Measurement Technique in Multiphase Flows
Dr. Rajesh Kumar Upadhyay
Department of Chemical Engineering
Indian Institute of Technology, Guwahati

Lecture – 03
Hot Wire Ananometry

So, welcome back we were discussing about the non-invasive measurement technique, and in that line we have discussed about the pitot tube. So, next invasive measurement technique is hot wire anemometry. Now this technique is one of the widely used technique to understand the turbulence in single phase flow, and the technique has also been used to analyze the multi phase flow.

And this is the technique you can say that whatever the understanding of the turbulence experiments, we have and initially which we have developed is all because of this technique is not this technical plays a major rule to understand the turbulence. And why because this technique have a very high response time, both spatial resolution as well as the temporal resolution of this technique is very high. So, we try to understand first the basics of this technique.

Then what is the measurement principle, and then we will try to up understand that how the same technique can be used for the multi-phase flow, what will be the limitation and overall advantage and drawback of this technique. So, this will start about this technique in this class. And as I said that the name itself is hot wire anemometry. So, you can understand it means that there is some wire is being used which is hot at certain condition and that hot condition is being used to measure the velocity, and that is why the name is called hot wire anemometry.

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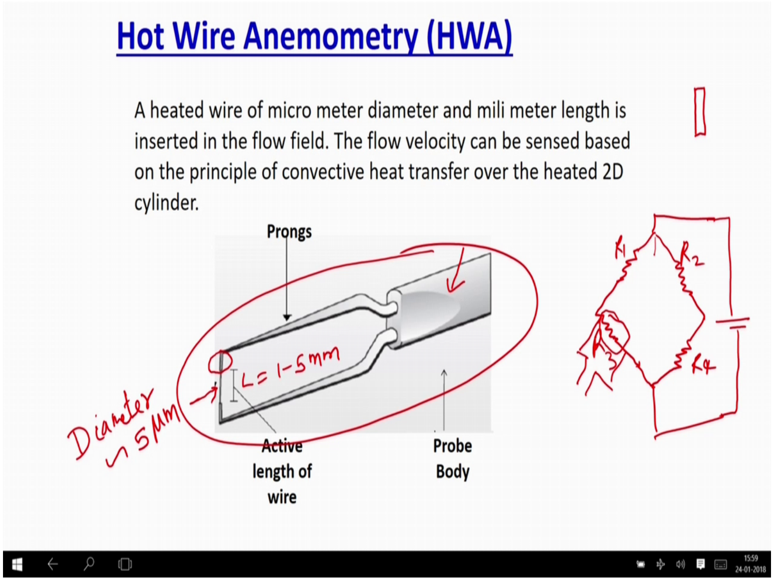

So, the typically the setup or the kind of a probe which is being used to in hot wire anemometry it looks something like this. So, it has actually 4 parts one is the probe body, which is this actually support to the probe and the backside of this the electronics is being there which is used for the measurements we will discuss about those electronics, then there is a prong actually which is being used as a support, then there is some other support here which you see from this side and then we use a small wire this is the wire because of that the name is hot wire anemometry.

And that wire is being used for the measurement how we will say about that we will discuss about that. So, this is the active length of the wire, and this is the diameter of the wire, and these are the support which actually hold the wire. So, this technique is being used and the basic major main principle of this technique is that it is being connected with this wire is actually one leg of the wheat Stonebridge.

Now we will discuss about the circuit also. So, what happened we know that in the Wheatstone bridge say this is a typical wheat Stonebridge, this is the typical say wheat Stonebridge. If I give a current voltage then what will happen at volt difference, then the current will be actually divided based on their resistance ratio say R 3, R 4. So, it will be divided based on their resistance ratio, and you can find it out that how much current will be flowing here, in each kind of circuit or each line. Now if you change the resistance of one then what will happen the overall current distribution of volt distribution will change, and that volt distribution will change will be proportional to the change in the resistance. And that is the basic principle which we use in the hot wire anemometry.

So, what we do? We give certain voltage potential initially. So, each because of the voltage potential some current will pass. So, each resistance or each wire, will be maintained at a particular temperature. Now if suppose one of the wire I connect with the fluid, if we are exposed to the fluid. So, this is my fluid like this is the wire, then what will happen that because the fluid will come it will change the temperature because of the heat transfer.

Now the change in the temperature will be recorded as a change in the resistance, and that change in the resistance will cause change in the current. And because of that the change in the current will be proportional, if you do that the calculation we will the numerical you see the numerical part, it will be proportional to the velocity. So, you can measure the velocity of the fluid, and that is what the principle is that in this place in hot wire anemometry a hot wire is used.

The diameter of the hot wire is in the range of micrometer, this is diameter, is currently this is the range of 5 micrometer earlier it was much bigger, but in the current state of art of HWA the wire thickness is very low, and it comes in the range of f5 micrometer. And the length is around 1 to 5 mm depending upon the application and different type of the probes. So, 1 length varies in the range of 1 to 5 mm diameter varies in the range of say 5 micrometer, this is being exposed, this is wire is being exposed to the flow field or being inserted in the flow field. Now what will happen the flow field actually the velocity can resist by the convective heat transfer measurement.

So, because of that that wire is being there, as I said that there is some temperature will be given because of that particular current or particular volt which has been applied, wire will be maintained at a certain temperature. Now it will expose that wire to the fluid, then what will happen because of the fluid some convective heat transfer will take place, and that convective heat transfer will change the temperature of the a wire, and that is why the it will change the temperature resistance of the wire and the current.

So, what you are actually solving is a very simple equation, which you will have might have done in your transport phenomena course, in which what we do a 2D cylinder is being suspended in the fluid. Now why we are taking 2D cylinder, because the diameter of the probe is very very small. So, if the diameter of the probe is very small you can always assume it to be a theta symmetric, and you can assume that the temperature is completely in kind of symmetric here.

So, it is a 2D cylinder something like this which is suspended in the fluid, and you find a convective heat transfer and that convective heat transfer coefficient you correlate with your resistance change. So, that is the basic principle of the hot wire anemometry, by which we record the signal.

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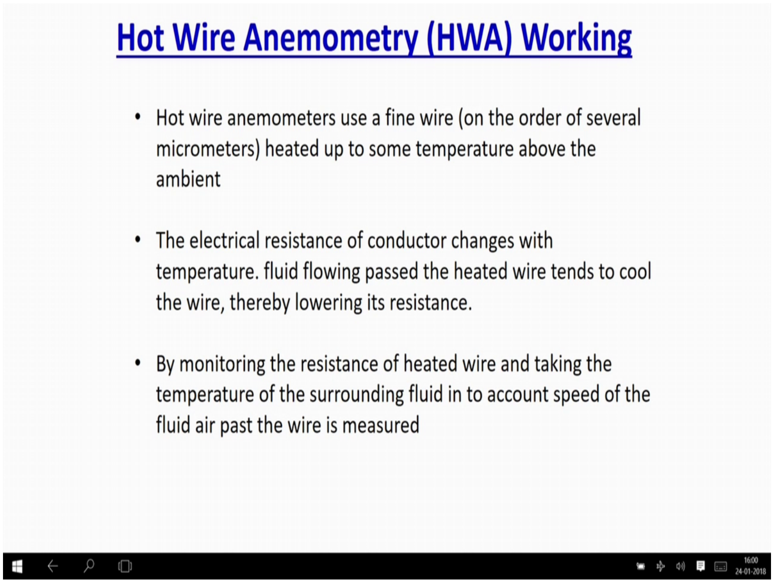

So, what as I said already said, but what is the formally the basic principle working principle of the hot wire anemometry is, that hot wire anemometry uses a fine wire as I said on the order of several micrometers in the order of actually 5 micrometer with the current state of the art, which are maintained at a particular temperature it is heated at a particular temperature, which is above in the ambient temperature. Then what we do the electrical resistance of the conductor actually is changes with change in the temperature, and hence the resistance of the wire is also changed.

And once you put that wire in a flowing fluid what will happen, because of the convective heat transfer the fluid will try to cool the temperature of the wire or cool the wire, and because of that there will be change in the resistance, and resistance will be reduced and because the resistance will be reduced as the current distribution will change. So, you can do that and by monitoring that resistance change of heated wire, and taking the temperature of the surroundings fluid. If you measure the surrounding fluid temperature we measure that how much resistance change has been taking place, you can calculate the velocity of the fluid. So, that is the basic principle which is being used in hot wire anemometry, to understand that.

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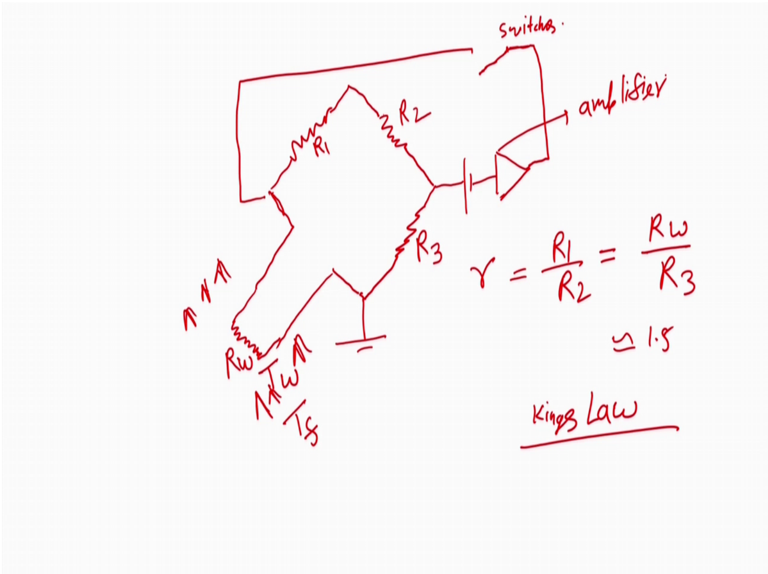

So, what we do actually again I will come back to the same that we make a wheat stone bridge circuit. So, I put some resistance here, I put again some resistance here, in this then again I put some resistance this resistance this ok.

Now, I connect it to say certain voltage, and I will make it a switch arrangement, and say I am making a amplifier, and this and then I am giving a voltage difference of voltage, we introduced it I will say that I will give a voltage. So, this is a typical circuit and this place you can if you want you can ground it. So, what will happen say this is my R 1 this is my R 2, this is my R wire, and this is my R 3. Now in the wheat in the hot wire anemometry what we do we stand this resistance, and I will write make this resistance something like this that this, and we have extended it and expose this resistance to the fluid and this becomes my RW clear.

So, what we are going to do, we know that if there will be current, will pass with the wheat Stonebridge principle that, it is going to be the ratio R 1 upon R 2 is going to be equal to R W upon R 3 these are going to equal, and that will be at a ratio which will be called at the resistance ratio R. And generally typically we balance a resistance ratio of around 1.5. So, that is the way this distribution will be there this R will be here, and the current will be passed through this if you give a voltage difference a particular current will be passing. Now because the particular volt difference we are already giving, the each resistance will be maintained at a certain temperature. So, let us assume that the temperature is T W here.

Now if I expose this to a fluid which is moving say in any direction, in this direction if suppose your fluid is moving, And I expose this wire to the fluid what will happen if suppose the fluid temperature is T f, then because of this fluid the resistance this wire temperature will cool down, because of the heat transfer the moment the wire temperature will be cooled down, this ratio will be disturbed, and then what will happen your voltage will change, your current will change.

So, what you try to do you maintain that you measure the change in the current, and that change in the current is actually being converted in terms of the velocity measurement, by using kings law I hope some of you might be knowing this, in the electrical engineering courses and even in heat transfer courses you might have heard about that. So, by using the king’s law we convert this change in the resistance in terms of the velocity. So, that is the basic principle of hot wire anemometry we use some volt difference, we which some switches we will discuss this this circuit again and gives you some amplifier, I will discuss this again once again.

So, that is the basic principle of the measurement, and based on that we calculate that change in the current, or change in the resistance, in terms of the velocity. Now you can do both you have both the luxury. And we will discuss that what is the type of this? So, as I said that there is different type depending upon whatever you are doing whether you are maintaining the change maintaining the current change, or you are seeing that resistance change you can divide the hot wire anemometry in different parts, or different types.

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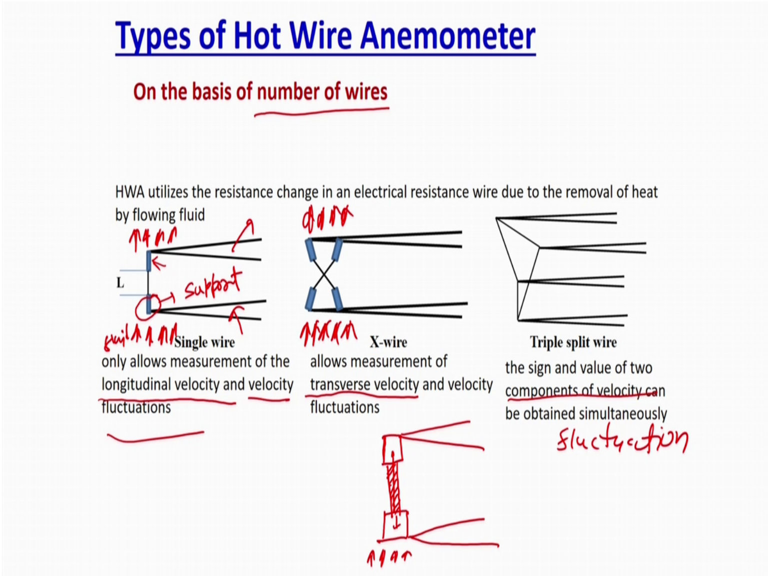

Now the types has been divided based on number of wires. And also based on the wave mode of operation. So, we discuss the wave mode of operation before that I will discuss that number of wires, that has been kind of divided the 1, first one is called single wire as I have discussed and the photograph I have already shown you, this is a single wire anemometer. So, what it does it does that the single wire anemometer is being placed in the flow ok.

So suppose this is the flow, this the fluid will be passed it in this way. So, that say this is the fluid what will happen, now the fluid will pass cylinder has been exposed through the fluid and it will be like a passed slow immersed body. Now this cylinder is being exposed because of the fluid temperature of loop velocity, and convective heat transfer the temperature of this this cylinder or this wire will be reduced, and you can convert that change in the resistance in terms of the velocity.

So, you can measure the velocity, but what happened with the single wire that it can measure only the 1 direction of velocity or if there is only longitudinal velocity it can measure, but if you have a 2 dimensional velocity, it means longitudinal as well as transverse velocity is there it cannot measure that. So, in that case we use a X wire type of hot wire anemometer. So, what it does the same thing the fluid is being flowing with it in this way with a particular velocity, what will happen both the wire will get cooled down. Now both the wires connected to individual wheat stone bridge the current will kind of the temperature will be modified; if their temperature is modified, what is going to happen the resistance is going to be modified, and the current will also be changed.

So, again whatever you are measuring you want to measure the change in the resistance or change in the current you can calculate the velocity, and you can calculate the both the velocity both directional velocity, in this how you can calculate that we will discuss again in the mathematical part of it once we will discuss the mathematical part. Now if suppose you have all the 3 dimensional velocity, then we use the triplet wire or triple split.

So, this is the name is being used some people say triple wire, some people say triple split wire, there is now there is a 3 wires are there again each wire is a individual wheat stone bridge it will measure that what is the change in the temperature, because of the fluid flow and the change in the temperature will be recorded in terms of the change in the resistance, or in terms of the change in the current. So, you can again measure the velocity. So, what happened that as I said that with the single wire you can allow to measure the only longitudinal velocity and velocity fluctuation for sure?

That is the major advantage of this you can measure the velocity as well as the velocity fluctuation, this allows you X Y allow you to measure the transverse velocity and velocity fluctuation that will be always been there, the 3 wire will give you not this the sign and value of the 2 component of the velocity, and they can measure simultaneously both the components of the velocity, and definitely they are going to provide the fluctuation too.

So, depending upon what kind of flow you have you have one dimensional flow you have longitudinal flow transverse flow, or 2 dial 2 component of the velocity whatever you want to measure you can use the number of wires and you can measure that. So, that is one way to divide the types of hot wire anemometer,s second way which is critical actually on the mode of operation. So, as I discuss in the circuit that what you will happen that you are going to see the change in the temp resistance. Now based on that and then that change in the resistance can be recorded in terms of the change in the current.

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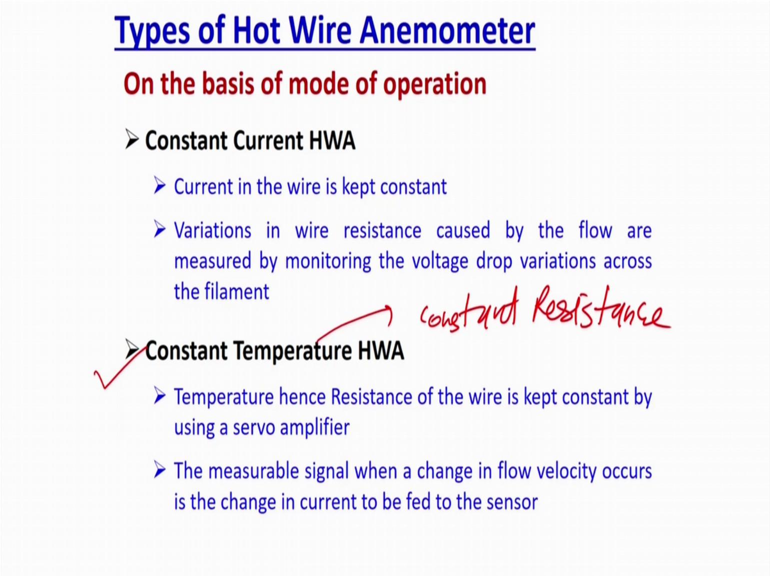

Now, based on the mode of operation, how you want to operate the hot wire anemometry is actually being divided mainly in 2 parts that, one is called constant current hot wire anemometer, and second one is called constant temperature hot wire anemometer. Now as the name suggests that in the constant current you are going to keep the currents same, and in the constant temperature you are going to keep the temperature same.

Now temperature same means resistance same. So, you can also say that is a constant temperature some people also say constant resistance. So, both are same. So, you can make the constant resistance or you can make the constant temperature. So, that is the way it has been divided each technique have their own advantage or each mode have their own advantage and disadvantage; however, mostly constant temperature hot wire anemometer is being used why we discussed. So, now what is the constant current hot wire anemometer?

As I said that constant current hot wire anemometer means you will maintain the current constant, and we will change the resistance. So, that is the way what is called constant current, constant temperature means you are going to keep the resistance same by using some servo amplifier or feedback controller, and you will keep on changing the current. So, that that the overall resistance you are going to keep on same. So, that is the basic way it has been defined the constant current, and constant temperature we will try to understand that.

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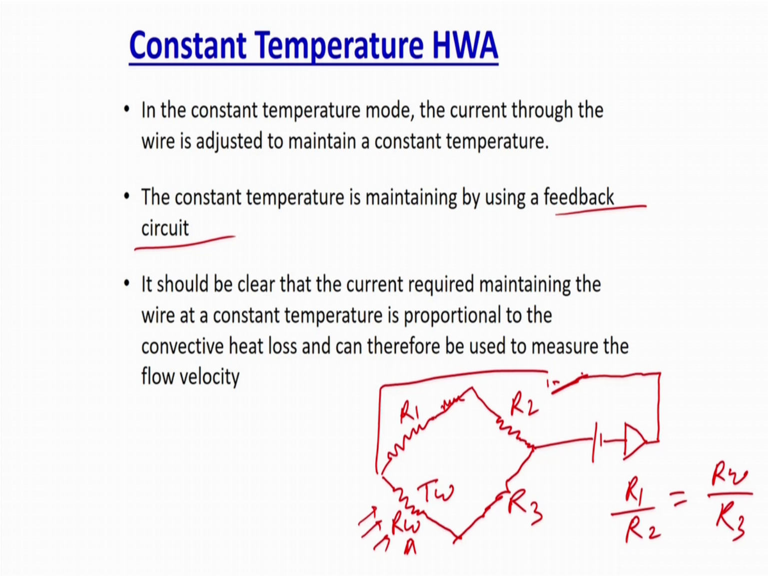

So, what is the constant temperature in constant temperature mode what we do, the current through the adjust wire is adjusted to maintain the constant temperature. So, how the temperature will be given, if I maintain that current constant then what will happen that sorry if you want to maintain the temperature constant, what you need to do you have to vary the current. So, suppose this is the Wheatstone bridge again I will make the same.

So, this is my say Wheatstone bridge circuit and say this, and I am going with this, this I put a switch, then I am coming here I went for a servo type amplifier and then I am given a voltage difference. Now what will happen initially say R 1, R 2, R W and R 3, they are maintained and this is maintained at temperature T W. Now if you expose it to the fluid. So, if I expose it to a fluid, then what will happen that the temperature of this wire resistance will change, and because of that the R W will also change.

Now the moment R W will change the ratio of the resistance will change, and you need to supply the extra current to maintain the same temperature, how because if you want to maintain a same temperature, the same current should be supplied in this length. If the current will be the same the overall temperature will also be the same. So, what we need to do now it has been cooler down resistance has reduced. So, you have to increase the current so, that your power to this wire remains same.

Now, to improve that current what you will do, you will use those server type amplifier feedback amplifier. And that amplifier will actually pass the current. If it will suppose cool down where it is in there. So, what will happen this switch will be not disconnected, and the current will be stopped, and you will see that that the temperature of the wire has changed so, that is the main circuit is being used and you use the amplifier.

If you want to use the constant current amplifier then what you have to do you have to keep the current similar? Now to keep the current similar, what you need to do you have to maintain this ratio same somehow. So, R 1 upon R 2 should remain same as R W upon R 3. So, what you will do you will put the extra resistance here somewhere, and that resistance you will be manipulating in such a way that your ratio remains same, this ratio remains same. So, the circuit is almost same only you maintain instead of varying the kind of current by using the server type amplifier you are now wearing the resistance.

So, that the resistance ratios remain same. So, that is the basic which we use in constant temperature and constant current. So, that is what we have said that, what will happen that because the flow the temperature will change, and the temperature need to be maintained and that will be maintained by supplying the extra current because the power will remain the same it is equal to i square p is equal to i square R. So, if the change in the temperature is causing change in the resistance if i increase that current what will happen your temperature will again be increased, because i square R value will remain same. So, that is the way we do it now we used to do that current manipulation we use a feedback circuit. So, this is the feedback circuit we kind of see that how the current is being reduced based on that we amplify the current, and that is the way it is being done. So, what is there that it should be clear that the current required maintaining the wire at a constant temperature is going to be proportional to the convective heat loss ok.

So, more the heat loss more the current you will require. So, that is going to be the proportional, and that proportionality will actually be can be related with the velocity, and because heat loss the convective heat loss is a function of velocity we all know that, and so the velocity can be measured or can be correlated with the increase in the current requirement. So, that is the principle which we use for the constant temperature hot anemometer.

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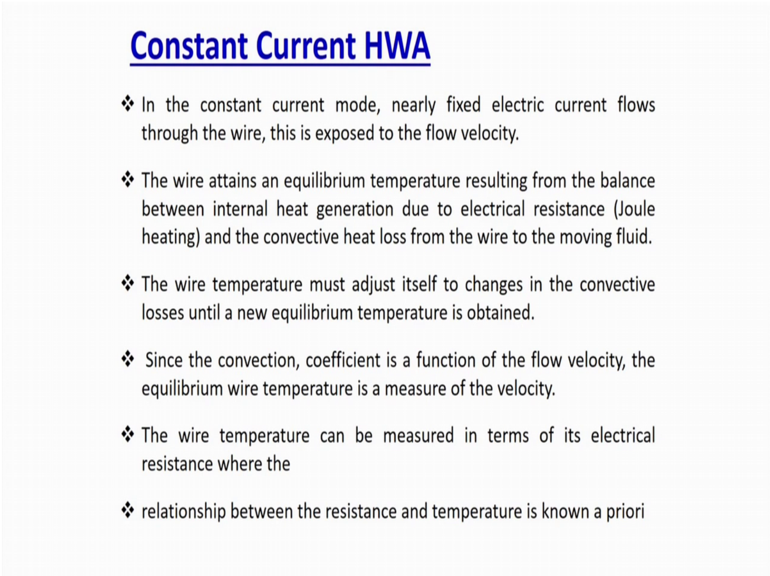

Now, in constant current hot wire anemometer as I said that what we do we maintain the constant current mode. So, constant current means your constant heat use there. So, what you are going to do? You are going to fit an electrical current flow through the wire, and that is what will happen that we have to kind of pass approximately same current through the wire, if you will pass the approximately same current through the wire, which is being exposed.

As I said that i square R value will remain same, and then you will have maintaining the constant current. Now though i square R value will not be the same, but you will maintaining the constant current so, that is what is the objective that you have to flow the constant current through the wire, now that is been possible to attain that the equilibrium temperature will change.

And that equilibrium temperature between the internal heat generation due to the electrical resistance, and the convective of wire convective heat conduction of the wire or convective heat transfer of the wire to the moving fluid will be actually get balanced. So, they will be equilibrium. So, that way what you can do that the wire temperature change must be adjusted with the convective loss, until the equilibrium of the temperature is achieved. So, what will happen because we are keeping the temperature current same that the temperature is going to be changed?

Now how much temperature of the wire will change that will depend on how much heat loss has been taken place from wire to the fluid. So, that will be the temperature change will be recorded, and that convict temperature change will be actually the function of velocity because again the convective heat transfer. So, the temperature change on the wire, will be actually the function of the velocity of the fluid.

Because how much temperature change you are going to see, that how much convective losses are taking place from the wire? So, in that way you can again correlate the temperature change recorded to the velocity of the fluid, and the velocity of the fluid can be measured. So, that is the constant current heat or a hot wire anemometer is being used, and the circuit what we do we put some additional resistance, and we keep on changing that resistance in such a way that your current flow should remain same. So, that is the way that is the principle of the constant current hot wire anemometry. Now obvious question will be which 1 I should use, whether I should use the constant current or should I use the constant temperature.

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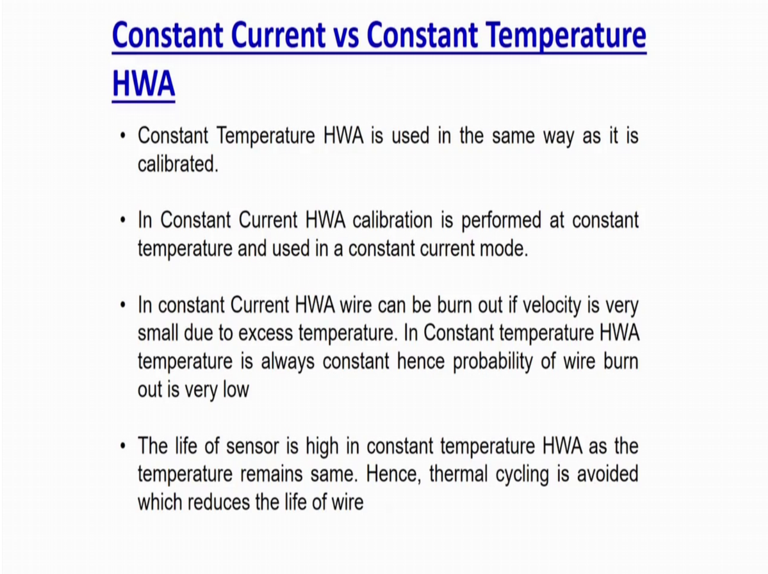

So, what is the basic principle of basic difference, in this in the constant temperature hot wire anemometer, it is used in the same way at is being calibrated. Now as I already said earlier in introduction class that most of the measurement technique is not a direct measurement, you are not directly measuring the velocity per se you are measuring some other quantity, and that quantity is being calibrated in terms of the velocity, or it is kind of being recalculated in terms of the velocity.

So, in such measurement which is indirect measurement definitely you need to do the calibration, and calibration is very very critical and the accuracy of your measurement actually depend on the accuracy of the calibration, and I will keep on repeating this thing because most of the technique, we will discuss will be actually doing the indirect measurement. So, the calibration becomes a very very integral part of all the measurement techniques.

So, in this also you do the calibration and while doing the calibration. The standard procedure is to maintain the temperature of the wire same. So, it means the major benefit of the hot wire anemometer which is operated on the constant temperature mode, that the way you do the calibration and the way you do the measurement is remain same.

So, that is the major advantage of this because it enhance the accuracy, then in constant current what happened that as I said that then the constant current also the calibration is performed by maintaining the constant temperature. And then that is being converted in terms of the constant current. So, what you have to do you have to again do a conversion, and then that conversion will be again being converted in terms of the velocity

So, one more extra layer of the conversion is coming, and that is why we would like to prefer the constant temperature because you are doing the calibration and measurement exactly in the same way. While in constant current you do the calibration by using the constant temperature approach, we do the measurement by using constant temperature mode.

So, that makes a difference and that me kind of hamper a little bit of your sensitivity of the probe. So, that is the major thing then the major disadvantage of the constant current hot wire anemometer is that wire burn out. Now what does the wire burn out means because we are actually allowing to change the temperature, now if you allow to change the temperature in the constant current mode what will happen, if the temperature increases beyond a certain point the wire will burn out, or if the temperature reduces we long a certain point it means the resistance will be very very low.

So, the power the current flow can be increased momentarily before you get into control into it, it can burn the element itself which can brown your wire. So, that that risk is very very high in case of the constant current hot wire anemometer. While in constant temperature hot wire anemometer, the wire temperature always remain constant. So, wire burnout is very very low, again because of some fluctuation some instability, or some kind of error performance, or kind of you are not good performance, of your controller it may kind of burn, the wire can burn, but most of the time if the probability of burning wire in case of the constant temperature hot wire anemometry is very very low. And that gives a major boost again because the cost of this hot wire anemometer, if you buy from any kind of commercial vendor like dentech, and all the cost is very costly it is not very E very cheap technique like a pitot tube it will be costly technique.

So, definitely you do not want a burn out of the wire, and because of that again constant temperature hot wire anemometer is being preferred. And again as I said that life of the sensor in the constant temperature hot wire anemometer is higher, not only because of the burnout possibility is low, but also because the wire is always maintained at a particular constant temperature.

So, it need not to go from the thermal shock or thermal cycle, in the constant current what will happen the temperature of wire will keep on changing. So, sometimes it will reduce sometimes it will increase. So, the tire is always having a thermal cycle of from the wire, or during in the wire that sometimes it is being gated heated sometimes the temperature is going down.

So, that will again what it will do it will reduce the life of your wire, and that is the region that most of the places constant temperature hot wire anemometer are used, but again it does not mean that you cannot use constant current, you can do that constant current also, but the constant temperature is being preferred because the life of the constant temperature wires, are much higher compared to the constant current probes or constant current wires. And then the calibration is always an edge. So, this is the major advantage that why the constant temperature hot wire anemometer are used.

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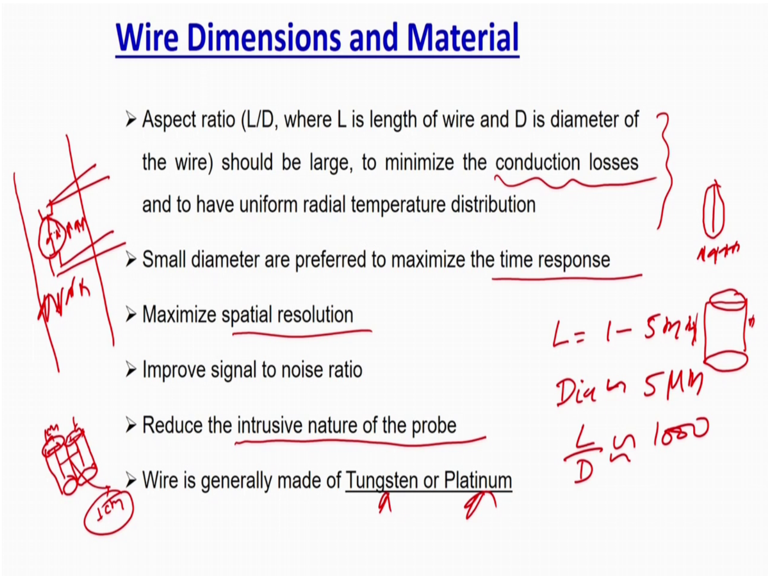

Now, this hot wire anemometer though we can buy from a commercial vendor, but ideally speaking you can also prepare the hot wire anemometer at your place, and is very simple to make you just need a wire made of tungsten or platinum. So, both of this kind of most of this wires used in the hot wire anemometer is either made of tungsten or made of platinum, some of sometimes they are mixed materials also.

So, you need just a tungsten wire or platinum wire you have to maintain a large L by D ratio, as I said that the length is in the order of 1 to 5 mm, and dia is in the order of 5 micrometer. So, if you see that L by D ratio is going in the range of 1000. If I take 5 mm and 5 micron. So, in the range of 1000 we keep a very large a your ratio L by D ratio.

Now why we keep a very large L by D ratio is important, because if you remember the picture and I will take you back little bit, that if you remember this picture whichever I have shown, that how it will look like there will be a prong or support which will be held this support so, I will tell it as a prong this is actually the support. Which is holding the wire, and then this is the wire which is being used for all the measurement.

So, what will happen if your wire diameter will be high, then conduction losses from the wire to this support will be higher are you getting my point. So, let me explain again suppose this is the support, what I am talking about and this is a prong, in between that there is a wire knife. Suppose the wire thickness is very very small, then what will happen because this wire is being heated, there will be conduction losses from this wire to this supports also.

Now if the wire thickness is very very small the contact area will be very very small, and in that case you can say that the losses because of this conduction is negligible compared to the loss because of the fluid motion, which is the fluid motion is being caused by convective heat transfer loss, but if your wire thickness is very big suppose now, you have increased the wire thickness something like this. This is now your current wire thickness.

Then what will happen your contact area is very big. So, the convective conductive losses will also be higher, and you cannot neglect that will not be in a position to neglect that. So, your calculation will be much difficult we will see the mathematics part, we see that how you do the measurement, but your calibration will be very very typical and we will show you that why it will be typical you have to take additional term into the account that will be the conductive loss to the support or to the prong.

So, that is the way it has been there. So, that is why the L by D ratio should be higher, why the L need to be higher because we know that the L resistivity of the wire depends on the length and the area both. So, if you increase the area resistivity will increase, if you increase the length resistivity will also increase you need certain resistance.

So, that there will be a particular temperature will be maintained either it will be burned out even at a small current pass i square R valance, if this is R is there you know the resistance will be very low it will burn out immediately. So, you need certain length so, that you can have maintain certain resistivity. So, that is why you are not doing that with increasing diameter, but you are doing that by increasing the length of this wire. So, that is the reason that why the L by D ratio should be very high in such a kind of a probe to measure the conductive losses to the support, then again the smaller diameter will increase your response time why, because if the diameter is small if you suspend it in the fluid, the fluid the temperature of this world will suddenly get uniform very fast it will get uniform because there is no radial variation, and the whole length is being dipped in the fluid.

So, the length wise the temperature will be the same, and there is no diameter there is no radial temperature gradient. So, it will maintain it will show the temperature difference very fast. If you suppose have a very big wire in this way then what will happen if you if you suspend in the fluid, it will take some time before the temperature becomes uniform and constant everywhere. So, it will take some time.

So, what will happen till it will not take that time, what you will see you will keep on seeing the change in the temperature and change in the resistance, whatever the mode you operate whether the constant temperature or the constant current in both the places you will see the problem. So, what will happen? It will reduce this temporal response why because you have to wait till it is not coming to a constant temperature so, the smaller diameter actually increases the temperature response, and the temperature response of this technique is very high you will discuss that is very very high because you are using a very thin wire.

Further thing it mean maximizes your spatial resolution. Now hot wire anemometry like a pitot tube also gives a point measurement. So, what does it mean because there is only one wire and which is being exposed so, this is my hot wire anemometer sorry. So, this is being exposed to the fluid no this is being expose this is the blown prong, but this is being exposed to the fluid.

So, what will happen it will measure the velocity at this location only it cannot mean give you the velocity distribution or radial velocity distribution, it cannot give you the velocity everywhere in all the flow field. Suppose if you put inside the column it can give you the velocity at a particular location only it cannot give you the velocity at all the locations. So, what will the possible way if you want to measure the velocity at all the location you have to keep the wire at all the possible locations if initially put it here, then you put at this position, then you put at this position, this position, this position.

Now what is the specialization how close you can measure the velocity, is smaller the thickness of the wire, a smaller will be that distance, and maximum will be the spatial resolutions say, if I use a wire of thickness 1 centimeter. The next point will be minimum after the 1 centimeters. So, suppose if I take the wire of 1 centimeter of diameter.

The next point will mean even if I keep it just next to it will be like this. If it will be like this this will be 1 centimeter. So, centre to centre distance also remain 1 centimeters. So, what will happen your spatial resolution will be limited to 1 centimeter clear so, the smaller wire thickness actually maximizes your spatial resolution, it minimizes your noise it reduces your noise and improves your signal to noise ratio.

It also includes reduces and this most critical the intrusive nature of the probe, because you are now reducing the diameter. So, the effect will be much lower compared to the bigger wire effect. So, suppose if you are putting a 1 to 5 micrometer your diameter wire there will be some change, in the probe velocity field I am not saying there will be no change there will be some change, but that change will be much lower compared to if you intrude a probe which is of one centimeter in diameter.

So, that is the major region and how the wire dimension should be taken place, and why it has been taken place, in this place and what should be the material definitely material should be very conductive, and it should have certain resistance to bear and the temperature. So, thermal resistance as well as the electrical resistance all the materials should be very good and it should be conductive very this would be very very conductive.

So, that is why the tungsten and platinum are generally used for the wire material. Now coming back to the measurement principle whatever we have discussed, now we can see that how exactly the things happen.

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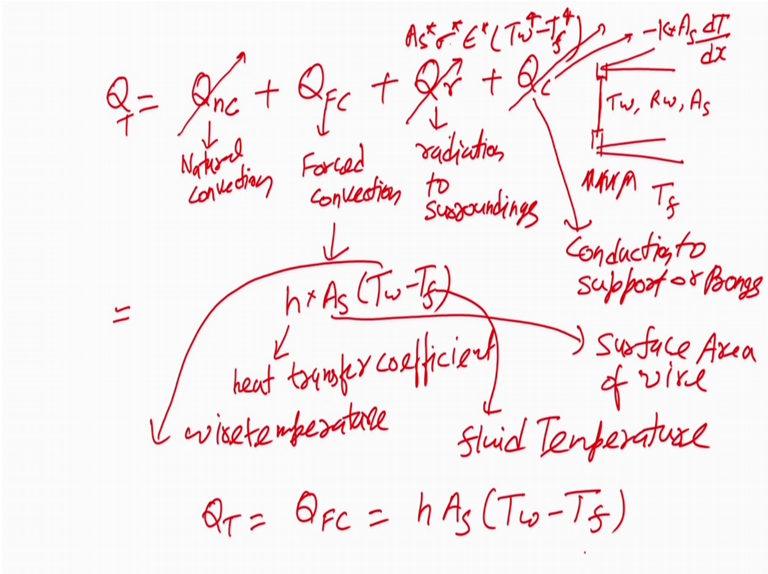

So, what I have said till now that suppose there is a hot wire anemometer is there is a wire and that wire is being suspended in the fluid, and we maintain that this wire is maintained at a temperature T w resistance is R w say area is as that is the wire. So, T w will write it anyway. So, now, if you suspend in the fluid what will happen there will be heat transfer taking place, because wire is maintained at a certain temperature fluid is maintained at a certain temperature.

So, because of that temperature gradient there will be some heat loss. Now what will be the heat loss or total heat loss say, if I write it in terms of the Q. So, that total heat loss I will say the Q T will be what it will be because of Q natural convection, I will write it as natural convection that will also take place, plus Q force convection, plus Q of r radiation, radiation to the surroundings plus Q c conduction and we will say that conduction to support or prong.

So, that is the way the heat transfer losses will take place. So, what will happen the fluid will be there, it will be taking the heat through the natural convection, it can take the heat from the forced convection there can be radiation lossless, and there will be some conduction losses. Now as I said that if the diameter of this wire is very very small the conduction losses to the prong can be neglected, anyway first let us see that how to mathematically write it. So, for natural convection what we know, we know that there are several equations available we can use that.

For the first convection the equation is generally we use Newtons law of cooling. So, h this heat transfer coefficient into A s into T w minus T f, that will be the natural convection h is heat transfer coefficient A s is surface area, area of wire T w is wire temperature, and T f is fluid temperature. Now the radiation we know that Stefan Boltzmann equation we can use.

So, it will be A s star sigma star epsilon star T w 4 minus or T f 4. So, we can do that emissivity it is the Stefan Boltzmann constant sigma surface area T w and T s, and then the conduction losses can be written Q c can be written as minus k into A s into d T upon dx that will be the conduction losses clip. So, we can have this equation and ideally if you want the total heat loss will be because of this.

Now we know that if the wire temperature is very very small or is relatively smaller not very very small, then I can neglect with kind of Q r value, and it will not generate much error in my measurements, and it will simplify my calculations. So, I can neglect the Q r value if the temperature difference is very very low, it is not very high. Similarly if your wire is very thin you can say that the convective losses conductive losses to the prong or to the support can also be neglected.

If the velocity is there if the fluid is moving with the velocity and sufficient velocity, the natural convection part can also be neglected. So, what is going to happen the heat loss which is going to take place from this wire will be purely because of the convective heat transfer? So, this Q T will be equal to actually Q F C and that will be equal to h into A s into T w minus T F, that will be your total heat loss which will be taking place from the wire.

Now we know that how the wire temperature will change, or resistance will change, with the this heat loss for that we know that equation, we know the correlation between the wire resistance and the temperature and that is being given say R w or of reference say a reference temperature or reference resistance which was there earlier, 1plus or constant alpha it will be T of w, T of fluid minus T of reference.

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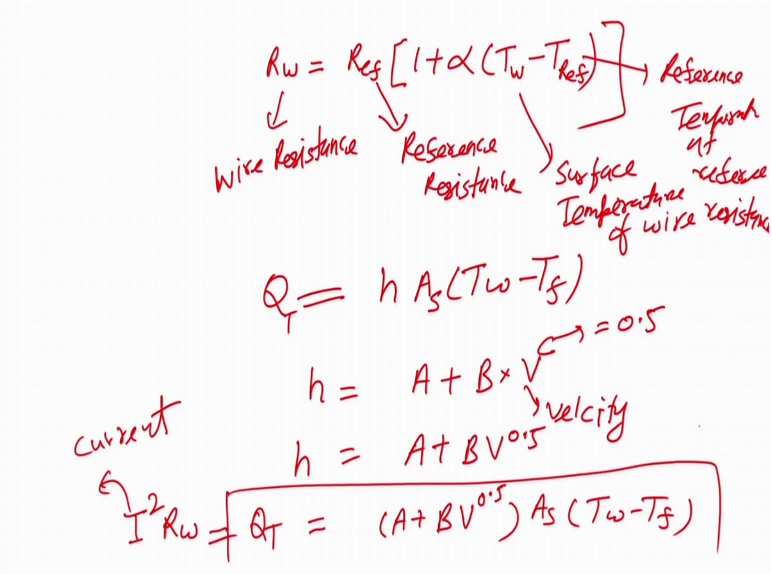

So, that is the way it has been maintained that the way it will be there. So, in this way it will be maintained. So, R w will be what it is the wire resistance R f is reference resistance, T s is the surface temperature of the wire, better if we write the same term as a T w instead of T s let us not kind of simplify this equation. So, we can say T w and T reference is the reference temperature, temperature at reference resistance.

So, that is the way we know that how the R w is changing. Now we can use that equation Q T is h A T w minus T of fluid, this is a of surface A s. Now this is the convective heat transfer, now we know that from the kings law that heat coefficient heat transfer coefficient is also a function of velocity, and how it has been related to the velocity h is being related to A plus B into V, where V is the velocity raised to the power C, and generally this value of C is equal to 0.5.

So, you can say that it will be A plus B into V raised to the power 0.5 h, what we can do we can replace the h value here in the Q T by this equation. So, your equation will be modified, and your equation will be instead of h you will get A plus B V raised to the power 0.5 into A s into T w minus T f, and that will be equal to Q T. Now this Q T the heat transfer will be take place how much heat transfer will be take place, it will be equivalent to how much power supplied to the wire.

So, that is the heat transfer which will be taking place or the kind of overall heat transfer will be there. So, whatever the voltage drop or the power will be given to the wire, that will be equal to the convective heat transfer loss once the equilibrium will be achieved at this condition. So, it means Q T the power to the resistance applied to the wire will be exactly what, we can write it in terms of the I R, I square R W which is nothing, but the current, you got my point that the electrical power input will be equal to the convective losses.

So, electrical power input to the wire will be equal to the convective losses based on this convective law of temperature so, you can write it I square R w will be equal to h A T w minus T f h I have converted in terms of the king's law. So, you will get it in this value.

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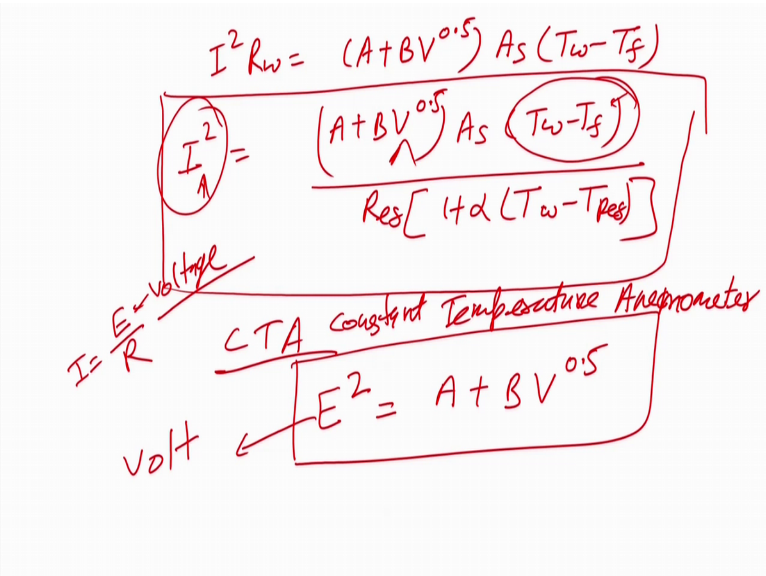

So, you can write it here I square R w will be equal to A plus V into V raised to the power 0.5 into A s into T w minus T of fluid. That is the way we can write R w again you can convert in terms of the T and T f so, in terms of the reference. So, I square you can say will be equal to A plus B, V raised to the power 0.5 into A s that will be into A s T w minus T f, and this R w can be written as R reference, 1 plus alpha it will be T s or T w minus T res so, that is the I square value. Now it means what it says it says that your current change is directly proportional to change of the fluid temperature, and that fluid temperature is measured with the velocity.

So, if you are measuring the current change, if you are measuring the fluid temperature what you can find you can easily find that, what is your velocity because you will get the R value also, that how your resistance value will change with this formula whatever I have done. So, if you know your reference temperature, you know that how much temperature, you have changed you reference temperature also, you know you can calculate the velocity. So, what you need? You need fluid temperature, you need I square if you know that you can calculate this value. If you do not know that what you can do you can convert it in terms of the constant temperature, if you maintain the temperature constant, you can find that how much current value need to be accounted.

So, either you can keep this I square constant, or you can keep this temperature difference constant. So, the temperature constant will be there this would be constant temperature, and you can measure the correlation you can measure the velocity, and the equation will be simplified and you will get that what will be the velocity for say constant temperature if we do the anemometer finally, this you can write I in terms of the V square so, this will be I square will be V square upon R square, it will come this will be cancelled out and it will be simply as a kings law A into B raise to the power 0.5.

Here the V is volt so, I will not confuse it I will write it as E, E square a E is volt. So, what is the volts applied? So, I is equal to V upon R. So, you do that or not be upon a say because sorry, I am just doing this E upon R where E is the voltage. So, you can measure the voltage difference, and that voltage difference can be measured in terms of the velocity, and in most of the constant temperature anemometer this is constant temperature anemometer.

We can reduce it into this form. E square is equal to A plus B into V raise to the power 0.5, we can find it out the A and B value, and we can see that how this E V and Z is being correlated, and what you need to do that you have to do the calibration. If you do the calibration, you will find that how the E and V is correlated in the constant temperature anemometer, you do the experiments you maintain the temperature constant by changing the voltage it means you have to change the kind of voltage or current in any way whatever you say, you measure the volt difference at the outlet, and you will find that how the velocity will be what will be the velocity.

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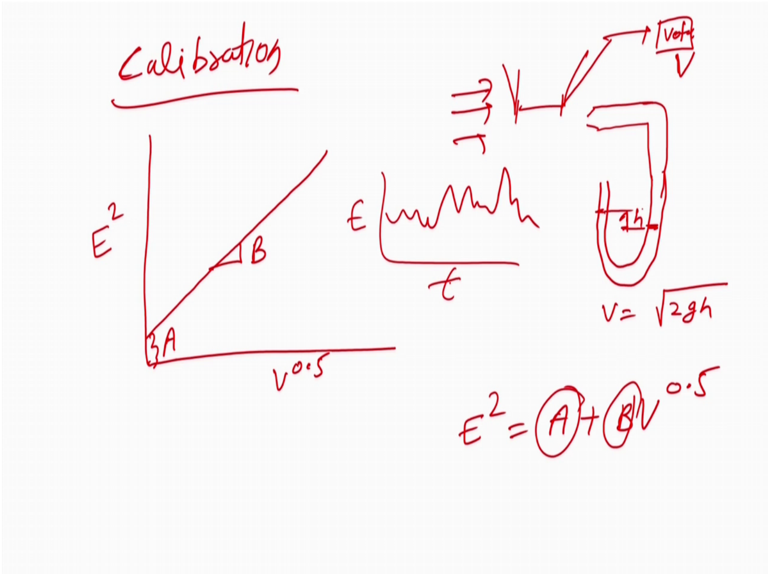

So, what we do we do the calibration, and in the calibration what we do in the calibration part, we suspend the probe in a domain say this is the fluid field or and I suspend the wire here, I suspend the wire. So, this is the probe I suspended it here, somewhere here in this way the prong, I suspend the wire and I measure that velocity. Now how I measure the velocity what I do I put a pitot tube, and that is the way the calibration is being done in hot wire anemometer.

So, I put the pitot tube and that pitot tube is being connected to say a manometer, you measure the h we know that velocity in this pitot tube is going to be under root 2 into g h or you can say rho p my p into rho p minus rho and p I have just converted in terms of the manometer reading. So, it will come into under 2 rho gh. So, that is the way you can calculate the velocity, and you can record that volt that. What is the volt difference say you put a circuit your voltmeter is there, you can see that what is the volt is recorded. So, what you can do you can put a plot between E square and V raise to the power 0.5.

If you put that E square whatever the formula we have get is A plus B into V raised to power 0.5, if I pot plot a graph between E square and V power 0.5, what I will get I will get a straight line which will have a intercept, the value of intercept will be A and the slope of line will be B. So, you will get this calibration parameter you will get the value of A, you will get the value of B, and then what you can do you can calculate that what will be your velocity.

Now in the real experiments here, what you do not want knowing you are knowing that at this velocity, what will be the volt difference, in the real experiments we will be measuring the volt difference, and you will be calculating the velocity. So, you will get that what is the velocity of the fluid, and not only the velocity now what will happen with the change in the current, if there is a turbulent flow, and that is the reason why it is being used so fast, because the temporal response of the electrical signals are very very high, it can go up to 1 megahertz it means you can acquire at tens power minus 6 seconds data acquisition time delta T.

So, what will happen if you do that you will see that you can find this slope you can acquire the data at a very high speed, and if the flow is turbulent if the fluctuations level is very high, you can acquire at a very high frequency, and you can not only get the velocity, but you can also get the fluctuations that how the fluctuation is taking place.

So, with each fluctuation the temperature kind of will try to be modified, you will keep the temperature same current will be modified, a volt will be modified, and you will see the volt fluctuation reading. And this volt fluctuation reading it in this way with the time, and this volt fluctuation or E reverses T you can get this can be calibrated with the velocity that how the velocity will be there, you can calculate the mean with the time average mean value, you can find it out how what will be the fluctuating component of the velocity in this case ok. So, you can do all this with the hot wire anemometer, and that is why this technique is very very famous and being widely used.

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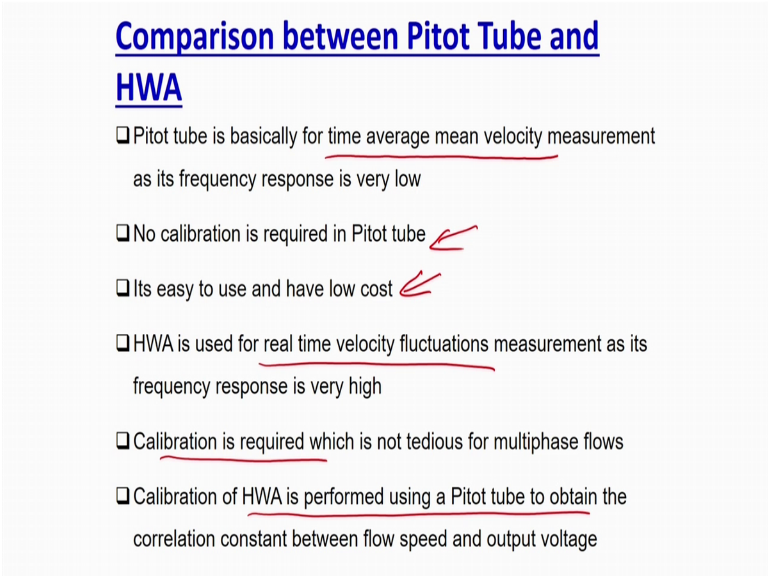

Now I would like to also do the comparison between hot wire anemometry and pitot tube, because we are calibrating the hot wire anemometer with the pitot tube, you should not confuse that it is only as good as pitot tube. So, what is the comparison? So, the major comparison major advantage that the pitot tube, because the response time is very low the manometer will take time before it will get to stabilize, it can measure only the time averaged mean velocity while hot wire anemometer the frequency response is very high. So, what you can measure you can measure the fluctuation velocity you can major the real time fluctuation velocity you can measure the mean velocity for sure.

The advantage of the pitot tube, and why it is being used also is that there is no calibration required you are using pitot tube to calibrate hot wire anemometer. So, no calibration is required definitely the cost is much lower than, whatever you are using in the hot wire anemometer. So, the cost factor is also coming into the picture its very cheap compared to the hot wire anemometer.

The major thing is that the hot wire anemometer calibration is very very tickly very very typical critical, and it is not a very easy job, it is a time consuming job, you have to do the calibration for sufficient long I mean, then only you will get that and as I said accuracy of your hot wire anemometer measurement will depend on the accuracy of your calibration curve. So, need to prepare the calibration curve properly, and the calibration in HWA is performed using the pitot tube to obtain the correlation coefficients to measure the speed at the and outlet voltage. So, you can find that correlation only by using the pitot tube.

So, that is the way so, the hot wire anemometer the major advantage is your frequency response time is very very high it means, it is a temporal its very high ideally speaking you can achieve very high spatial resolution, if you use an array of hot wire anemometer probes or you keep the probes at several locations, you can ideally speaking can use achieve a very high spatial resolution too, and it can give you not only the mean velocity it can also give you the fluctuating velocity and real time fluctuation velocities.

So, that is the major advantage of the hot wire anemometer over the conventional pitot tube, then the same approach because it was being used very widely and in 1942 to 48 this development has been done for the single phase flow, and then many people have used this for the single phase flow, and again I am telling that most of our understanding on the turbulence is generated with the data obtained for the hot wire anemometer. Now, the same concept in late 1970 we use for people have tried to use for the multi-phase flow.

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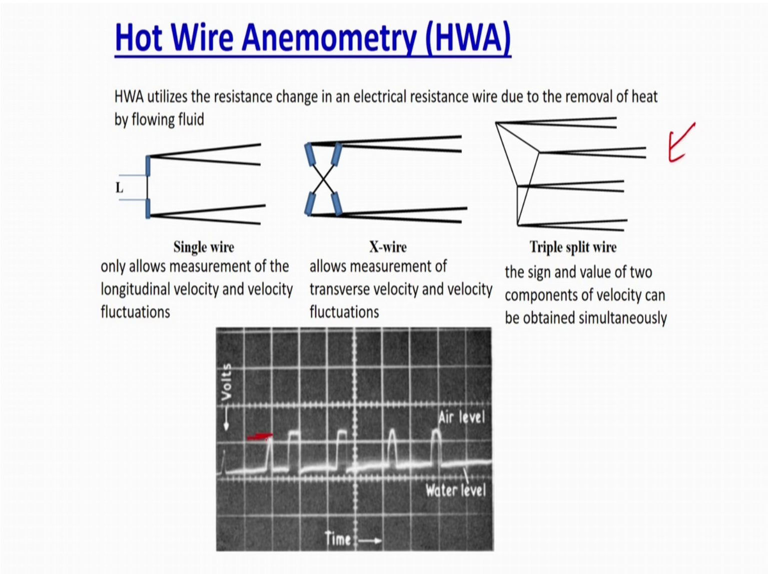

So, in the multi-phase flow all they were whatever I have said is remain same what you can do, you can use single wire you can use X wire, you can use triple split wire, depending upon what kind of a velocity coefficient you have, definitely the single wire has a very limited use because most of the multi-phase flow is having at least 2 dimensional velocity, if not 3 even. If you assume the theta directional symmetry you will have the 3 dimensional velocity, or at least 2 dimensional velocity.

So, you need to use either triplet or X wire most of the time this triplet, triple split wire is being used in the multi-phase flow, then there is additional complexity whatever the equation I have solved it. Is solved for only 1 phase, because each phase we have not accounted that heat capacity of that phase. Now because water and gas have a different heat capacity values, what is going to happen that the your heat transfer will be different in case of the water or a temperature difference will be different in case of the water is touching the wire.

And in case of air is touching the wire. If suppose you are operating a constant temperature. So, if you are using a constant temperature anemometer, then the current requirement to maintain the constant temperature once the air comes into the contact, and once the water comes into the contact will be different even if they are moving with the same velocity.

So, what you need to do? You have to do the double level calibration, 1 the calibration will be only with the water to see that what will be the volt level. Once the calibration will be only with the air and you have to see the what is the volt level, and you will able to measure the velocity of both the phases only and only if the volt level readings are different for both the phases, like it has been done by Davis in 1972 they have done the experiment with air and water, and they have found that with the air and water with the hot wire anemometer. The volt labeled readings are different air gives a certain volt of this range, and whenever it water comes the water volt rating is this. So, now, you have the reading volt reading for each volt reading, for each phase you have to do the calibration you will find that velocity.

Even if you want you can also find the volume fraction in the same paper they have tried to show that, that each curve we will show that how much is the contact time, it will show that how much fraction of the time that phase was staying at that time. You are measuring that funk fraction, the area under the curve with the time that will also give you that what will be the fraction of that phase, but whatever we are interested in mostly in the hot wire anemometer is the velocity measurement that you can easily do here.

The only thing is it will be typical, it will not be that easy why because you will have the multiple components here. Now the second thing which is important is that how to measure the velocity or 2 dimensional velocity particularly.

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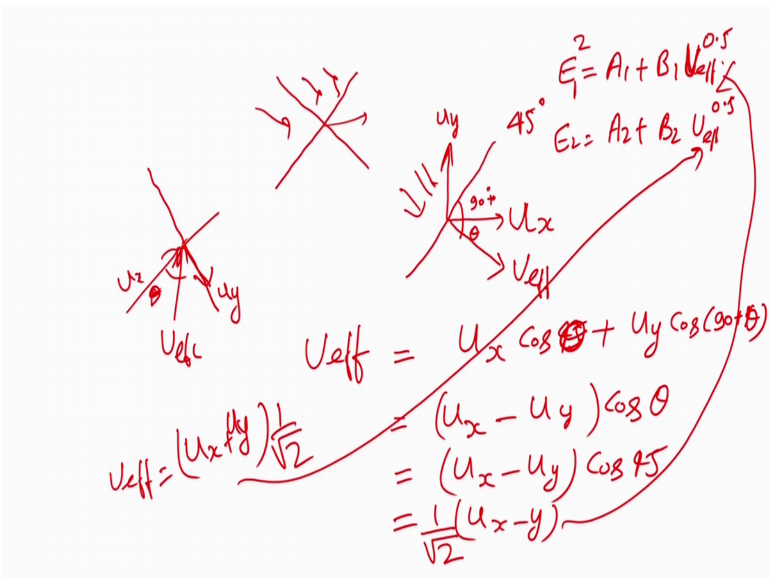

So, what you can do if suppose I use a x wire I will just so, 1 example triplet will be the same you can try to do that. So, suppose if I am using the at wire and there is a velocity in this direction. Let us do it with the 1 wire which is being inclined. Now this is say velocity, this is the you are going to get it in this way.

Now this say is U and this is being converted incog of U this, and the other thing is converted in terms of the U this. So, this is the way it has been converted this is U effective you are doing it in this way that this is say U effective, this is your U of x direction, this is u of y direction. And this is your angle which it is making with the wire, this is your theta say this is theta this will be 90 plus theta 90 degree.

So, what will happen U effective you can convert in terms of this? So, U effective will be what U effective will be equal to U x this, will be cos 45 plus u y into cos 90 plus 45,90 plus theta sorry, this will be theta this will be theta cos theta plus 90 plus theta. Now this will be what u x minus u y cos theta. So, if I know the angle between these 2, if what is the angle of this slope then I can find it out that what will be the u effective, most of the time this angle is kept 45 degree. So, this angle is most of the time is kept 45 degree not centigrade 45 degree. So, what will happen the cos theta will be cos 45. So, you can say u x minus u y cos 45, and cos 45 value is one upon under root 2. So, you can say u x minus u y 1 upon under root 2 for the probe which is coming at it in this direction. It means the probe is it placed it in this direction, and the fluid is coming from so, probe is in this direction, and fluid is coming from this side.

Now if the probe is in the opposite direction if the probe is in the opposite direction. So, in this way, and the fluid is again coming it in this way in this direction, what will happen again can do that that say, this is the fluid direction is coming this is 45, and this is the another direction. So, what will happen now it will be theta? So, it will be say this is your u effective this is your u x this is your u y.

So, what will happen this will be 45 it will be cos u effective u x will be equal to what u effective will be u x cost 45 u y cos 45, and you will get that values and that value will be equal to that what is your value. So, this will be u x cos 45 plus u y cos 45, and this will be u effective will be equal to your u x plus u y 1 upon under root 2.

I hope you got that point that in 1 case what we have done, we have seen that because this is the way this wire is there. So, if the fluid flow is coming at it in this way, this will be the angle. So, that angle will be for it will be 90 degrees for the u x, and then the u effective will be more than that theta. In this case once the wire will be on this side and the fluid is coming it in this way it will be within the theta.

So, that value will be within the theta. So, it will be 45 degree here if the wire angle is 45 this will be also at u effective will be at 45 degree. So, it will be u x cos 45 u y sine cos 45, and you will get that u x plus u y 1 upon under root 2. So, you get the u effective values we know that for each wire is say I will say even A square will be B 1 plus B 1 into V raised to the power 0.5, and V is nothing but is V effective or u effective.

Now, u effective can be written for depending upon E 2 will be E 2 plus B 2 into u effective 0.5, this also let consument u effective 0.5. Now this u effective can be written based on that which wire we are talking about the upward wire, or downward side wire, it means plus 35 or minus 45 wires, we can have the values, we can have u replace the u effective from this place say this will go here, let us say this is going here, we will replace that we will do the calibration 1 for the this wire, another for this wire, you will get the constant. So, you will have now 1 calibration curve that is why it will becomes typical, in triplet we have to do it 3 types. So, you can do that and you can have different wires to measure all the direction velocity in the basic principle again remains same ok.

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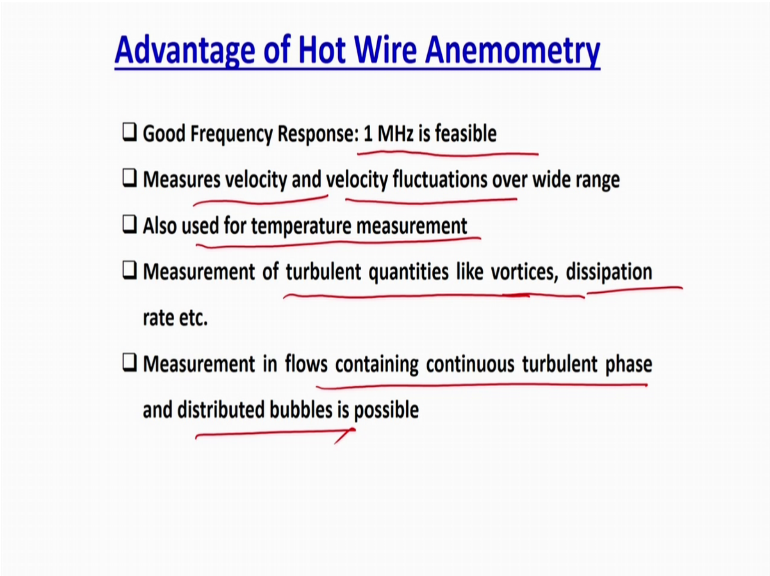

So, now concluding this part of hot wire anemometer, what I will say that advantage of the hot wire anemometer it has the major advantage there is a very good frequency response, it means the temporal response is very very high.

But that is the major advantage it can measure the velocity, and the velocity fluctuation over a wide range of distribution not in a small range, say not very worried about that what is the velocity you are worried about the lower velocity, we will see why you can use it for temperature measurement also, actually because you need the reference temperature. You can calculate the turbulent quantities because you are using the fluctuation velocity, you can calculate the turbulation quantities like vortices dissipation rate etc all the turbulence quantity, you can calculate it will scan me measurement the containing the continuous turbulence flow. And it can be used even for the bubbles, like in the pitot tube the problem as we discussed that if you use for the bubble flow, bubble can burst and then the local pressure difference will be very high.

So, in case of multi-phase flow the pitot tube applications are lower compared to multi-phase flow, because if you have a distributed bubble you can simply use this. The way I have shown the example, but it does not mean that it has all the advantage, it have several drawbacks and that is why the use is limited and advanced techniques more advanced techniques are needed and being invented.

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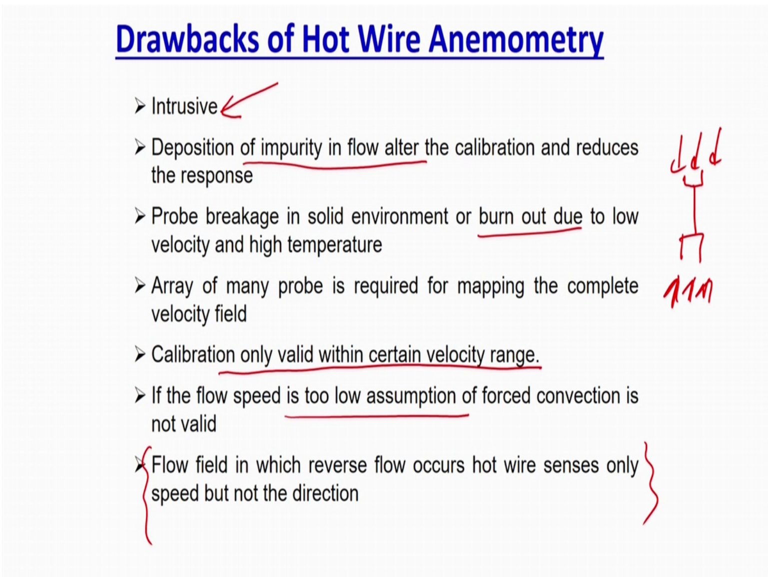

The major disadvantages it is intrusive in nature. So, even if you are minimizing the size of the wire we are not able to minimize the size of the probe. So, size of the probe or support of prong is actually little bit bigger, and that actually create the invasive nature a lot you cannot minimize that actually. And that is why the point the flow can change at the point of measurement itself, then the second problem is you are using a wire, and if you are using it in a fluid which is contaminated or having deposition can this tendency or it has been already contaminated with some solid or something some chemicals, what will happen the deposition will take place on the wire the moment you will expose it to a surface. The moment the deposition will take place, what will happen your resistance will change your overall calibration will also get modified. So, that is the major problem that in case of impure environment, when deposition tendency is there you cannot use it the probe can break in the solid environment.

If you put it in the solid it will immediately break can also be break due to the burnout, which will be because of very low temperature with very low velocity, or very high temperature. Why the low velocity because the low velocity will not able to remove the heat properly.

So, that the burnout is possible you can use array of multiple detector you multiple anemometer is used hot wire anemometer to find the radial distribution of the velocity. So, overall the cost if you want to find the radial distribution will be very high, the calibration is only valid with a certain velocity range, if you go outside of that velocity range you will not able to use that you have to actually calibrate it again.

In the flow of speed is too low assuming the force convection is not valid, you cannot use the equations which we have developed, if there is a natural convection is also taking place if the velocity is too low you have to include that, and then the process will not be very simple the only the can this assumption of force convection will not be true. And the major disadvantage is this that if you have a reverse flow somewhere in between.

Then your hot wire anemometer will still measure the velocity it is not going to tell you anything about the direction. So, you will get the speed, but you will not get the direction why, because if suppose the probe is being suspended whether the fluid is flowing from this side or it is coming from this side, somewhere the heat loss will be the same. So, it will not able to sense that whether it is fluid is moving top to the bottom, or bottom to the top.

So, it will not able to sense that. So, reverse flow condition if you are using that you will only get the speed not the velocity will not get the direction, and that is the major limitation in the multi-phase flow, because of the bubbles or discrete phase presence the flow can reverse at any moment. So, that is the major drawback and that is why the more advanced technique is being invented and which will be discussed later.

Thank you.