the velocity we shall be talking about that in just 5 minutes. So, that takes us toward the end of the discussion on flow meters. Just something that I promised in the previous lecture about introducing that is the use of the obstruction meters.

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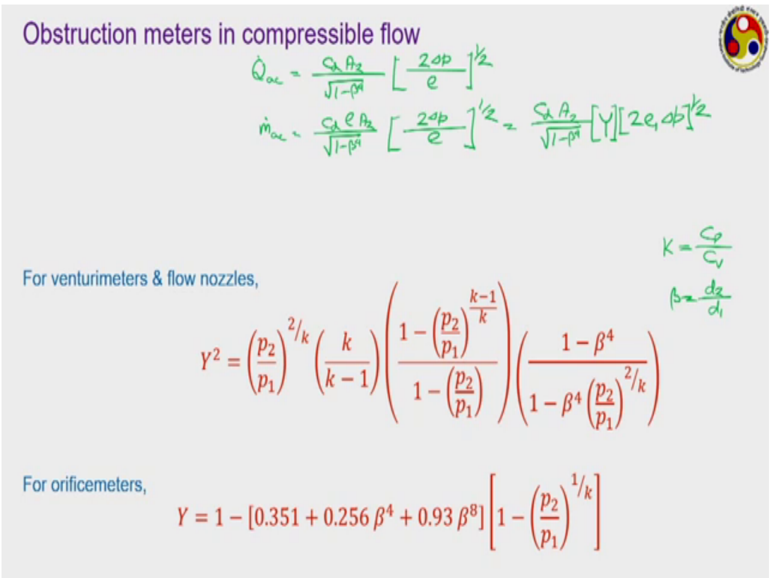

Incompressible term, whatever discussion earlier we have had about the obstruction meters they are all based for incompressible flows because we use the Bernoulli's equation, but when we are dealing with a compressible flow like gases they are the density does not remain constant. Just if we think about what we did earlier for compressible sorry for incompressible flows there we have seen that for a venturi meter kind of instrument the actual flow rate is generally given as C d into area 1 minus beta to the power 4 into to delta p by rho whole to the power half. And correspondingly mass flow rate actual C d into row 2 into a 2 or instead of putting the subscript 2 we can just write it as rho.

So, if we take the rho inside the equation then we have C d into a 2 beta to the power 4 2 rho delta p, whole to the power half, but now if we are dealing for an incompressible flow situation, this is ok, but if you are dealing for a compressible flow situation that is sitting there may be significant change in the value of the density. And there we have to be careful. Careful in the sense here which density to use that is the first question. And secondly, there can be certain other changes in the equation because the Bernoulli's equation itself is not applicable.

So, in that situation generally what we do, we incorporate this rho as rho one that is the upstream side density and then we use a corrective factor y. This y is some kind of density correction factor which takes into account the effect of compressibility. So, we are using the upstream density rho one in the equation and then we are using a current density correction factor as y. The expression for y for venturi meters and flow nozzles we can get such big expression for it this is actually a theoretical expression.

You can easily derive this one following the isentropic flow situation in a compressible flow theory you can refer to any standard books on fluid mechanics to get the source of this particular derivation. For orifice meters our we depend on an empirical relation some of this particular form which p 2 and p one are the downstream and upstream pressures respectively K refers to the ratio of specific heat that is C p upon C V. And beta is the like mentioned earlier beta is D 2 upon D 1 that is the ratio of downstream to upstream diameters of the flow measuring section.

So, with this corrective factor of y we can use the similar relations or we can use the obstruction meters in case of compressible flow scenario as well. I do not want to go to the details of this derivation this is just to show you what we can do or how you can extend the application to compressible flows just by adding one correction factor. Next we move on to the next category of our flow measuring instruments, which is velocity probes. Where instead of flow (Refer Time: 45:36) rate or mass flow rate or volume flow rate we are actually getting the velocity as the output.

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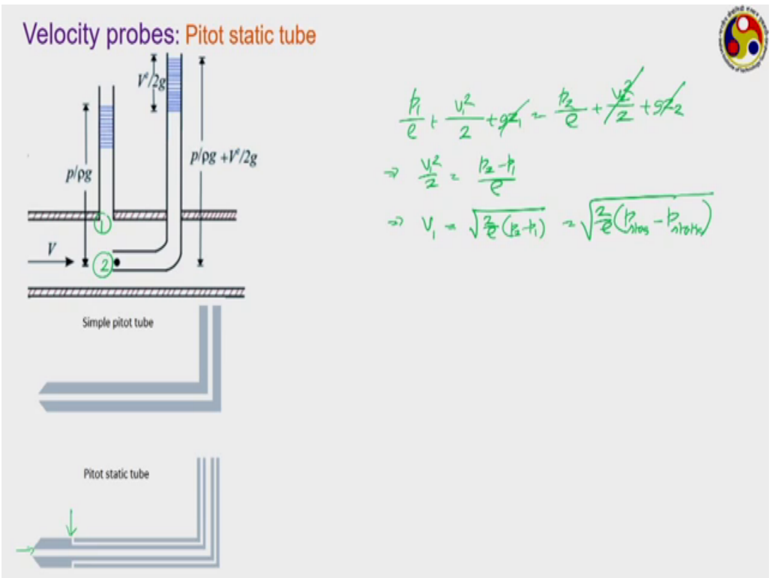

And the first one we you already know about this the pitot static tube or I should say the pitot tube. In the case of a pitot tube the configuration is shown we can have 2 piezo meters one connected on side of this tube which is going to give you the static pressure the other one connected to a inside a stagnation point inside the flow domain they were giving you a stagnation pressure.

And so, if you apply the Bernoulli's equation between the 2 then on one side you are if let us say this point is 1 and this point is 2 then you are having p 1 by rho V 1 square by 2 g or sorry V R square by 2 plus g z 1 is equal to p 2 by rho V 2 square by 2 plus g z 2. Quite often we can neglect the change in elevation because they are mounted at the same elevation almost and V 2 being as 2 being a stagnation point V 2 also goes out accordingly V one square by 2 is equal to p 2 minus p 1 upon rho V 1 is equal to 2 by rho into p 2 minus p 1 or we can also write this 1 as 2 by rho into p stagnation pressure minus the static pressure.

So, using just these 2 (Refer Time: 47:11) meters we can get the measurement or more commonly you can have the pitot static tube where we have both the stagnation part or stagnation probe and static probe mount with each other. We have already discussed in more detail about this one this more for academic purpose because to introduce you to or to let you know that pitot tubes are generally more used for pressure velocity measurement instead of pressure measurement.

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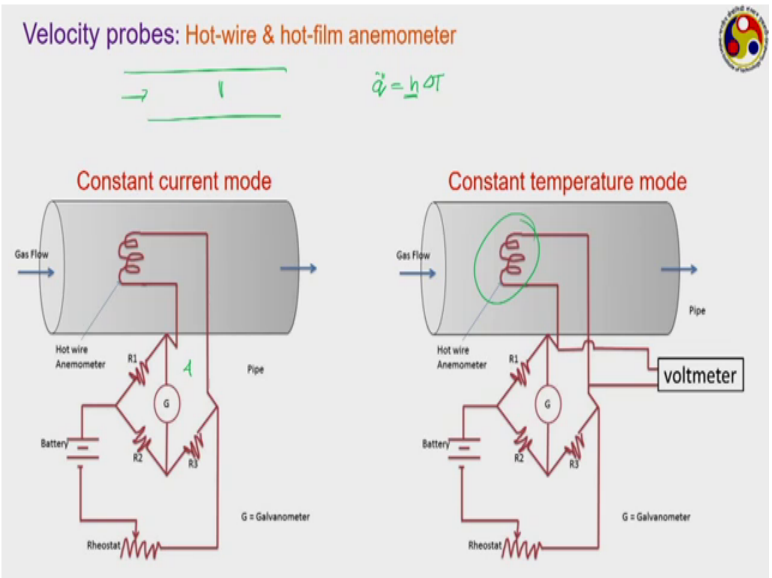

And next one a very common instrument is the anemometer, which as I shortly mention shortly back it uses the same principle as a thermal mass flow meter, but is used for velocity measurement. We can have 2 types of anemometers hot wire anemometer or hot film anemometer. The idea of anemometer is that in case of an anemometer, we generally have a if this is your flow stream.

We generally mounted small where inside this flow stream a very thin wire or very small dimension small in the sense it is the diameter can be the range of just 5 to 10 micron and length of one millimeter. And we kept we connect this one to some heater. So, that a particular amount of electrical energy is being is passing through this and accordingly producing some I square amount of power. And as the fluid which is passing through this that will be taken that energy.

So, once we reach an equilibrium condition then whatever electrical energy that is getting dissipated through this particular wire will be taken by the surrounding fluid. So, that the temperature of the wire surface that remains constant that is the working principle of this hot wire anemometer because, the temperature or sorry the ability of the fluid to extract heat from this will be governed by corresponding heat transfer mechanism.

Now, what is the mode of heat transfer here? It has to be convection and for convection we know that rate of heat transfer q dot is equal to some heat transfer coefficient, I should say heat flux is equal to heat transfer coefficient due to a temperature difference. And this heat transfer coefficient is a function of the velocity. So, from there we can get a measure of this fluid velocity. We can have two different modes of this hot wire anemometer. Actually one is constant current mode just like the thermal mass flow meter where you are going to supply a constant amount of current. And we shall be having a brief circuit just shown here with the probe acting as one of the circuits. This is the probe one and this is acting as this particular 4th arm of the base circuit.

Now, whenever there is a change in the temperature of the probe there will be a change in the resistance accordingly there will be some kind of current flowing through this bit circuit. And that current will give you a measure of the well flow velocity. The other mode can be a constant temperature mode. In that case we want to maintain a constant temperature of the probe itself.

Therefore, whenever there is a gas flowing through this that 2 and that is extracting heat and trying to cause a change in the temperature of the probe surface there is a feedback mechanism which is supplied through certain mechanism maybe the current that is produced or the rather the voltage that is produced in the bit circuit is sensed by the voltmeter accordingly it activates some heater to maintain a constant temperature at the anemometer surface. And the power that is required to maintain that constant temperature that gives you a reading of this velocity.

Hot wire anemometer is the most common one and that is generally more used for gaseous mediums. However, we can also have hot film anemometers which are preferred for liquids. In case of hot film anemometer, we have a quartz crystal and on top of the cross crystal we put certain kind of coating. For hot wires generally we make aware of some noble metal like platinum or maybe tungsten in case of a hot film over the crystal we put a platinum coating and that acts as the heat producing element.

More mechanical strength can be obtained in case of a hot film anemometer and that is why we need to make use of that in liquid flow. We cannot use a very fine wire of 10 micron diameter like in the hot wire in a liquid flow situation because that you will immediately rupture the wire. So, you have to go for hot film in liquids. If we quickly try to see how the mechanism works in case of a hot wire anemometer.

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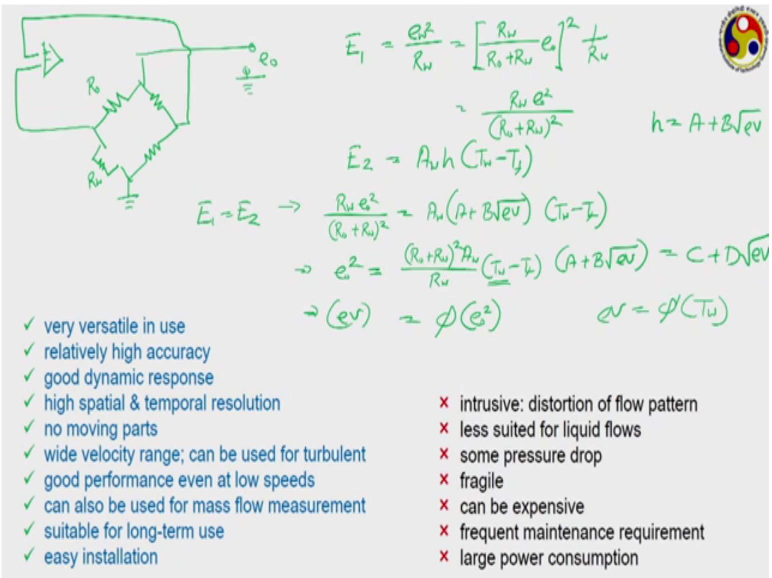

Let us say this is our brief circuit and the probe this resistance is R naught and this is your probe which is having a resistance of R w. This side is grounded and now this is the outlet voltage e naught and on this side we are using a comparator which is comparing the velocity or the difference in voltage between the 2 sides. That is the voltage difference from this particular end is going to one side and the voltage from this end is going to the other side is plus and this is minus. So, this is the voltage that is acting to your source which is having a voltage of e naught.

Now, how much is the electrical current that is being produced. The electrical power let us say that is E1 that electrical power will be e w square by R w, where e w is the potential difference that is acting across therefore, probe resistance now how much is e w? E w can be R w divided by R naught plus R w into e naught whole square that is equal to R w e naught square R naught plus R w whole square.

And how much is the current that has power rather energy that has been withdrawn by the flame or the flowing fluid that has to be the area of the flame into h into Tw minus T f, where Aw refers to the surface area of the wire or your probe h is the heat transfer efficient T w is the surface temperature of the probe and T f is the fluid temperature and these two has to be equal to each other.

Now, let us assume that h is equal to A plus B root V which is a quite common way of representing the heat transfer coefficient or generally we write this as rho into V, because it is depend on the flow rate this. So, if we under equilibrium condition E1 and E 2 R has to be equal to each other because E1 is the energy supplied in the mode of electrical heating E 2 is the amount of energy extracted in the mode of convection. So, if we equate this 2 and write all these expressions together then we have R w e naught square R naught plus R w whole square is equal to Aw to A plus B root rho V Tw minus Tf; that means, e naught square is equal to R naught plus R w whole square into Aw divided by R w Tw minus Tf A plus B rho 2 rho 2 V.

Now, if we are operating in constant temperature mode then just look at this expression. R naught and R w constant because R naught is a power part of the bit circuit R w is the resistance of the probe itself; so, this to a design constant at the design level. Aw is the surface area of the probe. So, that is also a constant T f is the fluid temperature. So, we do not expect the fluid temperature to change too much. A and B are also constant as for the form of heat transfer coefficient that we have assumed.

So, if we are operating in a constant temperature mode, then if; that means, if you are operating in keeping Tw is constant. Then what we can write this one can be written as sum C plus D into root over rho V where C and D are the just the excerpts from this particular equation and these are constants only. So, we get a relation between this e naught square that is the power and the velocity. From here we can get a measure of the total mass flow rate or I should say we can represent this one this rho V product as sum function of this e naught square. So, the power becomes a measurement of the total mass flow rate.

Similarly, or in alternate way if you are operating in a constant power mode we can also get it as a function of the temperature of the probe surface. In that case this rho V will become some phi prime of this where surface temperature. So, hot wire anemometer is very versatile used we can be used we can use this one for gas flow or liquid flow like we use in hot wire mode in gas flow and hot film mode in liquid flow; relatively high accuracy very good dynamic response.

So, very suitable for transient measurement whether is a significant change in temperature or velocity is quite frequently. High spatial and temporal resolution can be obtained no moving parts just a simple where or a flame and therefore, very less maintenance requirement wide velocity range can be covered starting from very low velocity of laminar flow. So, to highly turbulent flow we can easily cover by this one. Good performance even at low speeds also just what I mentioned can also be used for mass flow measurement because just with suitable alternate alternation or very small modification we can also make this one work as a mass flow meter. They are suitable for long term use and easy to install, but as we are talking about a very small where in case of a hot wire flow.

So, they are they are very fragile and that is one of the big disadvantage. One problem is this is an intrusive measurement. So, they distort the flow pattern. They does not cause that much of pressure drop, but the flow the velocity profile of the flow pattern itself get disturbs. Less suited for liquid flows, but for hot flame version can be used, but for actually we have other options for liquid flow measurement. So, hot wire anemometer or hot film anemometers are extremely popular for gas flow measurement, but for liquid flow is generally prefer other options.

Like very simple we can go for the obstruction meters like venturi meters. There can be some pressure drop because of the intrusive nature they are very fragile can be expensive depending on which range that you are working with frequent maintenance requirement and large power consumption depending upon which mode you are working constant temperature mode or constant heat flux mode you always need to supply large amount of power. Despite that hot wire anymometer remains probably the most common option of gas velocity measurement. And you can easily see this one in several laboratories like in our laboratory also we have this one we use this for undergraduate experiments.

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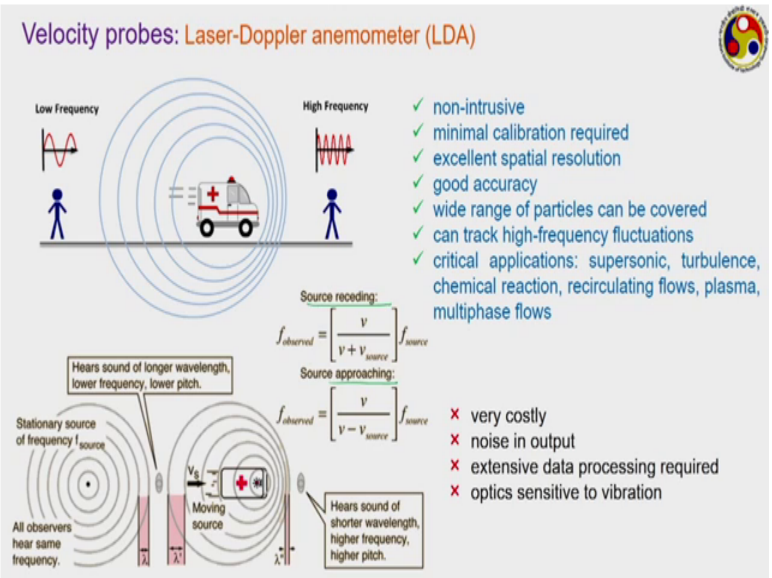

Finally, I would like to conclude these using two very advanced method of velocity measurement. One is the laser Doppler anemometer you definitely are aware about the Doppler effect like when a car is approaching like on shown here it is the car which Sidon is approaching you, you it seems that the pitch is higher when it is going away from you it seems the pitch is reducing despite sound is having the same velocity. That is happening because when there is a the source itself is stationary then all observer here with the same frequency. However, when the source is moving the frequency keeps on changing. Like when the source is approaching the observer there is an increase in the frequency. Whereas, when the source is moving away from the observer there is a reduction in the frequency.

And this particular effect is used in laser Doppler anemometer. Where we supply certain kind of sound wave and as it strikes the particles present in the flow and that comes back depending on which direction the particles are flowing there is a change in the frequency of the particle. That is the we use the scattering principle here scattering of sound with this. There again very advanced to a velocity measurement and non intrusive one hardly any calibration required they have excellent spatial resolution and dynamic response. Very good accuracy wide range of particles can be covered with this and they can easily track high frequency fluctuations.

So, even when highly turbulent flow you are dealing with you can make use of this laser Doppler anemometer or LDA which is more affectionately called. Critical power applications like supersonic flows highly turbulent flows chemical reacting flows recirculations natural convection flows plasma based flows multi phase reactions or multi phase flows we this one can is conveniently used. Problem is the cost there can be noise in the output also extensive data processing is required to get the final value of velocity. Optics can be sensitive to vibration. So, these are certain issues, but still it is a if you can afford the cost then this is something that you can always go for very precise velocity measurement.

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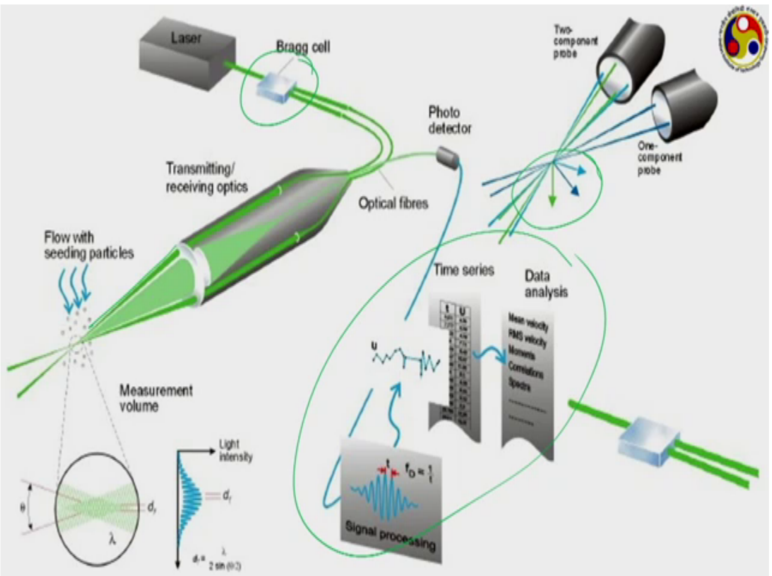

This is a more complete diagram. Here we it starts with a laser then we have a black cell here the objective of black cell is to split the laser beam into 2 beams it acts as a beam (Refer Time: 61:53). Then it goes through this transmitting receiving optics. And now there are 2 this a laser sheet is produced. There are certain particles which are present in the flow the beam gets deflected or scattered by these particles. And subsequently there since, there is several as shown in this here there are several software dominated data processing that are required for the final measurement.

If we are looking for one dimensional measurement then just one this particular item it is sufficient, but if you are looking for 2 dimensional measurement then we need 2 component probes just like this which is producing actually 4 beams and giving you 2 velocity components and if we are looking for 3 dimensional measurement then we combine 2 component and one single component beam like the arrangement shown here and thereby resolving all the 3 velocity components; an improvement on this l D s.

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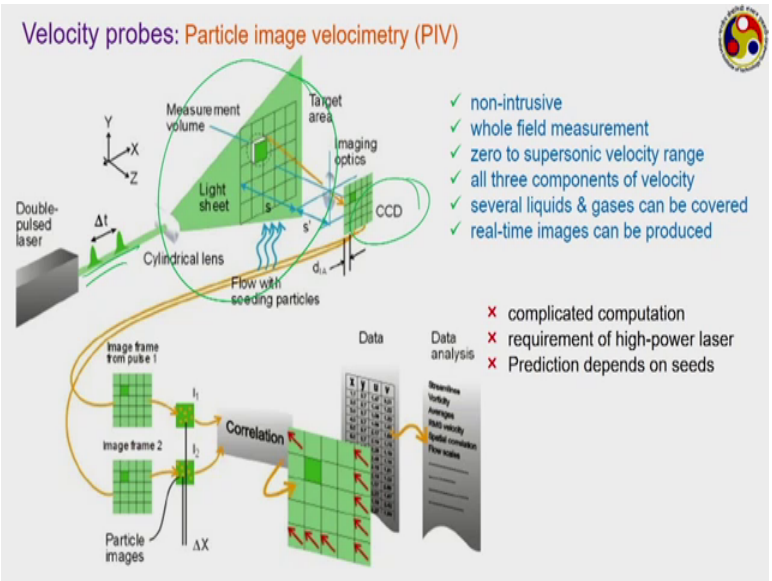

Particle image velocimetry where instead, of the scattering feasible actually we use the photographic principle. You we produce a double pulse later like shown here. And that produces a light sheet and then using some suitable camera like C Cd cameras we get a velocity field a picture of the velocity field. In case of something I forgot to mention in case of l D s there actually we need certain kind of scattering element. Now, if you are dealing with liquid there is already naturally sufficient amount of seeding a materials are present, but if you are dealing with gases then we additionally you have to seed them using some external particles.

And the choice of seeding particle is important because the particles should be light enough. So, that it can flow with the gas; however, it should also be large enough. So, that it can scatter the particles scattered the light. Generally, there of size one to 10 micron depending upon what kind of medium you are dealing with. The same is required in case of PIVs also, but here we are not depending on the scattering principle, rather we are taking a picture of the flow field as the light is falling with this and the particles are moving with the flow stream with the stream lines then we can get a proper picture of the stream line itself.

PIV is probably one of the most advanced way of flow measurement it is a non intrusive one whole field measurement because we get a picture of the whole flow field which is not possibility anything else that discussed here. 0 to supersonic velocity range we can go for with extremely high accuracy all the 3 components can be resolved. Several liquids and gases can be covered and we can get real time image. Just what you can think about a flow field exactly the same you can get from PIV.

Actually l D V and PIV etcetera and also the flow visualization these topics are advanced level topics not suitable for undergraduate course. That is why I am not discussing at all about the flow visualization, but still I thought about giving a very brief introduction about the LDA and PIV if any of you are interested you can go to knit. There are your innumerable amount of materials available you can go to u tube also to see some videos about the working. Just I have to mention for academic purpose of PIV has disadvantages the form of complicated computations but generally when someone purchases a PIV on the corresponding processing circuitry and processing software comes with thus that itself.

High power laser is required which is which can be dangerous for life cells. So, we have to be careful expertise is required both in handling the instrument and also in the subsequent data processing stage. And prediction is dependent on the nature of the seeds. Just to give you an idea the cost of one proper PIV machine can be easily in the range of 80 lakh to one crore. So, we are talking about extremely costly technology here. And expectedly they can be very precise in their measurement.

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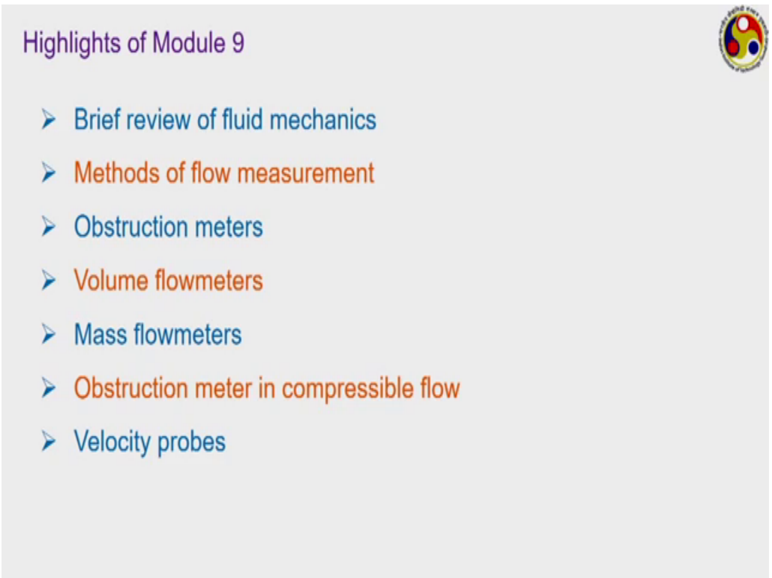

So, that takes us towards the end of this course as I just mentioned there is another way of flow measurement is the flow visualization in the form of leading seed shadow graphs etcetera, but we that is that are part of advanced level discussion. So, in a basic level course I do not think we should go there. And so, we are restricting ourselves here itself. Then what we have done in this week we started with a brief discussion of fluid mechanics Bernoulli's equation then we talked about different methods of flow measurement.

First one that we talked about is at the obstruction with mist meters like venturi meters flow nozzles laminar flow meters. Then volume flow meters several common ones have been discussed like the turbine flow meter electromagnetic flow meter ultrasonic flow meter. Today we have also discussed about the vortex shedding flow meter and also the positive displacement or so, called p D flow meters that you have discussed under this.

Then we talked about two different kinds of mass flow meters one is a Coriolis mass flow meter a very popular one and also the thermal mass flow meter then we discussed about the use of obstruction meter incompressible flow just a very brief introduction. Mind you the principle of this compressible flow can also be used in the pitot tube the expressions for pitot tube that we use they are also used the Bernoulli's equation. And so, they are applicable only for incompressible flows, but just the way we put a density correction factor in obstruction meters the same correction factor can also be used increase of pitot tube if we want to use that for compressible flows.

So, we finished with the discussion and velocity probes where we discussed about pitot tube. Then the anemometer e and then 2 advanced equipments in the form of laser Doppler principle and particle image velocimetry. So, that is the end of this particular module. I hope you have got idea about several very common starting from very simple to most advanced flow measuring instruments.

And I am sure you will find them interesting. Like I have shown a few sample videos here lots of such videos are available on YouTube you can search there and get more idea about the working process particularly the LDA or the PIV. So, that is it for this week. Next week I shall be starting the discussion on another very, very important parameter for process engineering, that is temperature.

Till then, bye.