Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer
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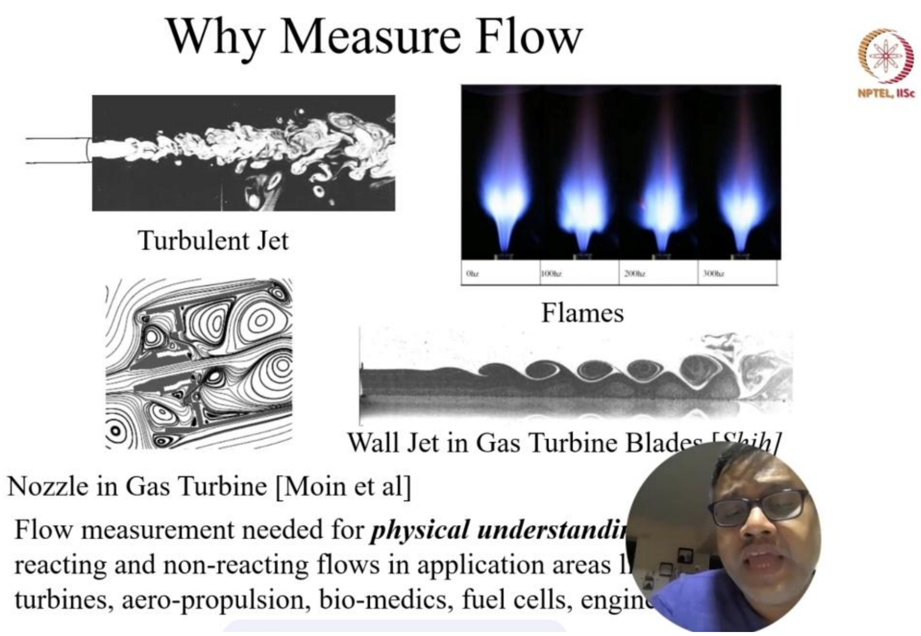
Week – 12
Lecture - 57
Hot Wire Anemometry – 1

We are going to have these lectures on flow measurements, and we have already done LDV. The next phase will be to do something that is called hot wire anemometry before we move on to particle image velocimetry. So we will see first, we will go step by step through what the different flow measurement techniques are that are available to us before we jump to anemometry. So in LDV, we already did something; now we are going to see anemometry and how it actually works. So the materials are compiled from various sources, such as Oxford Lasers, E-Fluids, LaVision, Dantec Dynamics, TSI, Virginia Tech Aero, Ocean Engineering, and some from my own work as well. Let's start.



So, as we know, the reason we measure flow is that we already covered a little bit of this when we did the LDV portion. For example, you can have different types of flow situations. Here, you see a turbulent jet, for example. Let me get the laser pointer.

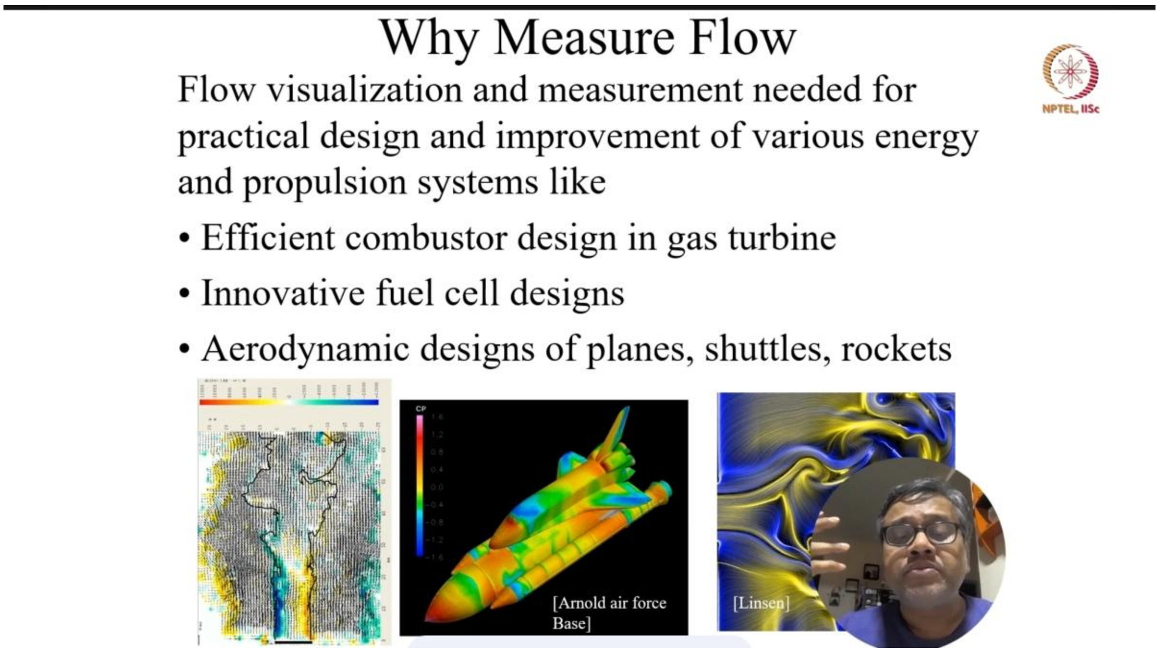
It's a turbulent jet. This is, for example, a flame. This is from Professor Setigen's work.

So this shows a bluff-body stabilized flame. This is the nozzle of a gas turbine.

So, these flows are pretty complicated. And as we already said, sometimes we need both spatial and temporal resolutions. And sometimes we need a high sampling rate at a very small location of interest. And that is where the LTV and the anemometry come in handy. So the flow measurements are needed for the physical understanding of reacting and non-reacting flows in applications like gas turbines, aeropropulsion, biomedicine, fuel cells, etc.

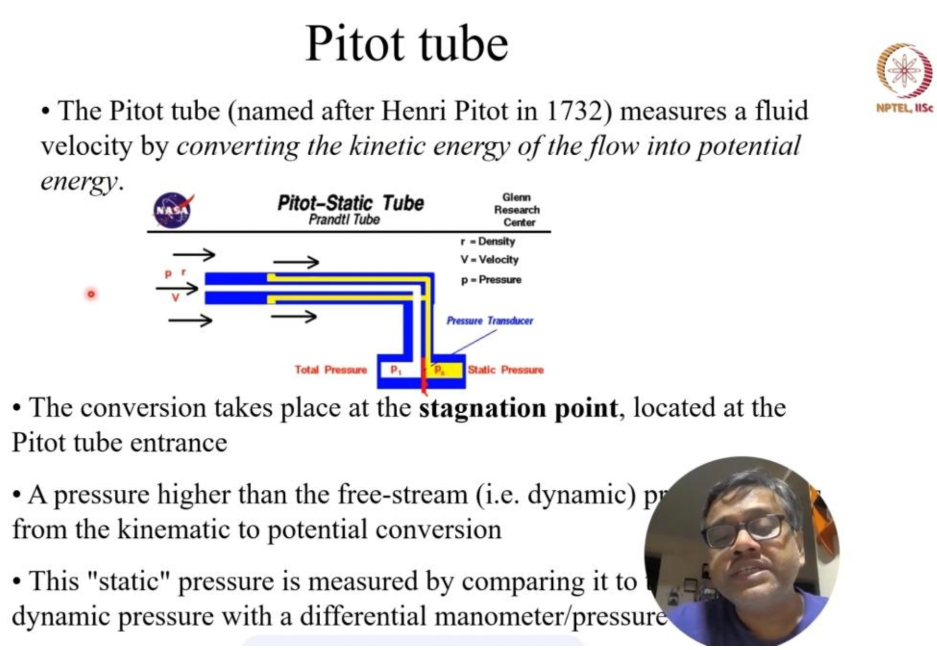
So these are the features that are kind of important. So why we measure flow is because flow measurement and flow visualization are actually needed for designing improvements. For example, in order to design an efficient combustor, we need to know what is going on inside the combustor, or for aerodynamic designs of planes, shuttles, rockets, and so on. All these things come under the ambit of flow measurement, so to say. So, of course, in this list, we have a list of four measurement techniques.

We have the pitot tube, the hot wire anemometry, the particle image velocimetry, and the laser Doppler velocimetry. The laser Doppler velocimetry we already covered in detail. Particle image velocimetry is what we will do next. So here in this case, we are going to cover the pitot tube and hot wire anemometry. So the pitot tube, as we know, is the simplest, but it is also the crudest of all the measurements.



And PIV is accurate because it is a full-field measurement. Now PIV and LDV, as we already said, are non-intrusive techniques, but LDV is very good if you want to measure very closely or if you want to have a very high spatial resolution. For example, a few microns, which the PIV may not always be able to get you the velocity at that kind of resolution. So you have to keep this particular thing in mind when you actually do it. Hot-wire anemometry will be similar in terms of spatio-temporal resolution compared to an LTV because we also have a kind of measurement volume here, but the principle is completely different, as we will see very shortly in the next few minutes.

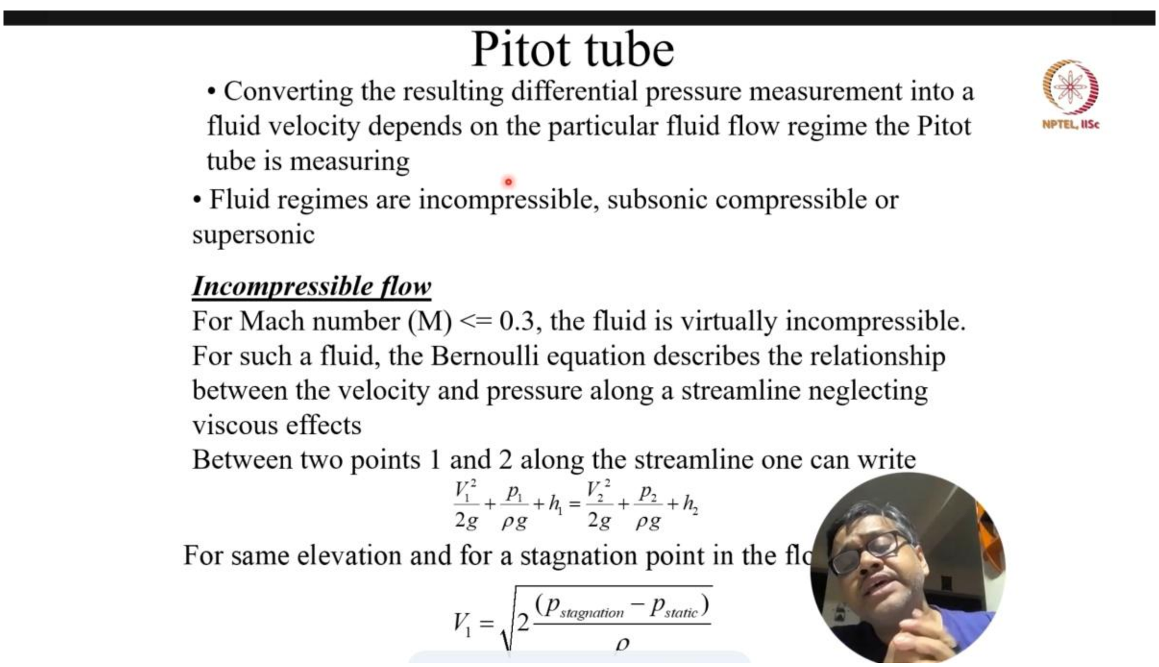
Okay, so let's start with the pitot tube. So the Pitot tube was actually named after Henry Pitot, and it measures fluid velocity by converting kinetic energy into potential energy. So, how does it do that? There is a hole and then there are side holes, so the velocity comes, and you basically create a stagnation point here, and then you measure it. So here, what you measure is basically the stagnation pressure and the pressure that is higher than the free stream pressure, and the static pressure that you measure through the side holes is also measured, and the difference between these two pressures is what you get. So the pressure that is higher than the free stream pressure is called the dynamic pressure, and the static pressure is measured by comparing it with the dynamic pressure; you use a manometer, basically, to see the difference in pressure between the two.



So, construction-wise, several small holes are drilled around the outside of the tube, and then there is a central hole that is drilled down the axis. So, if you look at it carefully, the outside holes are connected to one side of a device called a pressure transducer, and the central hole is kept separate from the outside holes; it is connected to the other side of the transducer. So, what does the transducer do? It can basically be a manometer, as simple as that; it measures the difference in pressure in the two groups of the tube. By measuring the strain, there is basically a thin element; if you have a difference in pressure, you induce a certain amount of strain. By measuring the strain, we can determine the difference in pressure.

The pitot-static tube is mounted so that the central tube is always in the direction of travel, which means they are kind of aligned. Head-on, it takes the flow directly, and the outside tubes are basically perpendicular to the central tube. So, like what you have over here, these are perpendicular; these are central. So converting the resultant differential pressure measurement into a fluid velocity depends on the particular fluid flow regime that the pitot tube is measuring. So if the fluid regimes are incompressible, subsonic, compressible, or supersonic, these are the kinds of flow regimes.

So this is not like the laminar turbulent kind of thing that we are looking at. We are looking at incompressible flow situations. We are looking at subsonic compressible flow, and we are also looking at, you know, supersonic flows. So, the incompressible flow, if you look at it, is for a Mach number that is less than 0.3; thus, the fluid is virtually incompressible.

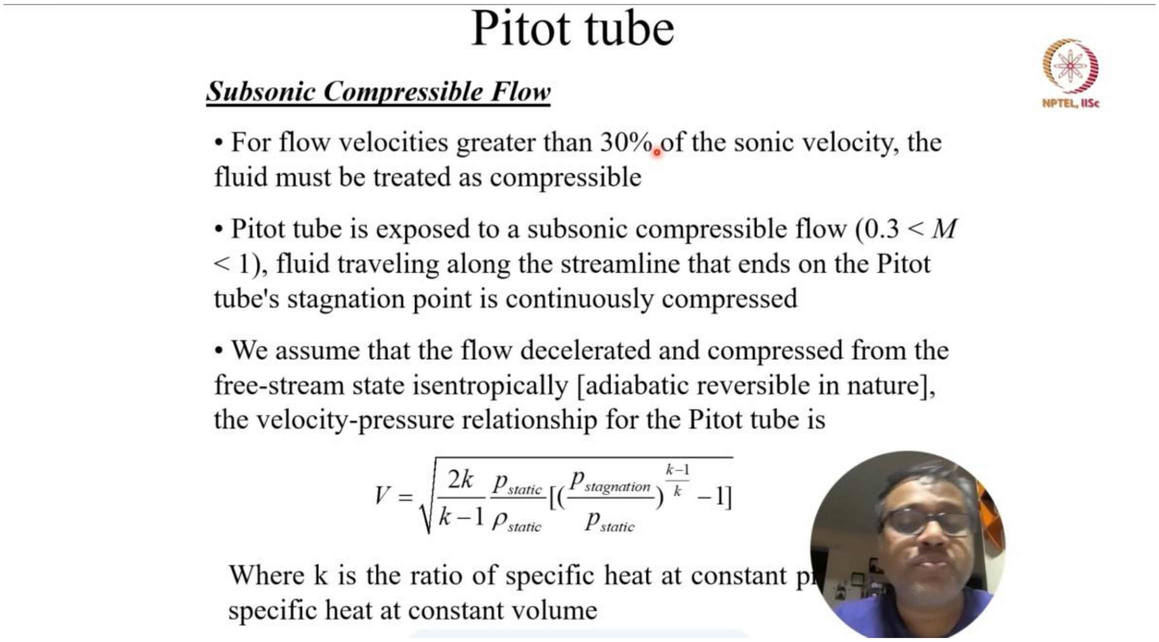


For such a fluid, what you can do is apply Bernoulli's equation, which describes the relationship between the fluid velocity. The pressure along a streamline, neglecting all the viscous effects. So between points 1 and 2, if you go back and see 1 and 2, one can write this particular expression for the streamline. So this is like

$$\frac{V_1^2}{2g} + \frac{P_1}{\rho g} + h_1 ,$$

etc. Now, for the same elevation and for a stagnation point, as you know, the velocity at a stagnation point is equal to zero, so this velocity now becomes

$V_1 = \sqrt{2\,(P_{stag} - P_{stat})/\rho}$. So this is what you are going to get when you actually have an incompressible flow. Alright, so it is pretty obvious that you are measuring this differential pressure, and because you are measuring this differential pressure, you can infer the velocity, which is basically the square of the differential pressure that will give you the velocity by simply using Bernoulli's equation. If it is subsonic compressible, that means when the fluid velocity is 30% less than the sonic velocity, in other words, the Mach number is less than 0.3, the fluid must be treated as compressible.

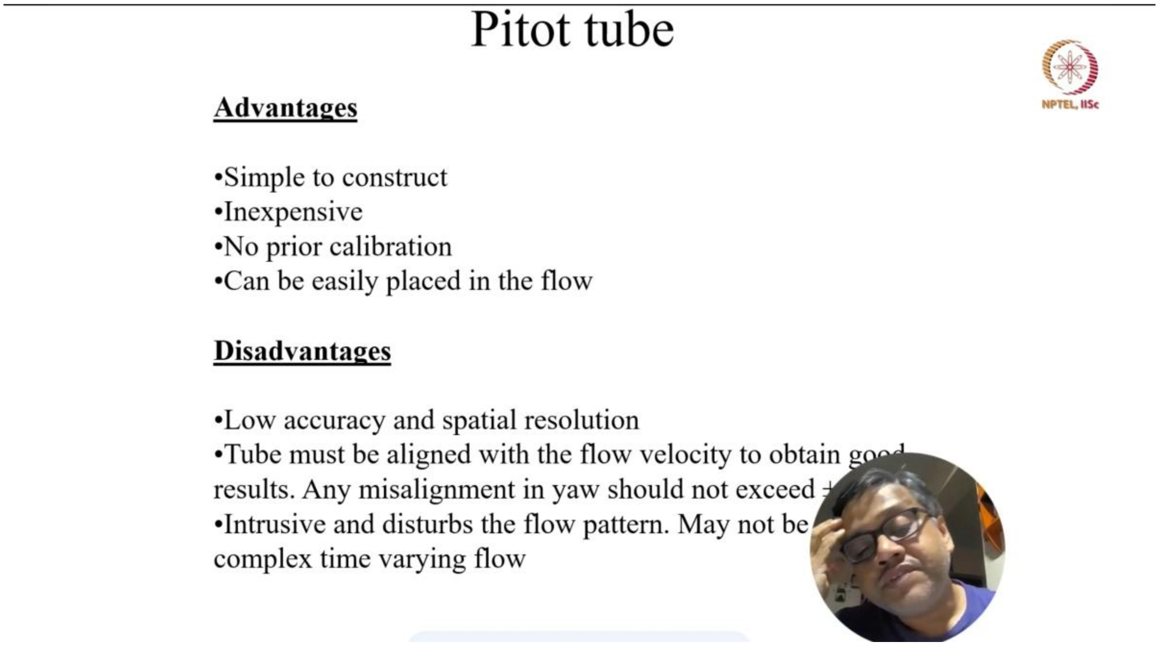


Now, if we do that, if the fluid is treated as compressible, what happens is that the pitot tube is exposed to a subsonic compressible flow. That means the Mach number is greater than 0.3 but less than 1. So the fluid traveling along the streamline that ends at the pitot tube stagnation point is continuously compressed. So previously you did not have this compression effect.

Now it is continuously compressed. So we assume that the flow is decelerated and compressed from the free stream isentropically, which means adiabatic and reversible in nature. Therefore, the fluid pressure relationship for the Pitot tube now gets a little bit more complicated. There is now $V = \sqrt{\frac{2k}{k-1}\left(\frac{P_{stat}}{\rho_{stat}}\right)\ [\left(\frac{P_{stag}}{P_{stat}}\right)^{\frac{k-1}{k}} - 1]}$. So K is the ratio of the specific heat at constant pressure to that at constant volume.

So, that is what you get. So this is the velocity expression now, which is a little different from the velocity expression that we had earlier. This is just because the flow is now decelerated and compressed at the stagnation point. So, this is valid for subsonic compressible flow. So the pitot tube can, in essence, find out the velocities in both cases.

All right. So the advantages are that the pitot tubes are very simple to construct. You can construct it yourself. All it requires is a central hole and a bunch of side holes, tappings, which are perpendicular to the flow direction. So it is inexpensive, and it requires no prior calibration because you are also measuring the differential pressure. It can be easily



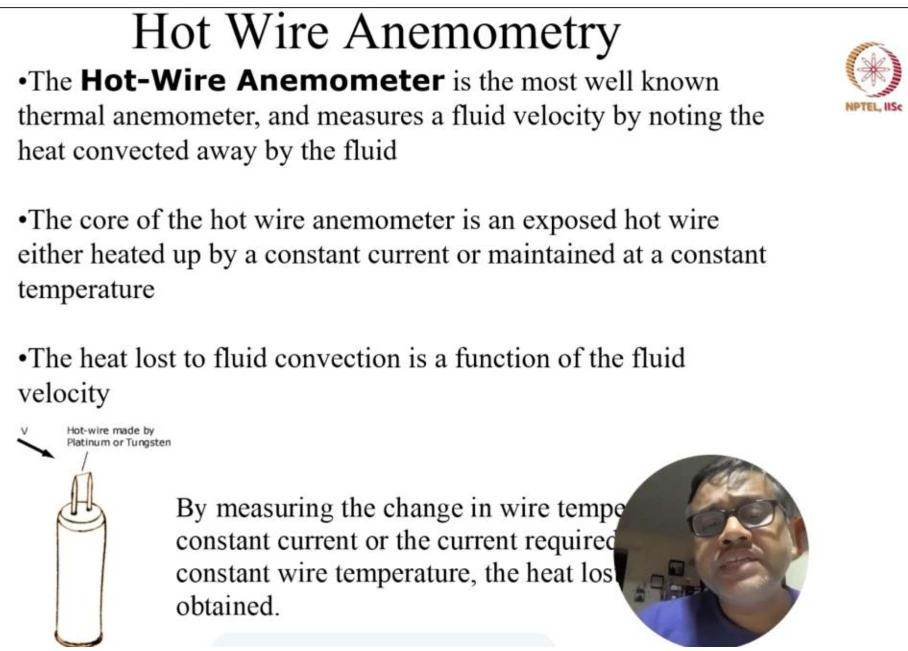
placed in the flow field, but the disadvantages are considerable.

It has low accuracy and spatial resolution because, you know, the pitot tube has a finite dimension. So it is kind of, you know, not very, it's pretty, it's actually a little bulky. So the tube must also be aligned with the flow velocity to obtain good results. Any misalignment in the yaw should not exceed a certain degree, as it is intrusive and disturbs the flow pattern. So it may therefore not be valid for, you know, complex and time-varying flow fields or flow fields that have a lot of structures.

So for a laminar, well-behaved flow field, this is not an option per se. I mean, this is an option to go ahead with a pitot tube. Okay. So, that is the advantages and disadvantages of a pitot tube. Okay, so it, of course, the pressure transducer; you can use a manometer, you can use the strain gauge type of pressure transducers.

All of them are good. The electronics are also very light, so that is an added advantage for this. All right, so now we move on to the case of hot wire anemometry. Now, hot wire anemometry is the most well-known. The thermal anemometer came before the LDVs and measures the fluid velocity by noting the heat that is convected away by the fluid; now here comes the crunch: it is actually measuring the fluid velocity by noting the heat that is convected away. So it does not directly measure the flow velocity.

So it uses heat transfer to find out what the flow velocity is going to be. So what is the core of an anemometer? It is the core of a hot wire anemometer; an exposed hot wire that you see right around there is either heated up by a constant current or maintained at a constant temperature. The heat that is lost to the fluid by convection is a function of the fluid velocity; this we know from convection heat transfer. The amount of heat that you lose is a function of your Reynolds number, so Reynolds number is a function of your fluid velocity. As a result of that, the heat that is lost to fluid convection is a function of the fluid velocity, so if we can somehow calibrate this.



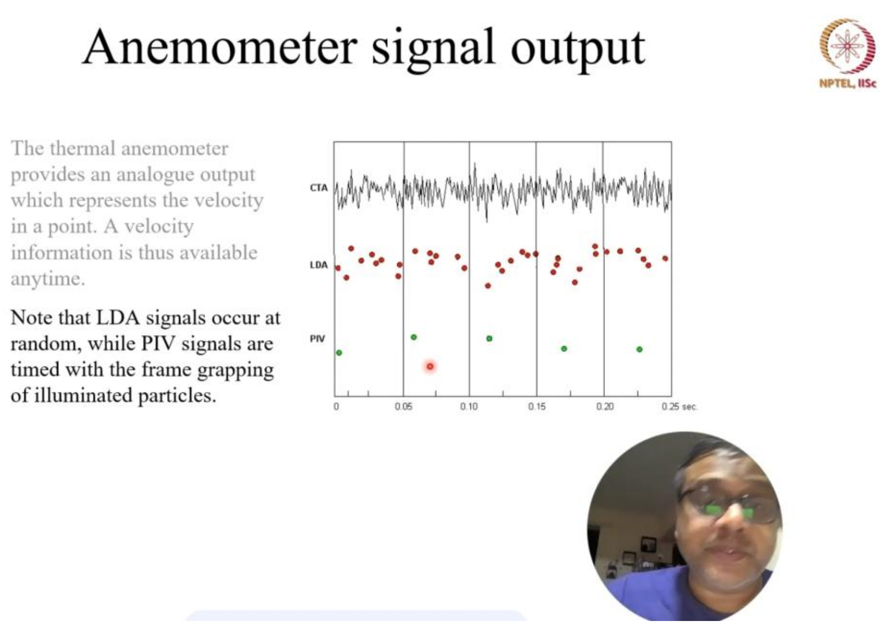
Okay, and then you can actually determine what the velocity of the flow field in which this hot wire anemometer is placed is going to be. So how is this done? This is done by measuring the change in the wire's temperature. Either in a constant current mode or the current that is required to keep the temperature to maintain a wire temperature, the heat loss is obtained, and as a result, you can measure what the flow velocity is. Okay, so just by measuring the change in the wire temperature, we can actually determine the current required to maintain the constant wire temperature; the heat loss can be obtained, and we can correlate it with the fluid flow velocity. Hot-wire anemometry can actually measure all three components.

It can measure one component, two components, or three components, all. So the velocity components like ux, uy, and uz are measured over a helicopter, for example, with 2D and 3D probes. So you can see how the velocities are actually obtained. You can see the velocities are about 25 meters per second, so in that particular range, there is no problem that you can do it.

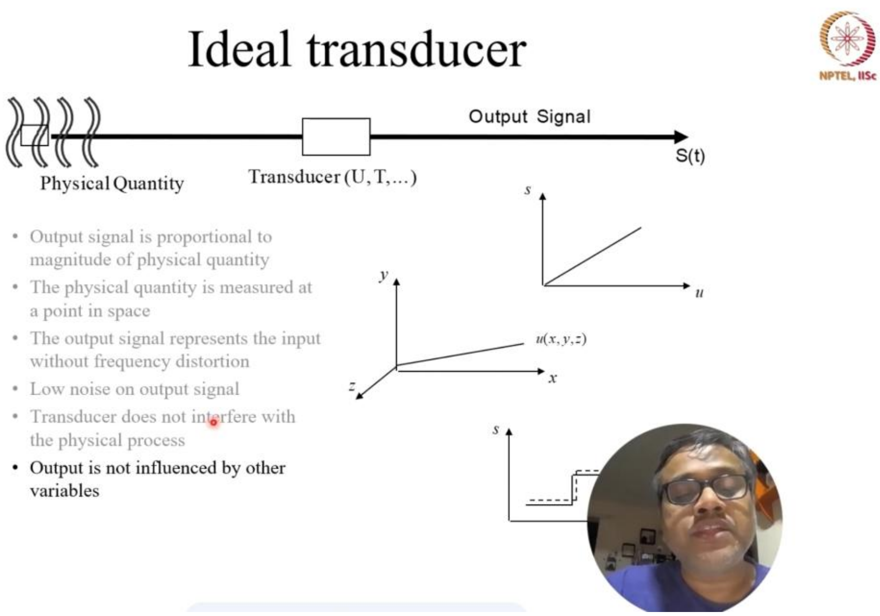
with a hardware application. So this is what the anemometer's signal looks like. So an anemometer provides what we call an analog output. That means it represents the velocity at a point; thus, the velocity information is available at any time.

Whereas LDA or PIV will give you information, LDA signals and PIV signals are timed with frame graphing of illuminated particles. So this is more of a continuous signal; this is more of a signal in which you get the information at certain discrete time snapshots, essentially.

Well, of course, this frequency can be very high depending on your lasers and high-speed PIV, so that's why LDV is a little bit more high-speed than PIV, but PIVs are also getting very high-speed these days. As a result of that, you can get a lot of data within a very short span of time, but unlike an anemometer, which will be very continuous, this will give you almost continuous data. Still, there is an analog-to-digital conversion, so you do. Lose a part of the signal depending on how you are sampling, but technically your data is available, so you can sample it as high as you can; whereas in an LDN PIV, this is not quite the case. All right, so what does an ideal transducer actually do? For example, if you look at any measurement principle, what happens is that you have a physical quantity that you try to measure.



So you get some signal out, which is passed through a transducer, and then this transducer generates an output signal. So, if in this case it can be anything, it can be velocity; it can be any other type of signal. So, the output signal is proportional to the magnitude of the physical quantity. So it has to respond. To the change in the physical quantity, the physical quantity is measured at a point in space, so this is like a point or whatever is the dimension of that point; therefore, it is exactly not dimensionless.



Either the output signal represents the input without any frequency distortion, which means there should not be any distortion in how you are actually gathering the data. There should be low noise on the output signal, so the signal-to-noise ratio should be quite good, allowing you to recover the data if it is buried in the noise; you cannot actually see what the exact value is. All right, and the transducer should not interfere with the physical process. That means it is not interfering with the physical; that means it's not changing. The act of measurement does not really change the physical quantity that you are trying to measure.

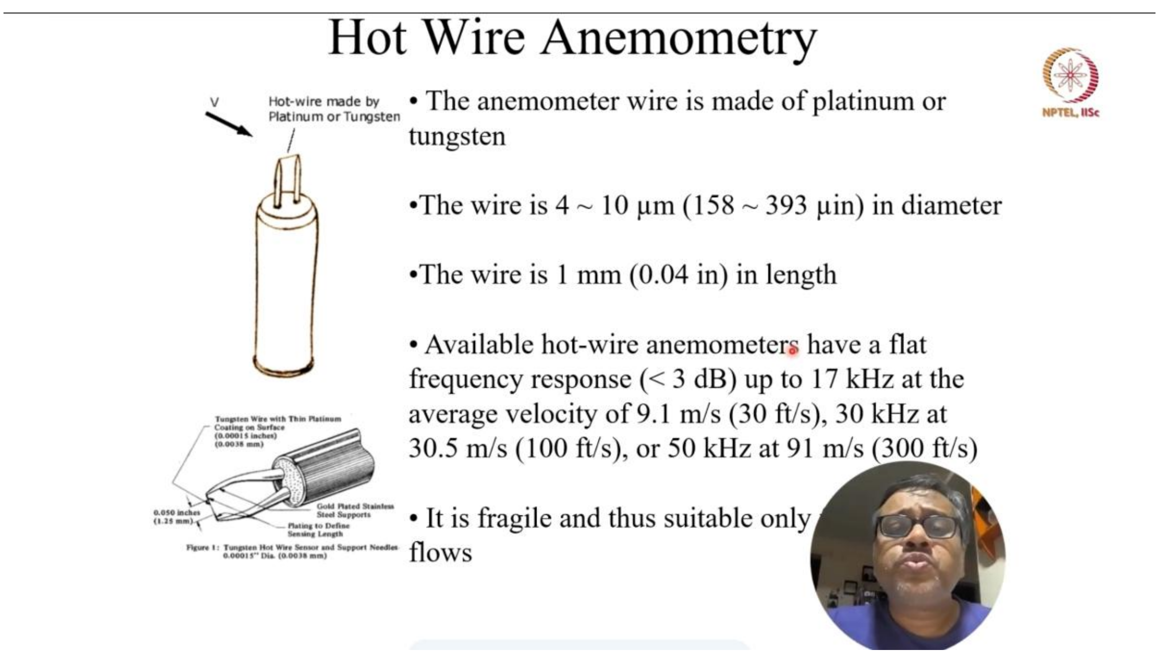
And the output is not influenced by other variables. So the output is not influenced by any other variables apart from the physical quantity that you are trying to measure. Okay, so these are the kinds of transducer dynamics. So real transducer dynamics means that you have a static transfer function, which is like a calibration curve. The spatial resolution is important because of the finite size of your measurement volume.

We also saw that, in the case of LTV, the same thing is valid for any measurement. The temporal resolution is its frequency response, which indicates how small or how large a frequency you can safely measure. It should have a very good signal-to-noise ratio; the interference effects are very important coming from other types, and it is normally the multivariate response, which means it is not only a response to the variable that you are trying to measure but also to all the other variables as well, so that basically convolutes your measurement. In the case of hot wire anemometry, if you look at it carefully. The hot wire of the anemometer is made of platinum or tungsten.

Okay, so this is the wire; if you look at it carefully, these are two prongs, and the wire is held between these two prongs. This hot wire is made of platinum or tungsten, and the wire is roughly about 4 to 10 microns in diameter. Okay, so this particular cross-section of the wire. The wire is about 1 mm in length.

So this length of the wire is about mm. So you can see that the measurement volume that it gives you is about 1 mm by about 10 microns. So it is like a very high aspect ratio. So it is 1 mm by about 4 micrometers. It is a very slender kind of stuff.

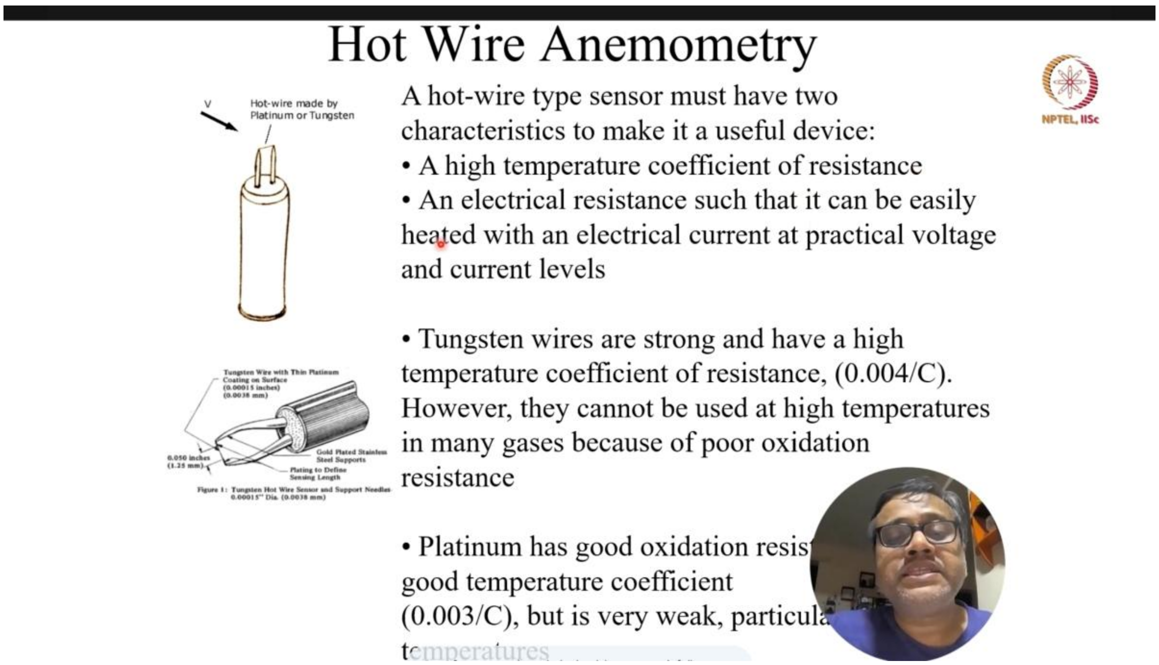
So you can see a practical anemometer over there. This is a tungsten wire with a thin platinum coating. And here you can see that 1.25 mm is the length. Then it is connected to the electronics. So the tungsten hot wire sensor and its supports, this is a practical example.



So all available hot wire anemometers have a flat frequency response of about 17 kilohertz at an average velocity of 9.1 meters per second, 30 kilohertz at about 30.5

meters per second, or 50 kilohertz at about 91 meters per second. Okay, so these are the anemometers that are available.

The newer ones might actually perform much better than this. It is fragile, which means if you touch this wire, it will break. So, it is suitable for very clean flows; you cannot actually have a very dirty kind of flow where there are a lot of, you know, particles or, you know, fragments that will hit the wire and break it. Okay, because we will see why that thinness of the wire is actually needed. It is a very fragile piece of equipment; that much we know for sure.

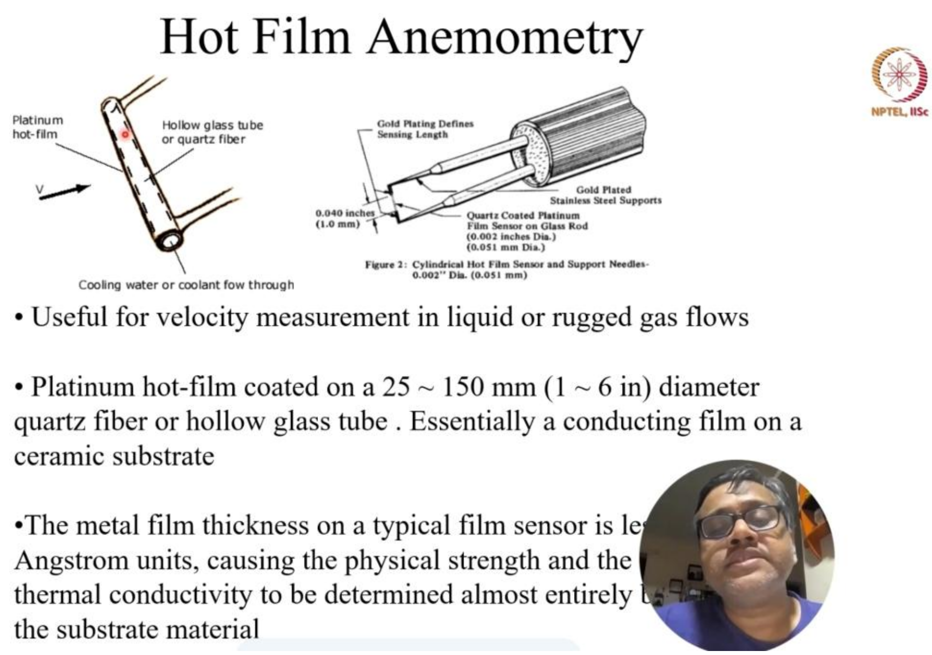


Okay. So the hot wire type sensor must actually have two characteristics to make it very useful. It should have a high temperature coefficient of resistance and an electrical resistance such that it can be easily heated with an electrical current at practical voltage and current levels. So that it can be easily heated up using the current level that our normal power sources can supply. So the tungsten wires that are used are very strong, and they have a high temperature coefficient of resistance, which is about 0.

004. However, they cannot be used at high temperatures in many gases because they can get oxidized. So tungsten gets oxidized in very high-temperature gases. Therefore, platinum has good oxidation resistance and a good temperature coefficient, but it is very weak. Particularly at high temperatures. So these are the pros and cons of the different candidates we can have.

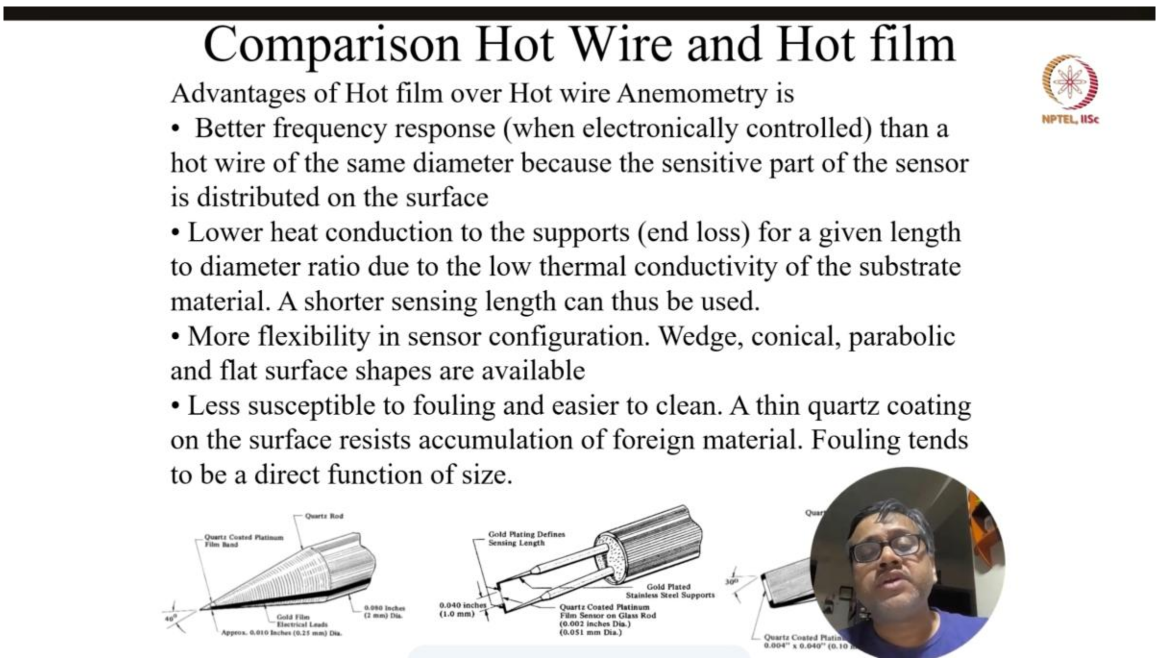
But the main part of the sensor is that wire because it is the wire that is actually exchanging heat with the flow, and that is what will give you the velocity measurements. So it is thin. It has a high aspect ratio, and it is usually made out of tungsten and platinum, keeping in mind what kind of flow situations you are dealing with. OK, so what happens is that sometimes you can have a platinum hot film. So this is a wire that is coated with a film, and then there is a hollow glass tube or a quartz fiber through which you can cool this wire as well.

So this is, for example, a gold-plating sensing length. This is a quartz sensor coated with a platinum film on a glass rod. So this variation is called hot film anemometry. It's like a wire, but it has a coating. So there is a film that is applied to a particular glass or quartz. So, this is very useful for velocity measurements in liquid or rugged gas flows because, as you saw, this will not break that easily.



The platinum hot film that is coated on a 25 to 150 mm diameter quartz fiber or hollow glass tube essentially creates a conducting film on a ceramic substrate; that's what you are doing: coating the ceramic substrate with a metal film. The metal thickness on the film is less than, you know, at the angstrom levels, which causes physical strength and also provides thermal conductivity. So those are the things that you take care of when you actually coat the hot wire using this kind of film. So this is one way of actually doing hot film anemometry, so to speak. So the comparison between hot film and hot wire anemometry is that the advantages of hot film over hot wire anemometry are that it has a better frequency response than the hot wire of the same diameter because the sensitive part of the sensor is distributed on the surface.

So it has low heat conduction to the supports. To the end loss, because it is connected to a frame for a given length-to-diameter ratio, due to the low thermal conductivity of the substrate material, which is coated on a substrate material, we can use shorter sensing elements, as that will reduce the measurement volume, allowing you to almost go to a point. So the spatial resolution improves; it offers more flexibility in sensor configuration. That means you can make it a wedge, conical, parabolic, or flat surface. This looks almost like a tool, like a chisel, but this part is what is actually coated with the film. So it is like a wedge that you incorporate into the flow; this is, for example, like a cone.



Okay, and this is the normal hot-wire type of arrangement. It is less susceptible to fouling, and it is easier to clean. The thin quartz coating on the surface resists the accumulation of foreign materials. So, fouling tends to be a direct function of size. So, all these things, there are certain advantages of hot film. Anemometry over hot wire anemometry, so to say, if you look at it now carefully, you will see that ultimately it is a heat transfer problem; it is heat transfer that we are measuring to infer the flow, so that is the crux of this. I mean, for each and every measurement technique, it is different, okay?