Fluid Mechanics and its Applications
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Lecture 18
Flow Measurement

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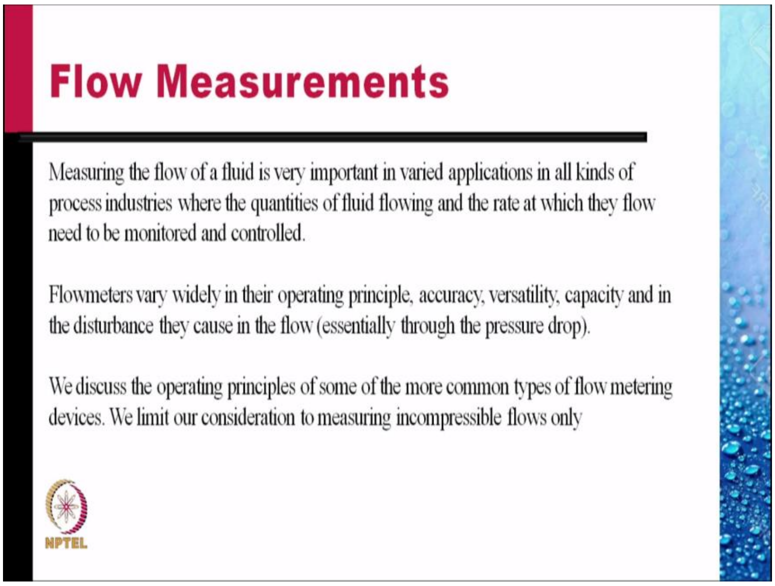

Welcome back.

In this lecture, we will cover flow measurement devices. Measuring the flow of a fluid is very important in varied applications in all kinds of process industries where the quantities of fluid flowing in and out and the rate at which they flow need to be monitored and controlled. Flowmeters vary widely in their operating principles, accuracy, versatility, capacity, and in the disturbance they cause in the flow, essentially through the pressure drop. We discuss here the operating principles of some of the more common types of flow metering devices. We limit our considerations to measuring incompressible flows only.

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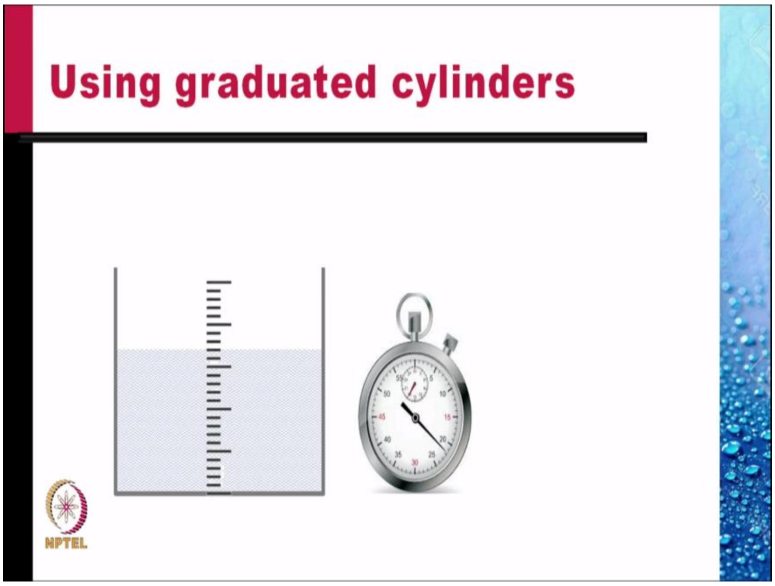

Of course, the simplest method of finding flow rate is to let the fluid or a liquid flow into a jar which is calibrated. We measure the amount of volume collected in a given amount of time as measured on a stopwatch, and from these we calculate the flow rate. This is a typical method you use in the undergraduate labs. But in industry, which are automated, this would hardly be desirable.

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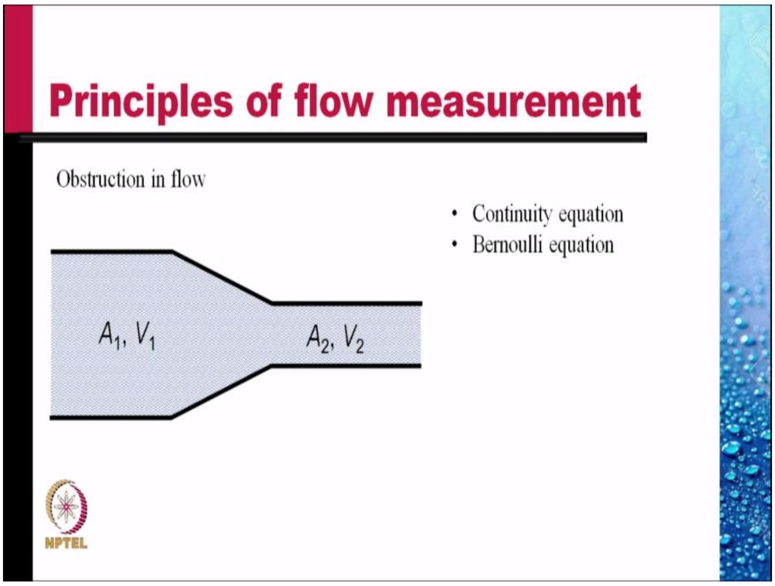

One of the basic principles of flow measurement is to create an obstruction in the flow, And as we create an obstruction in the flow, the velocity changes and the pressure changes, accordingly. If we carefully design an apparatus, we can create a situation in which the Bernoulli equation can be applied and then we can relate the flow rate to the change in pressure. So, we need continuity equation and Bernoulli equation to develop the relations for the flow measurement.

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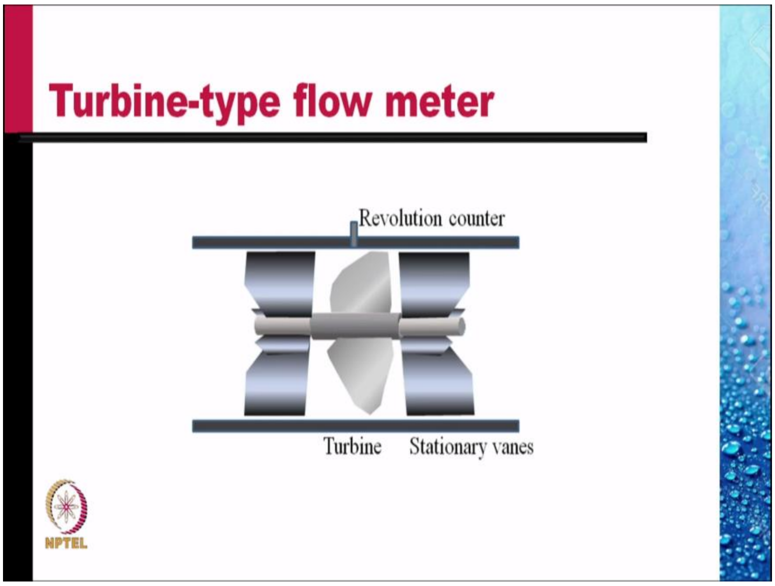

Another type of flow meter is what is called a turbine-type flow meter. In this a rotary blade, a turbine, is located between two sets of stationary vanes. As the fluid flows, the turbine rotates. The rate of revolution of the turbine is related to the flow rate of the fluid. A revolution counter is attached that will measure it.

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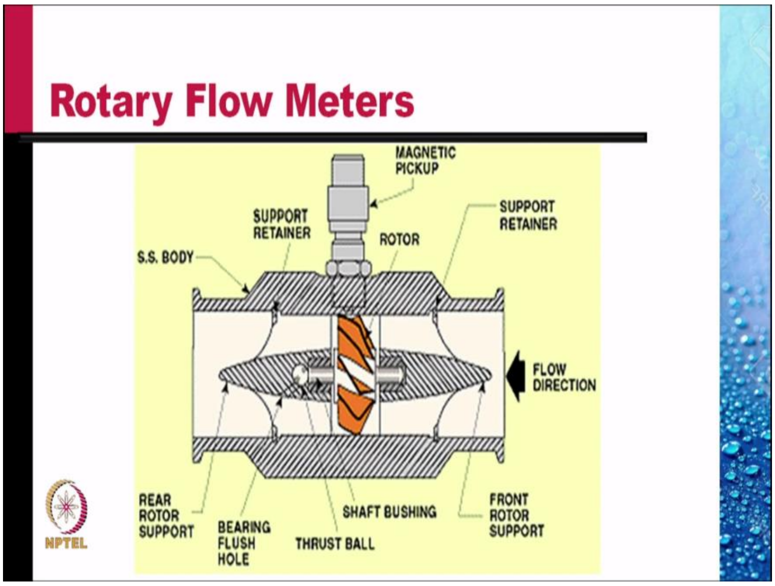

One design of such a turbine flow meter is given here. Here the central mandrel which holds a turbine. The mandrel is kept in place by a couple of retainers. A magnetic pickup picks up the rate at which the turbine is rotating.

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Another type of flow meter depends on what is called a pitot tube. It is very commonly used in aircraft applications. Here in this picture is shown a pitot tube attached underneath a wing of an aircraft.

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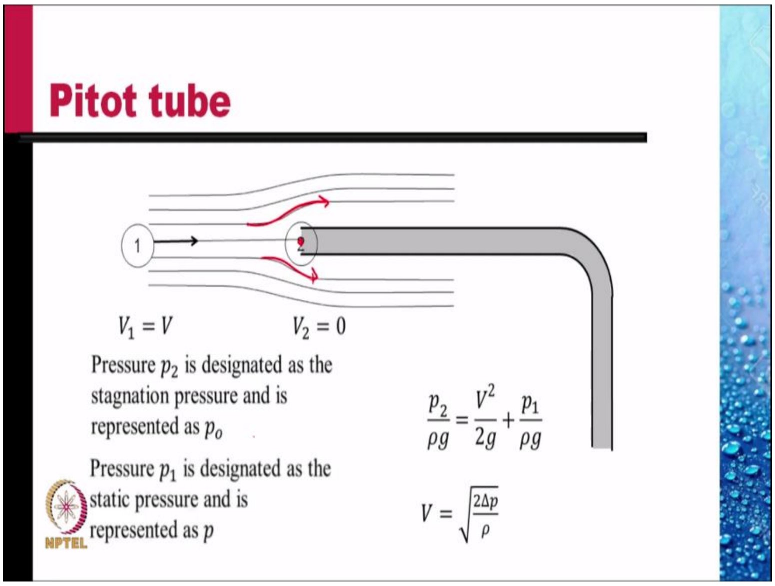

It works on the principle that can be explained in the following manner. Consider a central streamline. This streamline as it reaches the end of the tube, the front end of the tube, it is brought to rest. The fluid flows past this, around this. Since the fluid here can be assumed to be incompressible if the speed is quite low, then we can apply the Bernoulli equation between point 1 and point 2.

At point 1, the velocity V_1 is the velocity that we need to measure. The velocity V. At point 2, the velocity is 0. Because the fluid has come to rest, it is a stagnation point. If the pressure at point 2 is p_2 and the pressure at point 1 is p_1, then the Bernoulli equation simply gives you $\frac{p_2}{\rho g} = \frac{V^2}{2g} + \frac{p_1}{\rho g}$ and from this we get $V = \sqrt{\frac{2\Delta p}{\rho}}$, where Δp is a difference in pressure between point 2 and point 1. Very simple method of measurement, very accurate and has wide applications. Pressure p_2 is designated as a stagnation pressure, and is represented by p_o. Pressure $\frac{p_1}{\rho g}$ is designated at the static pressure, and is represented as p in most of the applications.

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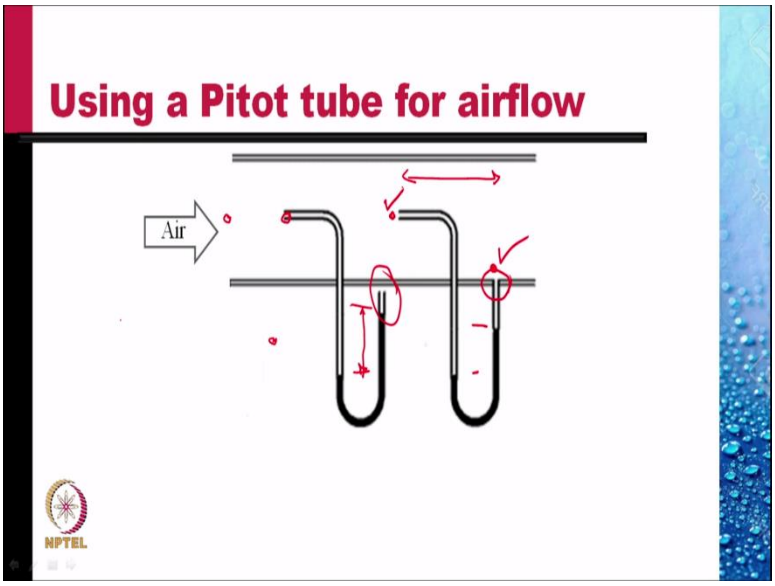

How do you use a pitot tube in an airflow? If the air is flowing, we could have the pitot tube arranged such that the end of the tube is facing the airflow. We could attach a manometer. The second limb of the manometer is open to atmosphere. So, the reading of the manometer would indicate the pressure difference between the stagnation point and the atmospheric pressure.

If the static pressure in the tube is atmospheric pressure, then this difference of pressure that this manometer measures is directly the pressure difference Δp of the last formula. In another arrangement, we connect the other limb of the manometer to the wall of the duct. And here the pressure difference measured by the manometer would be the pressure between this point and this point. If the pressure drop across this length of the duct is negligible, then this pressure here at this point can be treated as a static pressure p, and this is the stagnation pressure. So, the difference of the two pressure would be red here as Δp.

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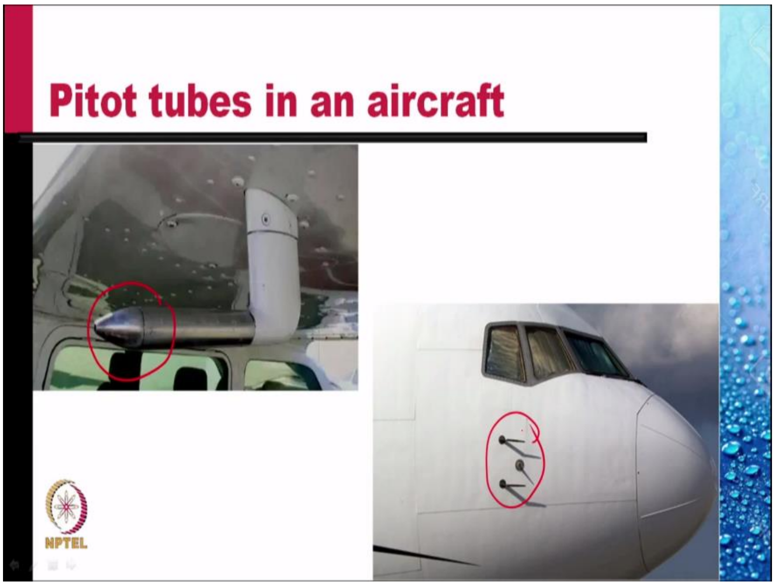

So, we need two pressures to measure velocity. One is the stagnation pressure or the pitot pressure, and other is the static pressure. The pitot pressure or the stagnation pressure is measured by the pitot tube. Same arrangement, another arrangement in the aircraft. These tubes are pointing in the direction of the motion of the aircraft, that is, in the direction of the oncoming fluid.

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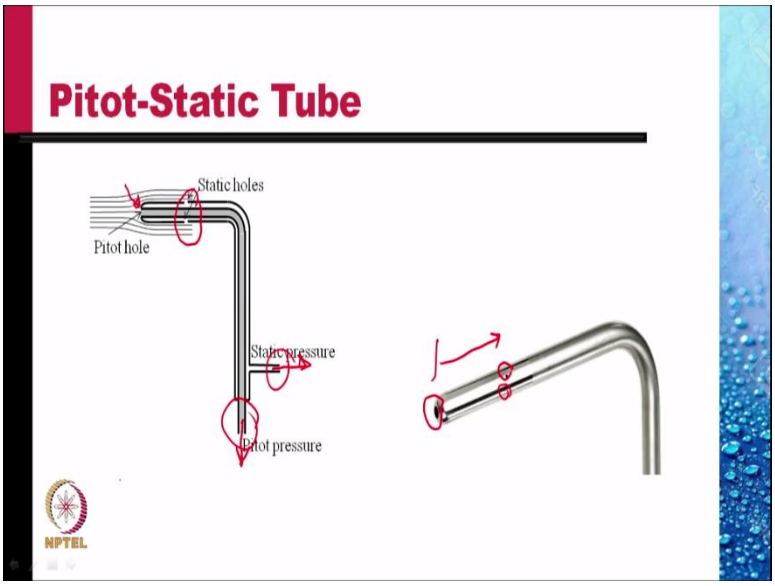

Another arrangement that is quite popular is what is known as a pitot-static tube, in which we pick up both the pitot pressure as well as the static pressure. The arrangement consists of two coaxial tubes, the central tube is open at the front end, here. So, it picks up the stagnation pressure, or the pitot pressure. On the outer sleeve, there are a number of holes which are called the static holes, and these pick up the static pressure at that location. And this outer sleeve communicates through this pickup point in the inner tube which picks up the pitot pressure communicates to this pick-up point.

So, we attach a U-tube manometer between these two ports, and that gives you Δp directly. Such pitot tubes or pitot-static tubes are used routinely in laboratory experiments. This is what a commercial pitot-static tube looks like. The pitot hole is right in front, and the static hole, a number of holes are about 10 diameters behind the tip of the tube. It is assumed that within 10 diameters, the disturbance caused by the introduction of the tube will die out, and the pressure here, the static pressure here, would be the same as the static pressure if the tube was not inserted into the flow.

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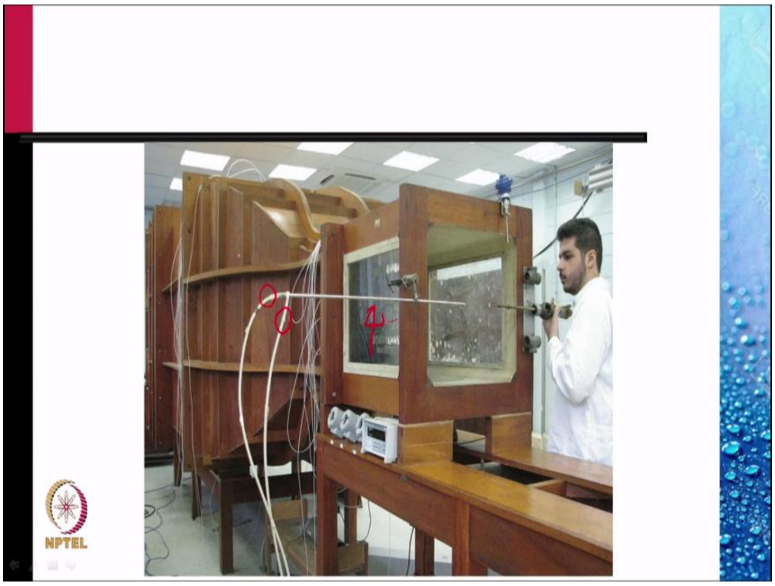

This is an experimental setup where a pitot-static tube is being used to measure the velocity profile across the test section of a wind tunnel. Here, this is the pitot static tube, two holes this is picking up the static pressure, and this is picking up the pressure, the pitot pressure. These tubes are connected to a manometer which measures the pressure difference. By moving this tube up and down, and left and right, we can investigate how the velocity of the flow changes across the section.

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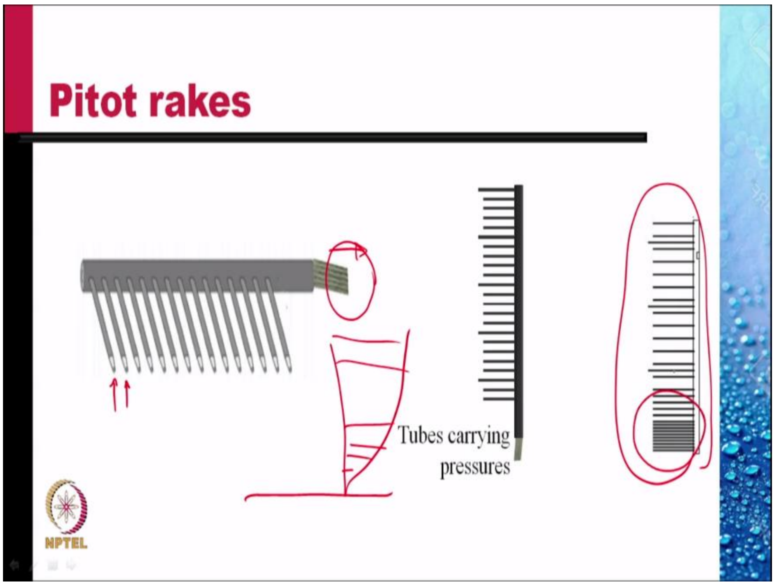

A pitot rake consists of a number of pitot tubes attached with a supporting structure. Each of these pitot tubes is connected to a tube, a flexible tube, right here, and if there are 15 tubes here, there will be 15 tubes coming out here. Each tube picking up the pitot pressure at the specific location. These are then connected to a multi tube manometer where you can read the pressure difference which is directly related to the velocity.

There are various arrangements for these tubes. For example, this rake could be used to measure the velocity profile across a boundary layer. When we have a wall, a boundary layer develops on it. In the boundary layer the velocity changes very fast near the wall and rather slowly later on. So, this rake allows us to pick up the velocity at very close points near the wall and points far away, away from the wall.

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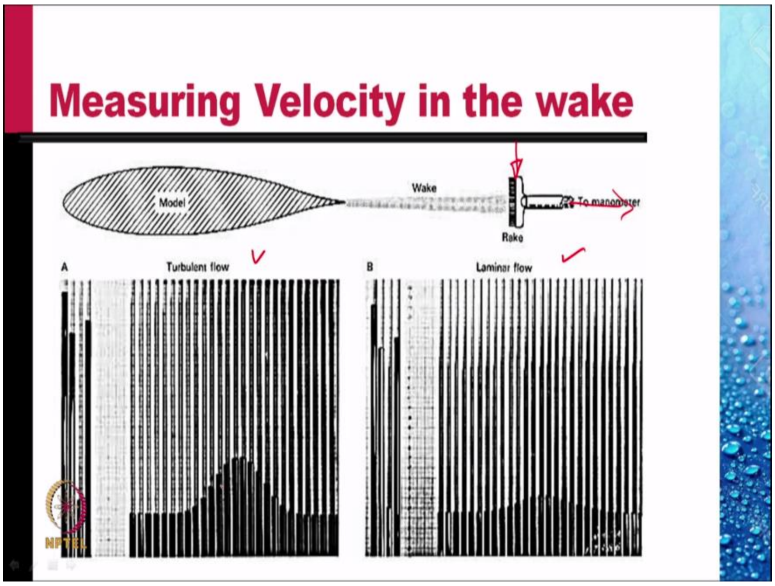

This is an arrangement in which we measure the velocity of the flow in the wake of a streamlined body. We use a rake of pitot tubes in the wake of the body, the number of tubes come out here and are connected to the various tubes of manometer. These are manometer tubes which are connected to a reservoir type of manometer. The first picture is about a turbulent wake, and the second picture is about a laminar wake.

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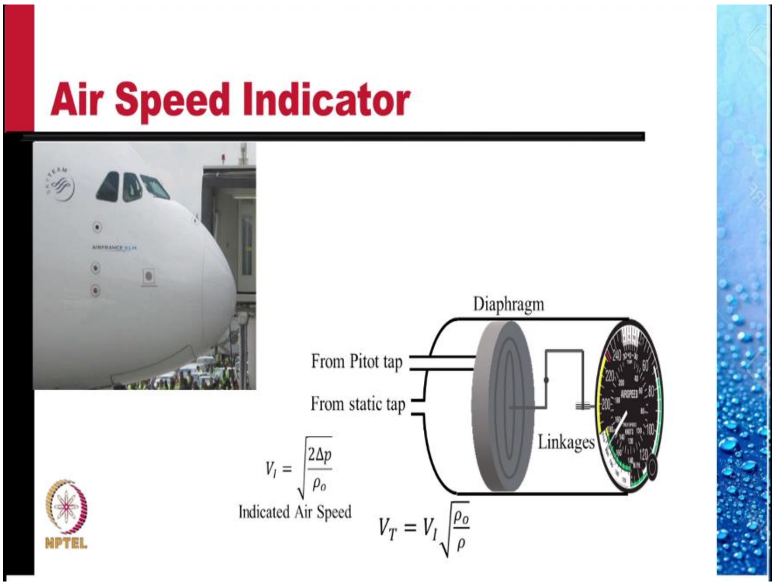

For measuring the airspeed of an aircraft, we need a pitot pressure, but we also need a static pressure, a pressure in the atmosphere which is not disturbed by the presence of the aircraft. It is a difficult proposition, and various methods are used to pick up the static pressure. One of the more common methods is to have static holes on the nose, or near the nose of the aircraft in the fuselage of the body. So, there are a number of static holes.

Experimentally, it is determined that the velocity of air past these holes, is almost the same as the velocity of the free air, or the undisturbed air, which is equal to the velocity of the aircraft in still air. So, these holes pick up static pressure, the pitot pressure is picked up from the pitot tube shown earlier, and these two pressures are fed: the static pressure into the body of an airspeed indicator, the pitot pressure into a capsule. Because of the difference of these pressures, the diaphragm moves, and as a diaphragm moves it through mechanical linkages, the needle on the face of the airspeed indicator giving us an indication of the airspeed.

The face of the dial is calibrated to read directly the speed using the formula $= \sqrt{\frac{2\Delta p}{\rho_o}}$. What is ρ_o? ρ_o is the density of air at the mean sea level in standard atmosphere. Actually, the velocity should be $\sqrt{\frac{2\Delta p}{\rho}}$, where ρ is the density where the aircraft flies. But that would be very difficult to determine if not impossible.

So, these dials are calibrated using density fixed as the density at the mean sea level in a standard atmosphere. And the speed measured in such a device is called the indicated airspeed, rather than the airspeed. Indicated airspeed bears the relation with a true airspeed like this. When we fly at an altitude the ρ is less than ρ_o. And so, V_{true} is more than the indicated airspeed. This gives you some idea of the airspeed not the true speed.

But fortunately, from the pilot's perspective, this indicated airspeed has more significance about the performance of the aircraft. And so, this is a very good indicator. The speed at which the aircraft stalls does not depend upon the true speed, but it depends upon the indicated airspeed. The optimized performance parameters are related to indicated airspeed. Therefore, indicated airspeed is truly what a pilot wants to know.

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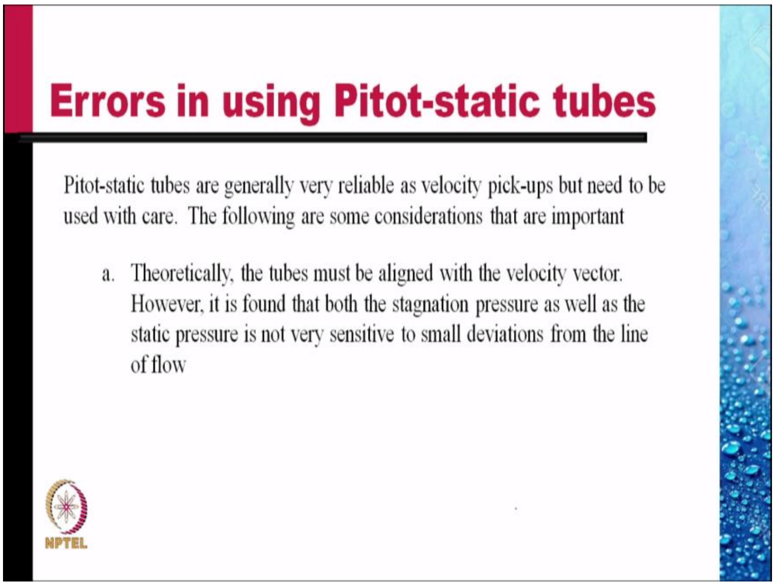

Pitot static tubes are generally very reliable as velocity pickups but need to be used with care. The following are some considerations that are important. Theoretically, the pitot tubes must be aligned with the velocity vector. They should be pointing straight into the oncoming velocity. However, it is found that both the stagnation pressure as well as static pressure are not very sensitive to small deviations from the line of flow.

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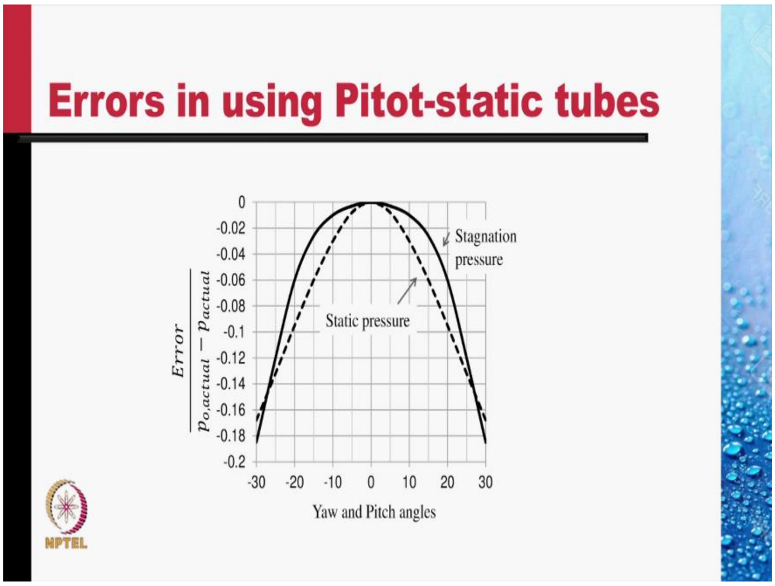

So, the error that you see in pitot pressure and the static pressure are seen here. You will notice yaw and pitch angles, or the angles that the tube makes with the flow direction, laterally as well as up or down. It is called pitch when the angle is up or down, and yaw when the angle is left right. It should be noticed that the static pressure is a little more sensitive but even for the angle up to $\pm 10°$, the stagnation pressure deviates from the true pressure difference by no more than 1 percent, and the static pressure difference varies by no more than 3 percent. These are quite small for many applications.

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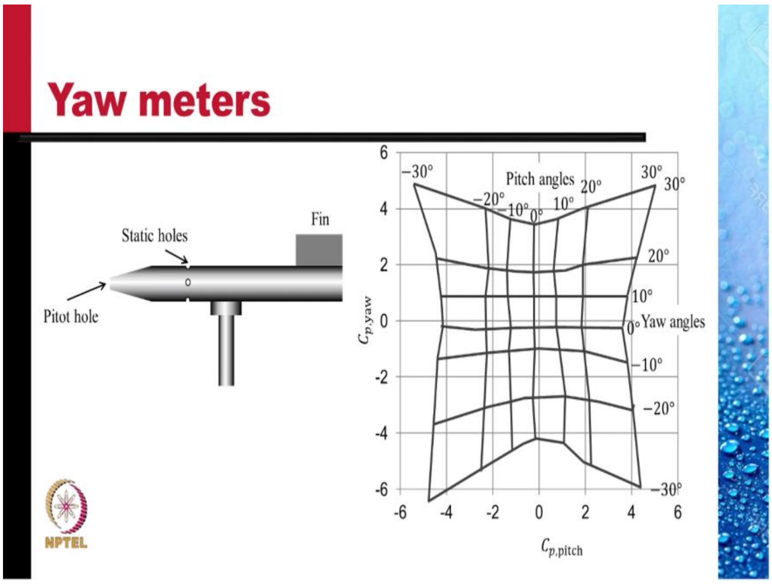

This property of being sensitive to the flow direction is also utilized in determining the angle that the tube makes with the flow. In this we use a tube with 1 pitot hole and 4 static holes. Two in the vertical plane, one at the top, one at the bottom, and two in the horizontal plane, one in front and one in the back. And we read the difference in the pressure between these static holes.

If the tube is pitched up, that is, if its nose is tilted upwards, then the pressure at the bottom static hole is more than the pressure at the top static hole. If the body of this tube is yawed in such a manner that the nose is out of the plane of the paper, and the tail is tilted backwards, then the pressure behind pressure at the hole behind the tube is more than pressure in the front.

These pressure differences then can be calibrated to give you the angle at which the flow occurs in relation to the axis of the tube. This is the typical plot of the yaw angles and the pressure differences that we observed in the flow. Using this kind of graph, we can relate the angle that the tube makes with the flow.

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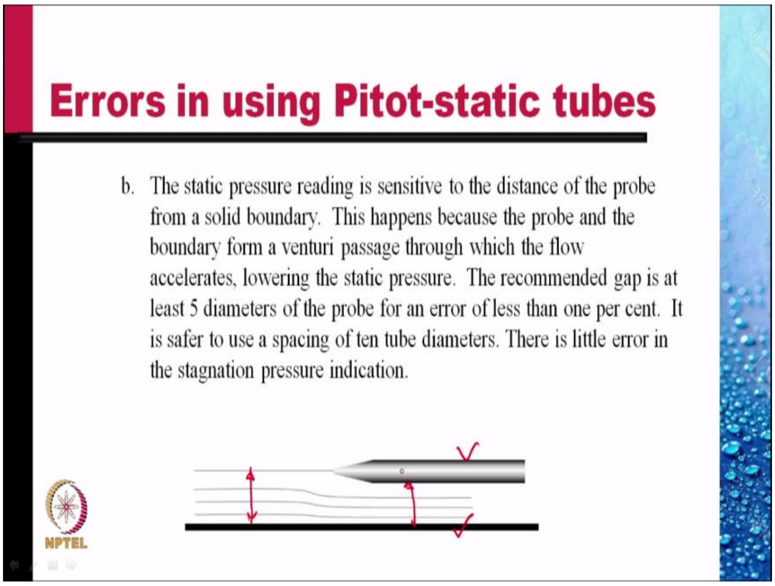

Another cause of error is because the static pressure reading is sensitive to the distance of the probe from a solid boundary. This happens because the probe and the boundary form a venturi passage, a narrowing passage through which the flow accelerates, lowering the static pressure. Thus, if the tube is very close to the wall, then the floor here as this area to flow in underneath the tube it is this area, a reduced area. So, the flow will need to accelerate.

The recommended gap is at least 5 diameters. The tube should be at least 5 diameters away from the wall for an error of less than 1 percent. It is safer to use a spacing of 10 tube diameters, but this error is largely in the static pressure measurement. The stagnation pressure indication is generally error free, or there is little error in the stagnation pressure indication.

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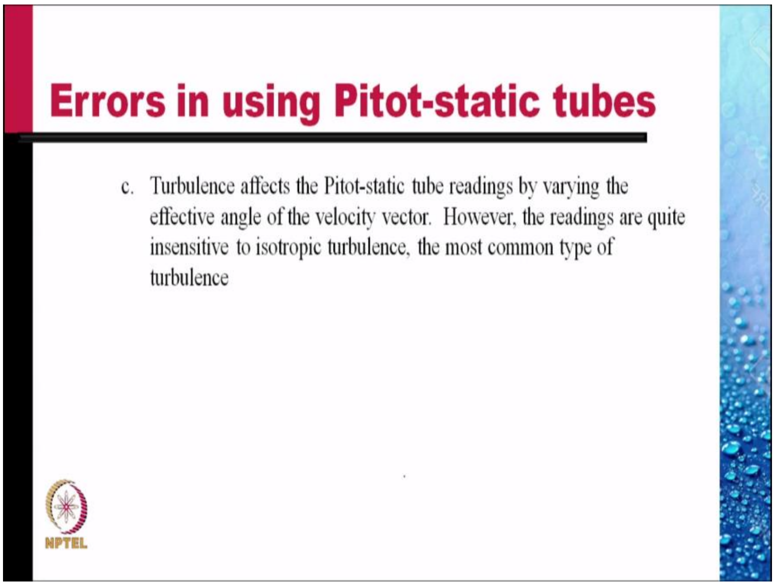

Turbulence affects the pitot static tube readings by varying the effective angle of the velocity vector. As the velocity components fluctuate, the net direction of the flow also fluctuates, and this could cause error in the reading. However, if the turbulence is isotropic, the readings are quite insensitive to the level of turbulence. And since the isotopic turbulence is the most common type of turbulence, this is not of much consequence.

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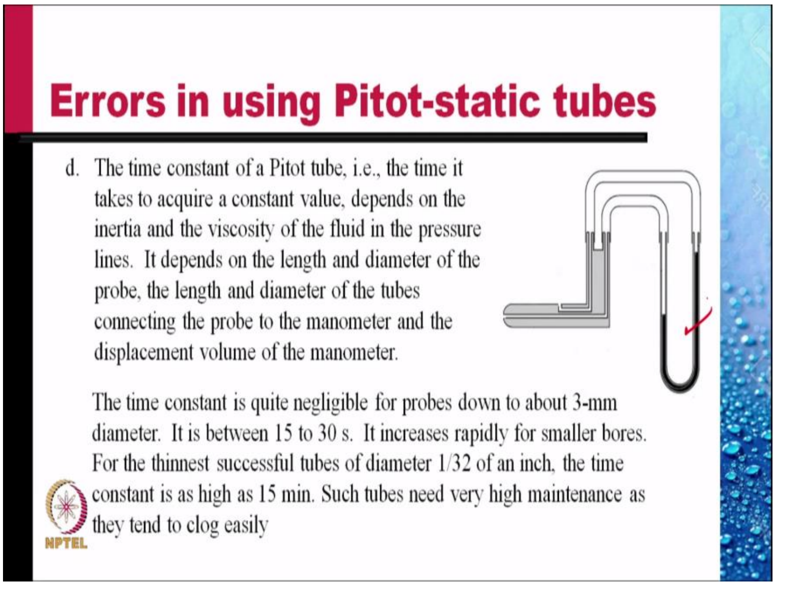

Another cause of error is a time constant of the pitot tube. As the pressure changes in the flow, the fluid through the tubes, the pitot static tubes and the connected tubes need to move. So, also the measuring fluid, the gauge fluid that we use for indicating the pressure needs to move up and down. It will take time for the fluid to accelerate and then come to rest. This limits how fast we can take the readings, or if we can take the dynamic readings at all.

The time constant of the pitot tube is the time it takes to acquire a constant value. It depends on the inertia and the viscosity of the fluid in the pressure lines. It also depends upon the length and diameter of the probe, the length and diameter of the tubes connecting the probe to the manometer, and the displacement volume of the manometer.

The time constant is quite negligible for probes down to about 3-mm diameters. It is between 15 to 30 seconds, it really is not negligible. So, you will have to wait for about 15 to 30 seconds before you take the reading. But if the tube diameter changes, or reduces further, the time constant increases rapidly. For the thinnest successful tubes of diameter 1 by 32 of an inch, a little less than a mm, the time constant is as high as 15 minutes. So, one has to be very careful.

It is not uncommon to use tubes of size one-sixteenth of an inch, about a millimetre and a half in diameter. And so, we have to wait for considerable time to take readings from such tubes. Such tubes also need very high maintenance as they tend to clog easily because of the dust in the moving fluid.