Mechanical Measurements and Metrology
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Module -2
Lecture - 26
Measurement of High Vacuum

Welcome to lecture number 26 of mechanical measurements. In the last lecture we were actually discussing about the measurement of vacuum pressures, pressures below the atmospheric pressure. We considered one simple case of measurement using a McLeod gage which is some kind of a mechanical contrivance because it uses the manometric liquid as a compressing fluid which is going to compress air or any residual gas in the vacuum system to a pressure higher than the pressure early at the beginning so that the change in the volume is related to pressure. We also solved a problem based on this McLeod gage.

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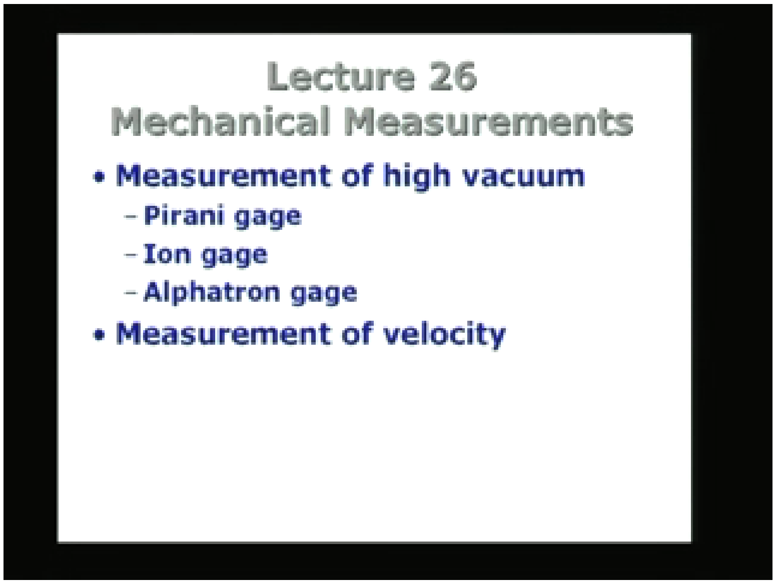

To continue with the measurement of vacuum we are going to look at the measurement of high vacuum. The three gages to be discussed are the Pirani gage, the ion gage and the Alphatron gage. We will also look into the measurement of velocity which is also a very important activity in most laboratory practice. As our part of study we must also look at the measurement of velocity because in many cases the velocity signal or the velocity information is converted to a pressure information. Measurement of high vacuum: The principle of the Pirani gage is very simple.

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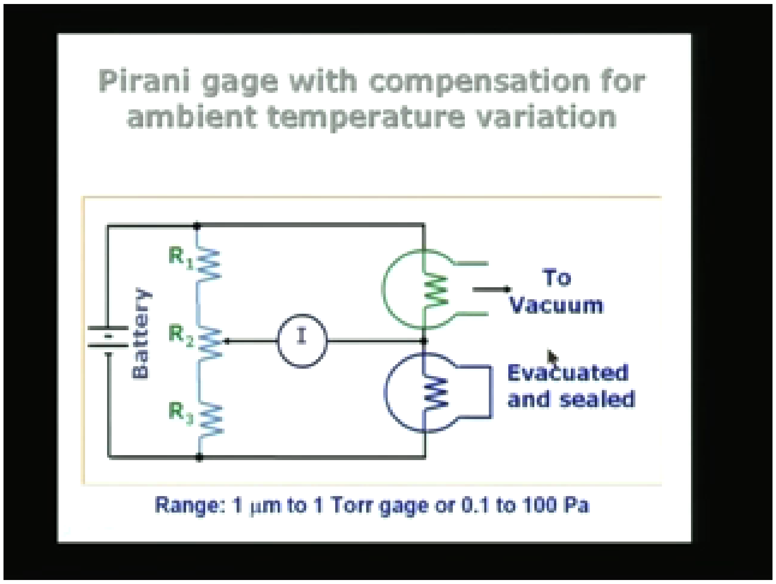

If you have an electrically heated element, the amount of heat that can be transferred from the heated element is related to the speed with which this can be carried by the surrounding fluid. And as the surrounding fluid pressure reduces the amount of heat it can take away also reduces. Therefore if you heat an element it will be in the presence of the background pressure which may be vacuum pressure. In the vacuum as the pressure reduces the temperature of the element will increase if we keep heating the same amount of current. In thermometry, if you have a resistance element and we heat it or we pass a current through that then its temperature is going to increase and as the temperature increases the resistance of the element also changes. So the change in the resistance is what is going to be measured just as we did heat thermometry. But here instead of relating the change in the temperature or the change in the resistance as a consequence of the change in the temperature we are going to link it with the pressure in the background.

So it is essentially the RTD principle but it is called the Pirani gage and what we have here is the schematic of a Pirani gage. We have two elements; this is resistive element one and this is resistor element two. the first one which is shown in green color here is in communication with vacuum whose pressure I want to measure and the second one is a compensating resistance which is going to be put inside a sealed vessel, evacuated and sealed, evacuated to a very low pressure, either very higher vacuum or very low pressure. Therefore the evacuated and sealed gage which is shown here will not respond to the change in pressure because there is no change in pressure here but it is going to respond to change in the ambient temperature.

So if the ambient temperature changes it is going to respond and the ambient temperature is also going to change the resistance of this therefore that is going to compensate. So when we said Pirani gage with compensation for ambient temperature variation what I mean is that I am going to use this evacuated and sealed gage as a compensating element whose change in resistance because of the ambient temperature is going to compensate for the changed resistance of the gage here. I have a source of power and the source of power is going to set a current through the gage here and also the gage. it is also going to send a current through R_1,R_2 and R_3, R_3 is a variable resistor. so what I do is I treat is I treat R_1 this gage, R_3 the compensating gage as a Wheatstone bridge here this forms one arm of the bridge and this forms the other arm of the bridge and the other side is connected to the negative of the battery and the battery is going to provide a source of power, it is going to heat the resistance here,and also the resistance here by sending a current through the element.

When R_1 this resistance, this resistance can be balanced and when the temperature of this changes with respect to the temperature of this, then the resistance is going to change. So I am going to keep a constant current through this circuit here or a constant voltage is supplied here, the resistance of this element is going to change because of the pressure to which it is exposed. Therefore the bridge is going go out of balance and a certain imbalance current will flow here and this imbalance current will directly be proportional to the vacuum pressure. So, in the case of Pirani gage we essentially have two RTDs or Resistance Temperature Detectors like structures here, these two are heaters, the temperature of the wires change in response to the vacuum pressure. Therefore the resistance changes and because of that the Wheatstone bridge circuit is go out of balance and the imbalance is measured by the current which is shown here.

The range of this instrument is from 1 micro meter of pressure that is 10 power minus 6 mm of mercury to 1 mm of mercury 1 Torr gage or point 1 to

100 Pascals is the range of this particular instrument. Usually the Pirani gage is used with the rough vacuum pump and the rough vacuum pump reduces the pressure of the vacuum space to a value lower than the atmospheric pressure and it reaches the value somewhere in this vicinity. Up to this we can use from 100 Pascals to about point 01 Pascal we can use the Pirani gage. If the vacuum pressure is even lower, that is higher vacuum, lower pressure I will have to use a different type of gage. And for that I use what is called an ionization gage.

Principle of ionization gage: Essentially what the ion gage has is, ionization gage or the ion gage consists of an evacuated glass envelope within which we have a plate, three electrodes essentially, one is the plate, second one is grid in the form of a perforated sheet or it may be in the form of a cylinder so I have a grid, and then, I have a hot filament which is the cathode. This filament is indirectly heated so that it is at high temperature. Actually it is going to glow like the filament in a bulb and therefore it is going to be quite hot. That is one type of ion gage where the temperature of the filament is high and if the hot cathode which is going to give out the electrons. The electrons are going to be released by the hot method by a thermionic emission.

Now let us see what happens to these electrons. Electrons are going to move from the filament to the grid because I have got a certain potential difference between the filament and the grid. I have connected a battery here therefore the grid is positive with respect to the filament or the cathode.

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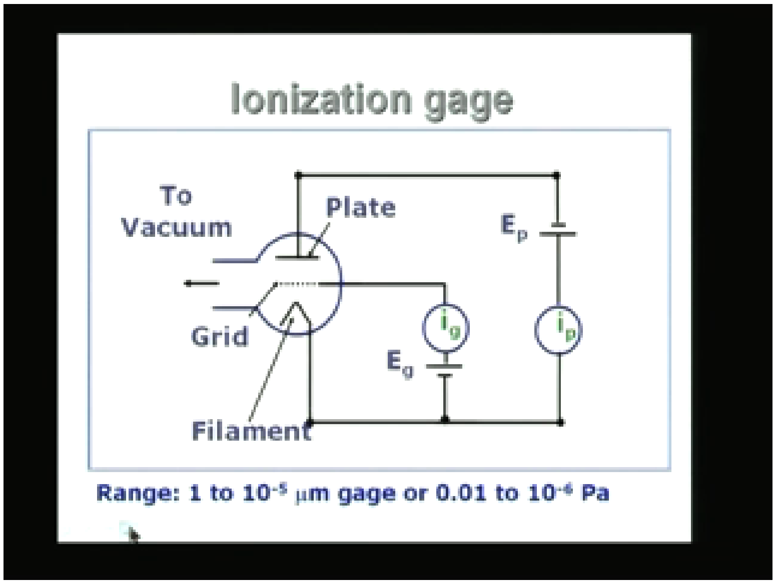

The electrons which are ejected from filament are going to be accelerated towards the grid because it is a potential higher than the potential of the filament. So the electrons are going to move in the direction from the filament to the grid. Here this is connected to the vacuum system whose pressure I want to measure therefore there are some residual molecules which are present inside this envelope here.

So, the electrons which are moving with high velocity because of the accelerating potential are going to hit or collide with the gas molecules which are still present within this space. Of course the number of gas molecules present will be reducing as the pressure becomes smaller and smaller. So the gas molecules are going to be hit by the electrons and the gas molecules are going to become ionized. Therefore these ions are going to be positive ions. Therefore if I have a plate which is connected to a battery here such that the plate is negative with respect to both the grid as well as the filament. Therefore the positive ions are going to be accelerated towards the plate and all ions are going to be neutralized on the plate and therefore the ions will go through this circuit and give a current due to the ions which I call as the plate current i_p. The plate current is because of the ions which are going to go and hit the plate and go through this circuit.

You also remember that we also talked about the electrons to start with. These electrons are going to accelerate, hit the molecules, ionize them and continue towards the grid and the grid is at a positive potential with respect to this therefore the grid will pass through this circuit and provide a grid current. There are two currents here. The first current due to electrons is through the grid circuit and this is called the grid current i_g. The second one is the current through the plate circuit which is called the i_p or the plate current. There are two currents; one due to the electrons and the other due to ions.

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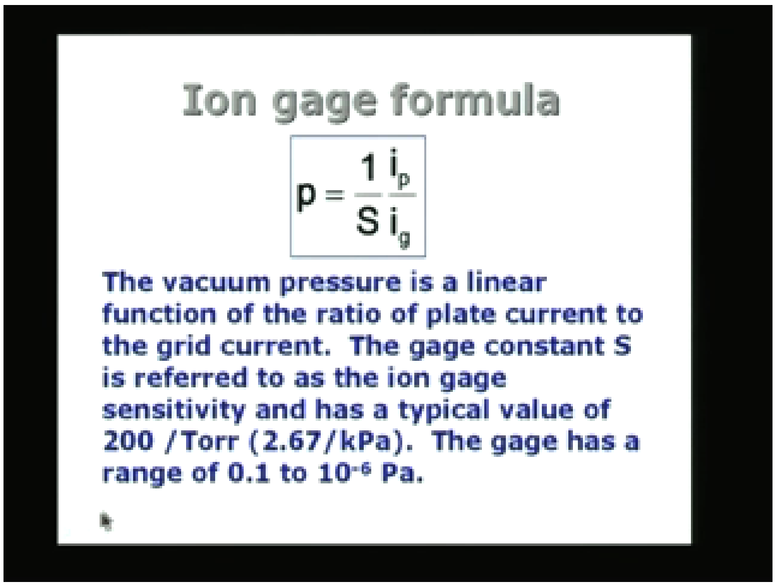

The relative magnitudes of this: as the number of molecules are going to dwindle, going to come down, the plate current is going to reduce because the number of gas molecules which are there to be ionized are becoming smaller and therefore the plate current will become smaller and smaller as the vacuum becomes higher and higher. Therefore the ratio of these two currents the plate current and the grid current is the crucial thing which is going to tell us what is going to be the pressure. The range of this instrument is 1 to 10 to the power minus 5 micrometer gage or point 01 to 10 to the power minus 6 Pascal. Here we are talking about very high or very low pressures.

The relationship is, the pressure inside the chamber inside that glass envelope is given by the ratio of plate current to the grid current. As the vacuum pressure is becoming smaller and smaller, the plate current is going to become smaller and smaller and the grid current is going to become relatively larger. Therefore this ratio is becoming smaller and smaller so as the pressure inside the chamber becomes smaller and smaller. That means it is higher and higher vacuum. The pressure is actually proportional to ratio of the plate current and the grid current with a sensitivity factor 1 by S where S is called the sensitivity factor.

The vacuum pressure is a linear function of the ratio of plate current to the grid current. Therefore you have to measure the plate current, measure the grid current and take the ratio. Of course all these can be done electronically multiplied by 1 by S and what you see is the meter that indicates the pressure directly in so many micrometers of mercury.

The gage constant S is in fact called the ion gage sensitivity and typical value of that is 200 by Torr per unit pressure. The unit of pressure used is 200 by Torr or it will be given in terms of 2 point 67 by k Pascals. The gage has a range from point 1 to 10 power minus 6 Pascal. This is the range of the pressures which can be measured. The plate current becomes smaller and smaller as the pressure becomes smaller and smaller. The gage pressure remains more or less the same. Therefore the pressure is directly proportional to the gage current and of course inversely proportional to the grid current and the grid current will also vary to some extent and the plate current variation is actually going to mirror the pressure inside the envelope. Usually the envelope is made up glass and the filament operates around 2500 degrees like the electric bulb and usually it is connected to the vacuum chamber either from outside or it is allowed to hang inside the vacuum chamber. If it is allowed to hang inside the vacuum chamber it also provides illumination. So we can actually use it to see what is happening inside the vacuum chamber. So there is an advantage of putting it inside the vacuum chamber, allow it to hang inside there and it is going to measure the pressure at the same time also provide illumination within the chamber itself.

And usually the way we operate the ion gage is, first you turn on the rotary vacuum pump which will reduce the pressure to a sufficient low value so that we can turn on the high vacuum pump, either the diffusion pump or any other pump which is going to be used for creating higher vacuum and that will be operated or that will be started only after the pressure has reduced sufficiently. During the first part when the rough vacuum pump is on we can use the Pirani gage which will be attached to the vacuum system. It will show the minimum value after sometime. After the pressure has come down to a sufficient low value the Pirani gage will indicate almost 0.

That means it cannot indicate anything sensitive and the sensitivity is very poor there. So at that time the ion gage will take over and the ion gage will give you the pressure. This is how it is going to operate. The ionization gage can also replaced by what is called a penning gage. The working principle between the ion gage and the penning gage is the same but the only thing is in the case of the penning gage the filament is not hot. However what we do is we have a very large potential difference so that the ionization of the residual gas takes place because of the high electrical field near the cathode. So when you have a very high electrical field that ionizes the gas instead of the hot cathode which is going to evolve electrons.

The way the ionization is going to take place in different in the penning gage. Penning is the name of the gage, it is different from this. You can also have a cold cathode gage which is also called the penning gage. The third one is called the Alphatron gage. Again the principle is similar to the previous gages. The principle is that, you must some how ionize the gas. If you ionize the gas or the residual gas which is present inside the gage or in the vacuum chamber it will create a current, this is the principle and the current will be smaller, smaller the pressure. So, the way we are going to create the ion is different in the case of Alphatron.

In the Alphatron we have radio active source and it ejects the alpha particles. for example, I can have a piece of radium here it gives out alpha particle these alpha particles are going to bombard at the gas molecules and the gas gets ionized. There is no high temperature involved, no current involved here, the radium source is put inside the gage and the gage is of course connected to the vacuum chamber at the side here, the radio active source is kept here and we have a needle which is the ion collector. The needle is introduced like this and is insulated from the body and the body itself is in the negative electrode. On the outside I have got a resistor and a potential difference by a battery.

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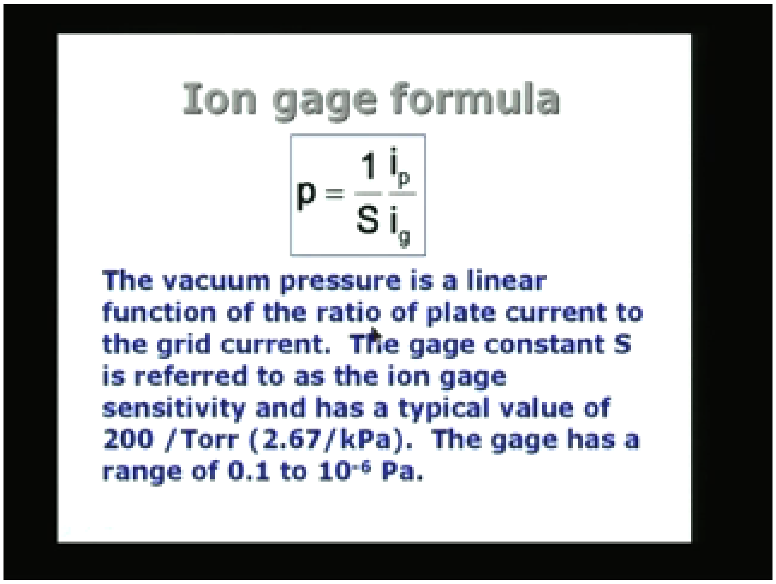

And what happens is that, the ions are going to create a current and the current is going to pass through this, and there is a certain potential difference across the resistance which is going to mirror the pressure inside. The advantage of Alphatron gage is that we can work from the highest pressure to the lowest pressure without any problem because there is no filament and there is no problem with any of those structures and it will work even at the atmospheric pressure. That is why I have said that the range is point 001 to 1000 Torr point 001 mm of mercury to the 1000 Torr or point 01 to 10 power 5 Pascals.

Alphatron is actually the trade name or the gage made by the Alphatron Company. So the advantage of this is that we can go from atmospheric pressure all the way to the vacuum pressure. There is no need to worry about the safety of the gage. Only the radio active piece of material is going to be present there. To summarize we have considered different types of pressure measurement instruments starting from manometer we also considered different types of gages and then we also discussed the transient response of these gages due to process connections and so on and then we have looked at the measurement of vacuum pressures of very low pressures.

The next quantity I am going to look at is the measurement of velocity. Of course velocity measurement may involve the velocity of particles; it can involve the velocity of the liquids or gases. Let us look at only the measurement of velocity of liquids or gases. We are going to concentrate on the measurement of velocity of either liquids or gases and therefore we can say the fluid velocity is the 40 degrees special. Corresponding to the fluid velocity,there is the measurement of flow rate. Suppose a flow is taking place within a duct or a tube we may be interested in measuring the velocity at every point within that fluid flow domain. We may also be interested in finding out how much fluid is crossing any cross section of the tube in unit time. So the measurement of flow rate is a sequel to the measurement of velocity.

I am going to look at the measurement of flow rate as a measurement of quantity, to start with you are looking at the pressure, temperature and the velocity are all variable with respect to location within the domain and therefore we are talking about functions of space and therefore these are field quantities. The velocity is now looked upon as a field quantity.

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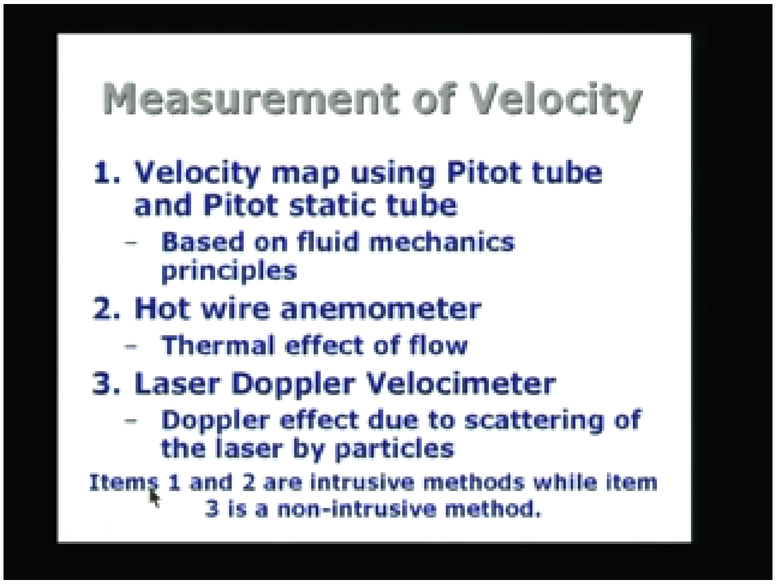

What are the different ways of measuring the velocity of a fluid? Here are few different types of measurement practices. One is to use velocity measurement use a pitot tube, this is a pitot tube or a pitot static tube. Either a pitot tube or a pitot static tube is going to help in determining the velocity at a point. Therefore I can use a pitot tube or a pitot static tube to map the velocity variation within a flow domain. That is an advantage of the pitot tube or pitot static tube. The operating principle of the pitot tube or pitot static tube involves fluid mechanic principles. Therefore we will learn these principles so that we can use pitot tube or the pitot static tube for the measurement of velocity.

The second method which you can think of is the thermal type of measurement. A hot wire anemometer is simply nothing but a resistance whose temperature is going to respond to the velocity of the fluid which is flowing pass time. Just a little while ago we talked about a Pirani gage. In the Pirani gage the temperature of the heated element depends on the ambient pressure.

So the pressure reduces the temperature is going to increase because we are putting a certain amount of heat into it by sending a current and the temperature is going to increase as the pressure decreases. In the case of Pirani gage we are looking at the pressure as a function of the temperature of the element whereas here in the case of a thermal velocity measurement technique which is known as hot wire anemometer, I am going to send a current through an element and either keep the temperature of that element constant or allow it to vary there are two different ways of working with it.

The basic principle is that, the amount of heat that can be dissipated from the element depends on the flow velocity. If the flow velocity increases we know from our heat transfer studies that the heat transfer coefficient is going to increase because of convection. And the heat transfer coefficient increases for a given temperature can dissipate more heat or if you put a given amount of heat the temperature of the element is going to become smaller. If the temperature reduces the resistance of the element will change and again change in resistance can be measured as the change in the temperature and the change in temperature can be ascribed to the velocity of the fluid. So the hot wire anemometer is a thermal effect meter. Thermal effect or flow on a hot wire element is what is used in a hot wire anemometer.

The third one is called the Laser Doppler Velocimeter. In this case, of course, the Doppler effect is going to be the main method. The Doppler effect takes place when the laser light is scattered from particles present naturally in the flow. When the flow consists or contains some particles, if we assume that the particles are moving along with the flow at the same velocity the laser beam is going to strike on the particles and therefore they are going to be scattered. And because of the velocity of the laser the light which is scattered is going to have a different frequency. So we are going to measure the Doppler shift in the frequency and we are going to relate the Doppler shift to the velocity of the particle. And the velocity of the particle is going to be related to the velocity of the fluid which is carrying the particles.

If we assume that the particles are very small, and they do not have any slip with respect to flow of the fluid that means the fluid velocity and the particle velocity are the same and then by using the Doppler shift we can measure the velocity of the particle and say that it is same as the velocity of the fluid. The advantage of the Laser Doppler Velocimeter is that it is a non intrusive method while the two methods the pitot tube and pitot static tube as well as the hot wire anemometer are intrusive in nature. That means I am going to introduce some probe into the flow field and whatever may be the size of the probe however small it is, it is going to certainly affect the flow field. This is from fluid mechanics where we learn that there will be some kind of an effect of the probe on the flow field to disturb the flow field.

However, in the case of Laser Doppler the laser beam itself is not going to disturb significantly. Therefore we can say that the Laser Doppler Velocimeter is almost like a non intrusive method. So the three methods are labeled here. The first two are actually the probe techniques because we are going to introduce something into the flow and the third one is a non intrusive technique. We have only a light beam or two beams of light are going to intercept the molecules or the fluid which is flowing.

The third important point is that in the Laser Doppler Velocimeter the control volume over which is measurement is done is very small. That means it is almost like making point measurement. In the case of pitot tube, pitot static tube as well as the hot wire anemometer there is a physical size to the probe and therefore the velocity is average over this physical size which is not insignificant, it is going to be finite. Whereas in the case of Laser Doppler instrument the size of this control volume is so small almost like measuring the flow or the velocity at a point, that is the main advantage.

Therefore if I use a laser Doppler instrument and measure the velocities at various points within the flow I can get a very good map of the velocity field. Whereas the other two are going to give some what less accurate picture and the laser Doppler is going to give you a very accurate picture of the velocity field. The other types are as follows: The first type is the pitot tube and pitot static tube. The first one we have to look at is the velocity measurement using pitot tube and let us look at two things. One is how the pitot tube is arranged, what is the principle of operation and then the example.

Here is a tube which is carrying fluid flowing with a velocity v and my intention is to measure the velocity of the fluid. Actually the pitot tube is nothing but a small diameter tube with a hole in the front here at the tip and the hole communicates through this to a u tube manometer and the other end of the tube is connected to a static tap on the periphery of the tube. So there are two connections to the pitot tube. One is the connection here at the side of the tube that is called the static tap. We also have a hole in the tube which is going to be facing the flow. And here I have got a manometric liquid.

Now what is happening is that the flow is coming from this side, it is going to come and it is going to come to rest at the front stagnation point of the pitot tube which coincides with the whole in the front of the tube. The stream lines are going to divide and go from the sides. Therefore the pressure at this point it is going to be the stagnation pressure whereas the pressure measured by the static tap connected to the side of the tube is going to be the static pressure. The difference between the static pressure and the stagnation pressure is actually the dynamic end. At the end due to the velocity of this liquid or the fluid which is moving in the tube.

So the difference here hm is the manometric height which is measured here is convertible to a delta p and delta p which is measured by this head hm is nothing but the difference in pressure between the stagnation point and the static pressure at the valve. So the head h_m which is measured here, now we are converting the velocity which is going to give rise to an increased pressure at the stagnation point. This increase in pressure is because V is going to be brought to be 0 so this process called stagnation process. The velocity V is going to become 0 at the stagnation point here and therefore along this stream line if you apply the Bernoulli principle the pressure is going to continuously increase and become equal to the stagnation pressure at the stagnation point and the velocity is going to be 0 at that particular point. Here the pressure is going to be the static pressure.

Therefore the pressure difference between here, and here measured by the manometric head h_m is related to the pressure difference in turn related to the dynamic head which is in terms of V square by 2 which is the kinetic head or the velocity head. Therefore I can measure the velocity head from

h_m which is measured. This is the pitot tube with a static tap on the valve of the tube and the stagnation being shown by the hole which is going to be connected to this, this tube is going to give you the stagnation pressure and static pressure. In the case of pitot static tube what we do is, we combine the two on the same probe, we combine the static tap or the static hole as well as the stagnation hole on the same probe. In the case of pitot tube the pitot tube is separate, stagnation hole is different, the static hole is on the periphery of the tube. In the case of pitot static tube both the stagnation as well as the static holes are present in the probe itself.

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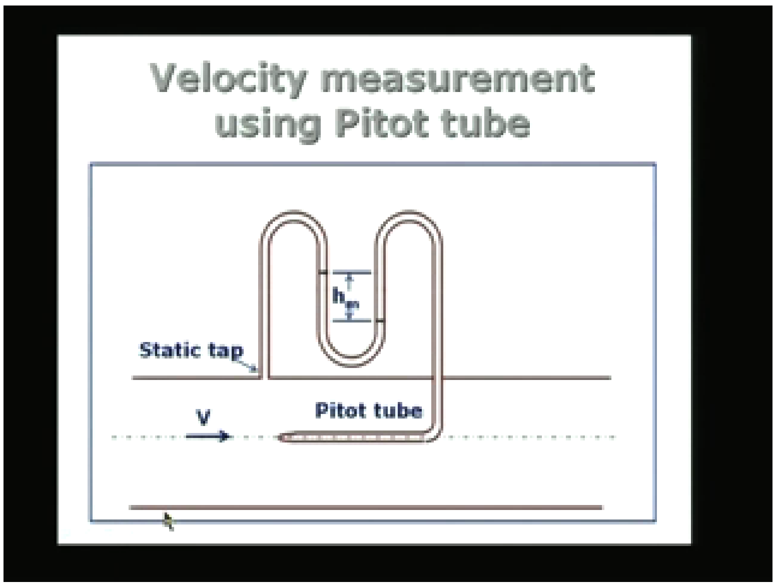

I have a tube which is going to face the flow, the velocity is here, the flow is taking place here. The probe consists of an inner tube, and there is an outer annulus which is connected to the other side of the manometer. So the outer annulus is connected to the other side of the manometer and here there are holes on the periphery of the outer tube somewhere down stream of the stagnation point. The stagnation point is here, the static holes are some what in the down stream of that hole.

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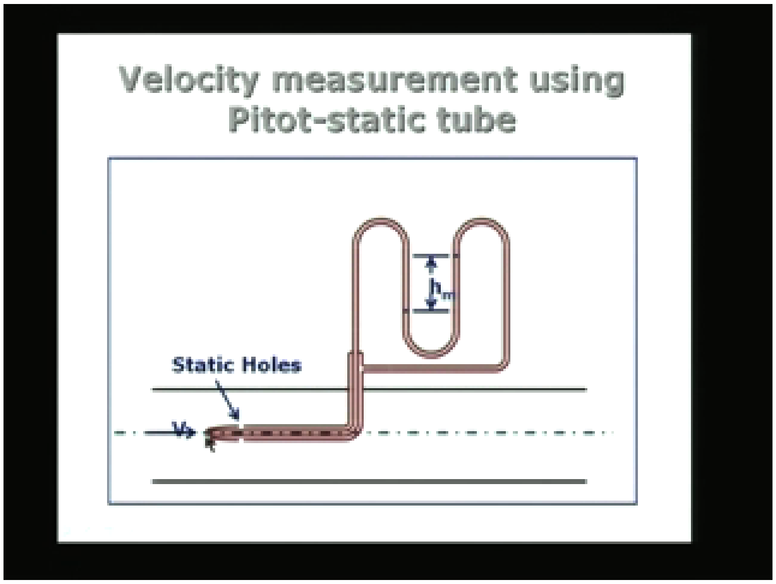

The static holes are on the annular portion, the stagnation hole is on the front and the pressure difference is between the stagnation point here and the static pressure through the static holes. And in fact what we normally do is, on the periphery of the outer tube there will be small holes uniformly spaced along the periphery of that tube. Therefore it actually averages of the pressure around the tube at this particular section. Again the stagnation pressure is acting on this side, the static pressure is acting on this side, the difference in head between the two sides is actually going to be dynamic head and the dynamic head is going to be related to the velocity and the velocity is therefore measured by measuring this head here.

Details of how the pitot static tube is actually made. This inner tube is connected to this portion here and the velocity is going to be v here and this is going to come to stagnation of this particular point .The static holes, about 4 to 8 1mm diameter holes on the periphery are going to be at down stream location, greater than 4D at least it should be greater than 4 diameter where diameter is the diameter of the probe, the probe can be about 7 to 8mm, this is about 8mm, 8mm is about third of an inch and the location is more than four times of that diameter typically eight diameter 8 into 8mm will give both 60mm from here to here. And between these holes and the place where this is going to be bent I must have eight diameter. The length from here to here is roughly equal to 16 diameters.

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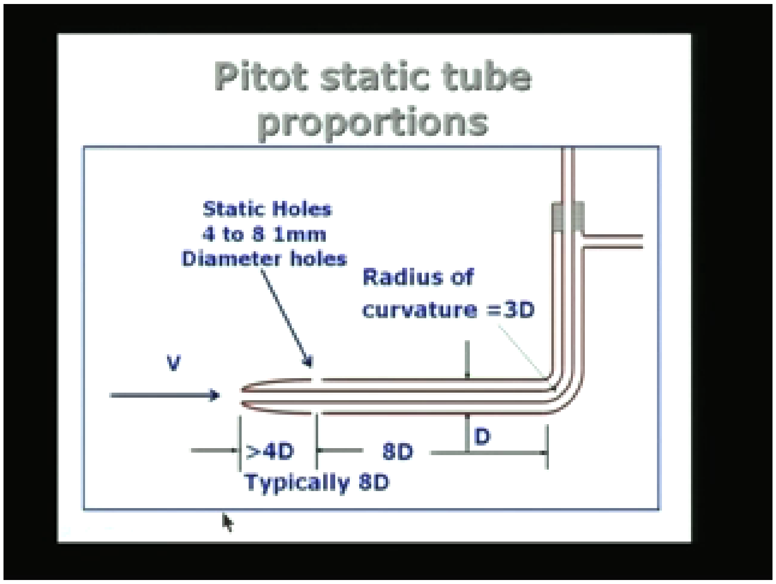

So, if you make the pitot static tube smaller in diameter this will become smaller. The length from here to here is dependent on the diameter of the probe itself. We can make probes as small as 2 to 3mm in diameter also. The curvature in this portion should be something like three times the diameter. The radius of the curvature of the mean line, I am talking about the tube mean axis of this one which should be about 3 diameter. Now let us look at the pitot tube as a means of velocity measurement.

Let us look at the basic fundamental ideas about it as what are the principles involved and let us look at what is going to be the relationship between the velocity and the pressure head we are going to measure during the manometer which is an integral part of the pitot static tube or the pitot tube. The pitot static tube or pitot tube I can represent by a bluff body like this. This is a body, the cross section is circular like this and it is facing the flow.

Flow is coming like this, and what will happen to that stream line is that the stream lines comes here, the neighboring stream lines are going to go like that and at this point we have what is called the stagnation point. So, I am going to apply the Bernoulli principle or Bernoulli theorem to a stream line. I will take a point very far away or I will take the point A_o here. Let us call this as point A, point A is far away. When I say far away I can interpret in the following way: Suppose this is the diameter I can take it a few diameters away essentially and I am going to apply the Bernoulli's principle which says that the total pressure or the stagnation pressure is a constant along the stream line. So I will say p_t is the stagnation pressure.

It is also called the total pressure. at the point A I am going to have a pressure equal to p infinity, this corresponds to p infinity and the velocity is U, U plus 1 by 2 $rho_{infinity}$ U square this is at the point A. And at O again the stagnation pressure equal to the pressure at O because U is equal to 0 at O. When U becomes 0 at that particular point the pressure goes up because the total pressure remains constant. I am assuming ideal fluid flow that means there is no friction and other things are ignored.

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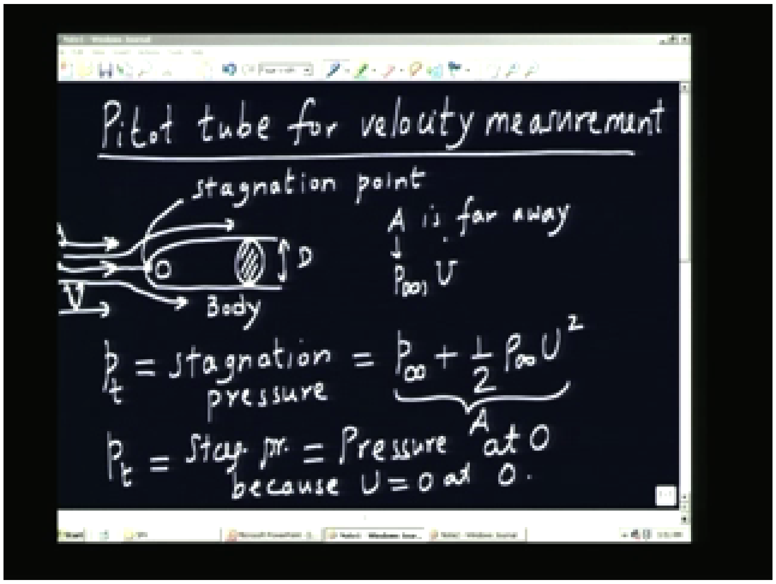

The total pressure or the stagnation pressure given by $p_{infinity}$ plus 1 by 2 $rho_{infinity}$ U square is the same as the pressure at the point O. So let us look at the consequences of that. The h_m is the pitot static tube or pitot tube reading using a manomteric fluid of density rho_m. We can see that delta p_m which is measured, the pressure difference which is measured will be given by rho_m g into h_m where rho_m is density of the manometric liquid. So, we have the manometric liquid density equal to rho_m.

We know that the pressure difference which is measured by either pitots tube with a static tap on the valve of the tube or pitot static tube both are going to give the same information. The advantage of pitot static tube is that

there is only one probe, you do not have to make hole on the periphery with the tube, otherwise there is no difference really.
The advantage is that you can just make one hole and introduce the pitot static tube into the stream. So rho$_{m}$ into gh$_{m}$ is equal to delta p$_{m}$ and this must be equal to p total minus p$_{infinity}$ because that is the pressure difference I am measuring. And from the expression for p$_{t}$ we know that p$_{t}$ minus p$_{infinity}$ is nothing but p$_{infinity}$ plus 1 by 2 rho$_{infinity}$ U square minus p$_{infinity}$ is equal to 1 by 2 rho$_{infinity}$ U square.

Remember that rho$_{infinity}$ is the density of the flowing fluid. And rho$_{m}$ is the manometric fluid density, rho$_{infinity}$ is the density of the fluid which is flowing in the tube. So I can combine these two now and say that 1 by 2 rho$_{infinity}$ U square is equal to rho$_{m}$ gh$_{m}$. Therefore I can solve for U the velocity. You can see that the velocity u I can make a little space here so U is equal to 2rho$_{m}$ gh$_{m}$ by rho$_{infinity}$ under the square itself.

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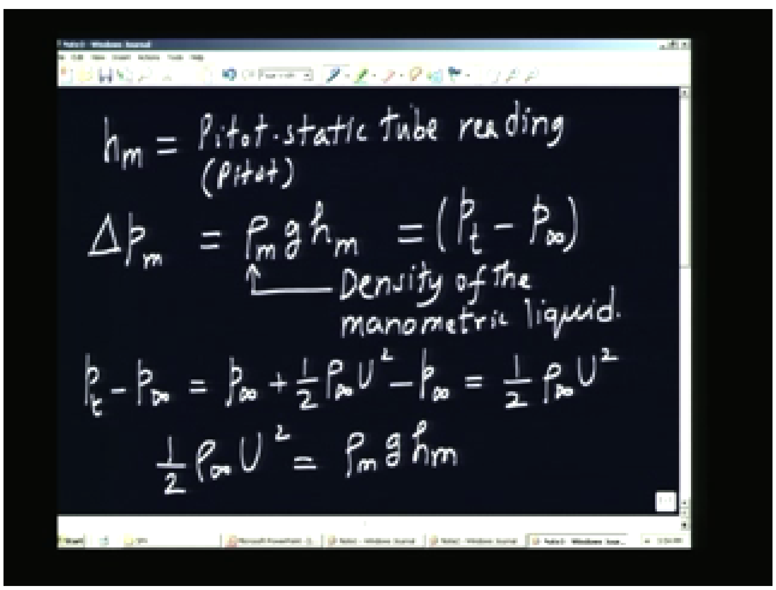

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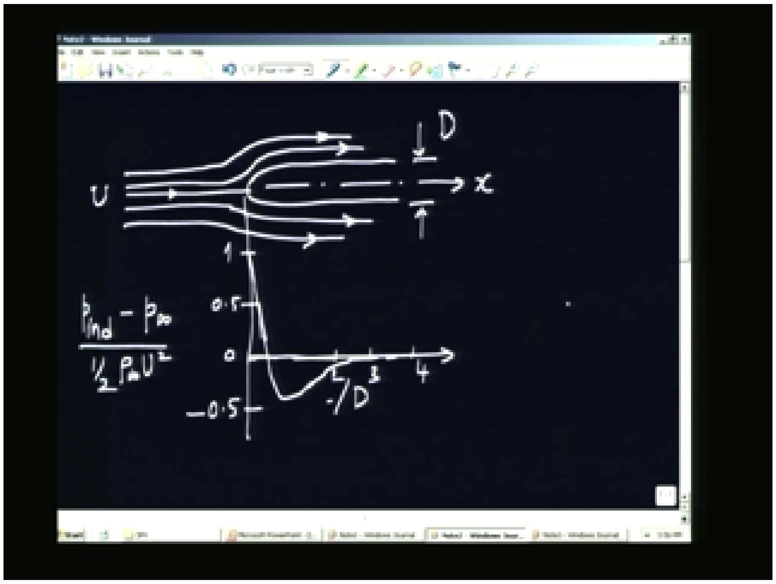

So the velocity of the fluid is equal to square root of two times in manometric density multiplied by the gravitational constant multiplied by the head which is measured by the manometer divided by the $\text{rho}_{\text{infinity}}$. Now we have converted the measure of velocity. This is nothing but some constant K square root of h_m, the relationship U is equal to some constant. Constant is nothing but this square root of 2 into rho_m g by $\text{rho}_{\text{infinity}}$ into this square root of h_m. So, the instrument is non linear basically because the velocity is proportional to square root of the head developed square root of h_m and the velocity information has been converted to pressure information and the manometer has further converted the pressure information to the head of the height of the column information.

Therefore I am measuring the velocity in terms of a manometric height which is going to be the result of the pitot static tube being used for the measurement of the velocity. Now let us understand the proportioning of the pitot static tube. Again I have indicated the pitot tube as a bluff body and I am looking at the change or the flow around this body. The flow is coming with a velocity U and because of the body it has to go around it. We are assuming that the flow is ideal without friction. The friction effect can be taken care of by a suitable factor. The diameter of the probe is D and what I am doing is I am trying to find out the relationship pressure variation with respect to the location along the body. For that I plot the p indicated at any location x measured as shown here.

Actually I am measuring x as a ratio of x to D. So I have plotted x by D so x by D is equal to 1, 2, 3 etc. I am measuring the difference between the pressure at any particular point minus the static pressure divided 1 by 2 $rho_{infinity}$ U square, this is the dynamic head or dynamic pressure. This is the pressure difference as a ratio of the dynamic pressure. And you remember, at the stagnation point this difference must be equal to the 1 by 2 $rho_{infinity}$ square.

Therefore the value of this will be exactly equal to 1 at the x is equal to 0 or x by D is equal to 0. And let us see what happens as we move along this. If I move along this the velocity is going to be change because it is now encountering a body it has to adjust itself so the velocity is going to continuously change. And in this portion the velocity is increasing and because the velocity is increasing the pressure indicated minus p infinity by 1 by 2 $rho_{infinity}$ U square is going to become smaller and smaller and at some point it is going to become equal to 0. That means indicated pressure equal to static pressure and then it keeps going down because the velocity is now increasing beyond that. Therefore it goes to a minimum somewhere here about point 8 or point 9D and then again the pressure starts increasing. And if you see here about x by D roughly equal to 4 this difference has become 0, the pressure has become equal to the static pressure.

That means somewhere here, if you measure the pressure by making a hole on the probe it will be nothing but the static pressure. Therefore the requirement is that x by D must be greater than 4 and normally we take x by D as about the value of 8 to be on the safer side. The second point is let us look at the flow around this body. If we assume that the fluid flow is taking place at a sufficiently high Reynolds number, so Reynolds number R_e if it is more than about 300 based on the diameter of the probe so R_{eD} will be nothing but U multiplied by D divided by nu where U is the velocity, D is the diameter of the probe and nu is the kinematic viscosity of the fluid which is flowing, if this is greater than 500 the boundary layer is very thin. And the pressure loss or loss due to friction is also very small. Therefore for values of R_{eD} greater than 300 the formula which I gave earlier is more or less fine. The formula can be modified by introducing a coefficient. Why do we require the coefficient? If there is friction there will some pressure drop due to friction.

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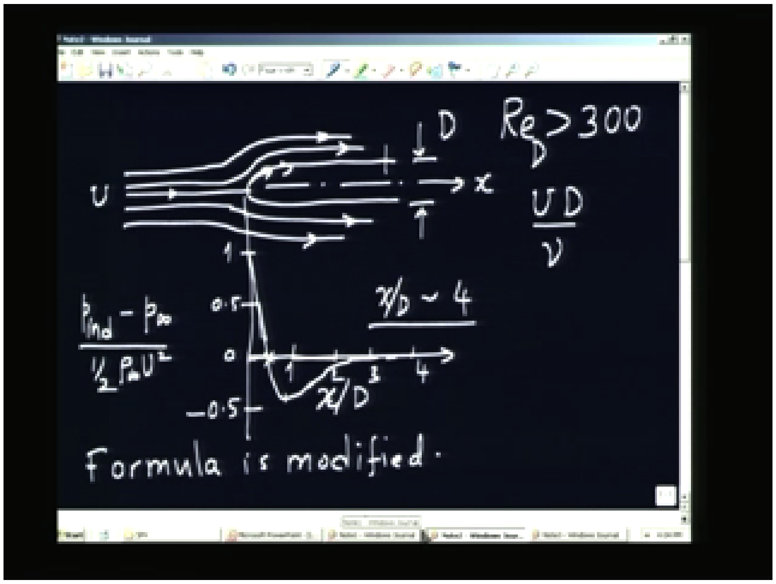

Therefore whatever pressure drop I am measuring it also contains some amount of pressure drop due to friction effect. But when I am measuring I do not know which portion is due to friction and which portion is due to the stagnation process. When I am stagnating the velocity it is going to added to the static head.

Now, because there is a certain amount of friction the amount of pressure difference consists also not only of the dynamic head but also of some amount of frictional head due to friction loss. As I do not know what it is, what I will be interpreting is that the pressure difference h_m rho$_m$ into gh_m is nothing but U square by 2, rho U square by 2 but it is not that, it also contains little bit of friction. Therefore I have to multiply the formula by a coefficient which you call as C. So, if I go back to the previous slide I will multiply this by a factor C. This C is something like point 98 to 1 depending on the Reynolds number. The Reynolds number is greater that 500 so R_{eD} greater than 500 C is equal to 1. So we can multiply by a small factor point 98 to account for the effect of friction. If you look at the flow around this body, if the boundary layer is very thin the boundary layer theory tells us that the pressure across the boundary layer remains the same. That means the pressure I am measuring is the same as the pressure in the main stream of the free stream here.

Therefore when I said the pressure has become equal to the static pressure the meaning is very clear. From here to here whatever pressure differences I am showing here are also the change of the pressure along the boundary itself. If you were to put a static hole all along this periphery and measure the pressure locally we will see that whatever value we are getting here is nothing but the static pressure variation along the boundary, this comes for the boundary layer assuming that the boundary line is very thin and that is satisfied once we have Reynolds number based on the diameter greater than about 300 it going to be thin and therefore it is more or less a satisfied requirement. But in order to allow for this small effect of friction we can multiply by the factor. I introduced a factor C which is between .98 and 1 to account for the presence of friction. I have conveniently put the probe such that it is exactly normal to the flow which is coming in the direction; the flow is coming directly on to the right.

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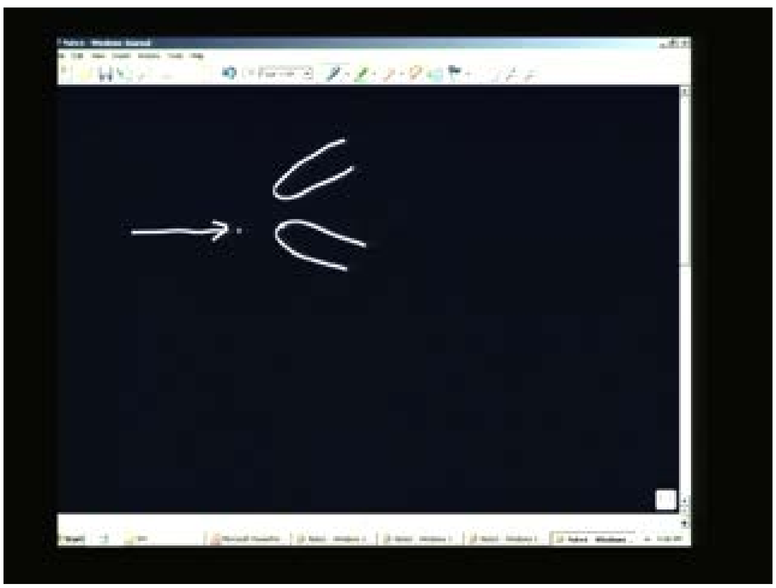

Suppose I do not know the flow direction, let us assume that is the flow direction, if I put the probe like this will it also give you the proper value. If I put it in an angle we can see what is going to happen. In some situations we may not know the direction of the flow and therefore we have to be careful about how to align the pitot tube to get the proper value. There are some probes which are specifically developed where a small amount of angular in accuracy or small angle in between the direction of flow and the direction of axis in the probe is not going to be important. Thank you.