Mechanical Measurements and Metrology
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**Module - 2**
Lecture - 13
Measurement of Temperature under various Conditions

This will be the 13th lecture on our series on mechanical measurements. We have been discussing about thermometry, the measurement of temperature. We consider in some detail the use of thermocouples to measure temperature using what is called the thermoelectric properties of materials.

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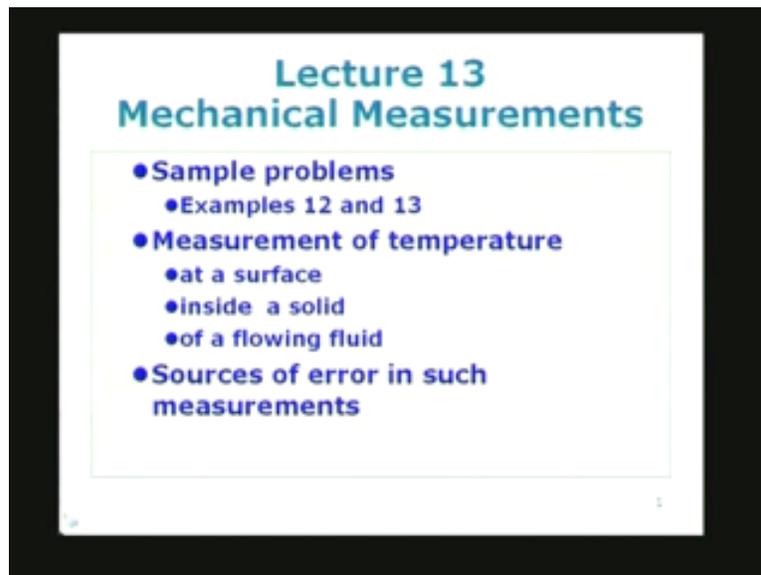
And what we will do today is to complete that discussion by taking two examples and then I will take up the study of measurement of temperatures on various circumstances. Like for example the measurement of temperature of a surface, measurement of temperature within a solid and of course measurement of temperature of a moving fluid. These are typical applications which occur in engineering practice. And then more importantly, we look at the sources of error in such measurements and how to either estimate these errors or what are the methods which we can use to minimize these errors. These are the things we are going to discuss. I do not

think everything will be possible in this one hour. So we will do whatever is possible and then continue in the next lecture.

So to start with, let us look at the two examples which demonstrate the use of some of the principles we have learnt in the previous lecture and thermocouple, thermometry.

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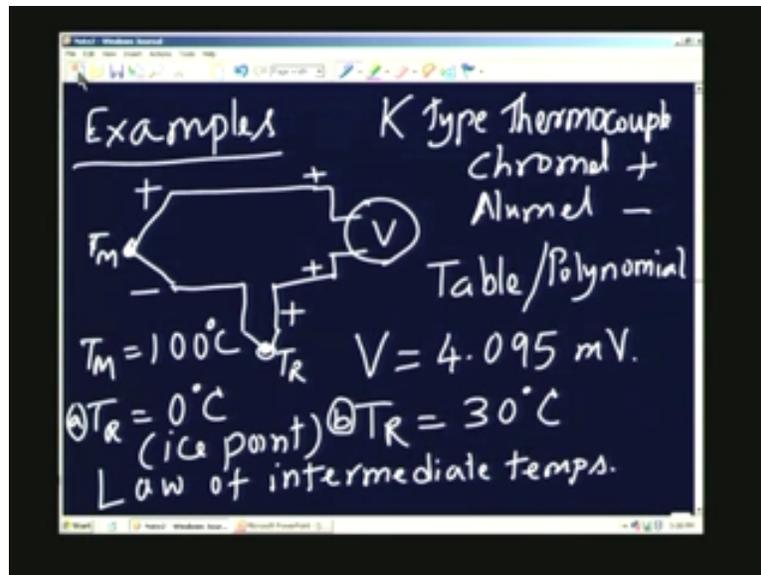
And the first example will be the measurement of temperature using a typical thermocouple circuit and let me just indicate how we are going to do that. We have a thermocouple junction here, and we have a simple thermocouple circuit which is familiar to us. This is the reference junction, this is the measuring junction, this is the positive and the negative here, again the positive, and here the measurement is done across the two positive materials.

So in the first example, I have the measuring junction at 100 degree Celsius and the reference junction T_r is at 0 degree Celsius at the ice point, and I am using K-type thermocouple. So we already know what I type and what K-type thermocouple is and the student is expected to remember what K-type means. It is the chromel alumel thermocouple.

Chromel is the positive element and the alumel is the negative element. So if the reference temperature is at the ice point and the measuring junction at 100 degree. We can refer to either a table or we can use a polynomial which

we have already indicated earlier and obtain what is the value of voltage we would be measuring. In this case from the table,we take the value of 4.095 millivolts. So it is a very simple example.

I want to just make a small change here in this example. Instead of taking the reference at the ice point, suppose the reference is not at the ice point but changed to 30 degree Celsius, If I say this is case a, corresponding to temperature equal to 0 degree, this will be case b where I have taken the reference junction to be at 30 degree. So we can use the law of intermediate temperatures. Actually the example here, is to demonstrate the use of, the application of three laws we proposed in the last lecture. So the law of the intermediate temperatures is going to be used to figure out what is going to be the output of the circuit. So, we have the following.

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I will just repeat the same sketch here. This is the voltage V, this is T_m, T_r which is at the room temperature instead of being the ice point now. We know from our very earlier discussion of the law of intermediate temperature is that the output now V will be output with T_m with respect to 0 degree Celsius. That means the voltage which would be indicated in the previous case minus voltage between T_r and 0 degree Celsius.

In fact again we go back to the same table which gives the (7:06) thermoelectric Seebeck voltage versus temperature and the table is with

respect to 0 degree Celsius. Therefore I will be able to directly read these two quantities from the table, and this already has been done. This is equal to 4.095 as in the previous case, minus corresponding to the room temperature it is equal to 1.203 millivolts. So the difference between these two will be 2.892 millivolts.

That means, if we do not have the reference at the ice point, but the reference is maintained at the room temperature,the output of the circuit is actually less than in the case where the reference is at the ice point. So another way of looking at the result is, we will be measuring 2.892, to this we have to add 1.203 to get 4.095, corresponding to 4.095 from the table I will be reading 100 degree. So, it is in the reverse order. This is an example which shows how to use the law of intermediate temperatures. Let me take another example which is slightly more interesting.

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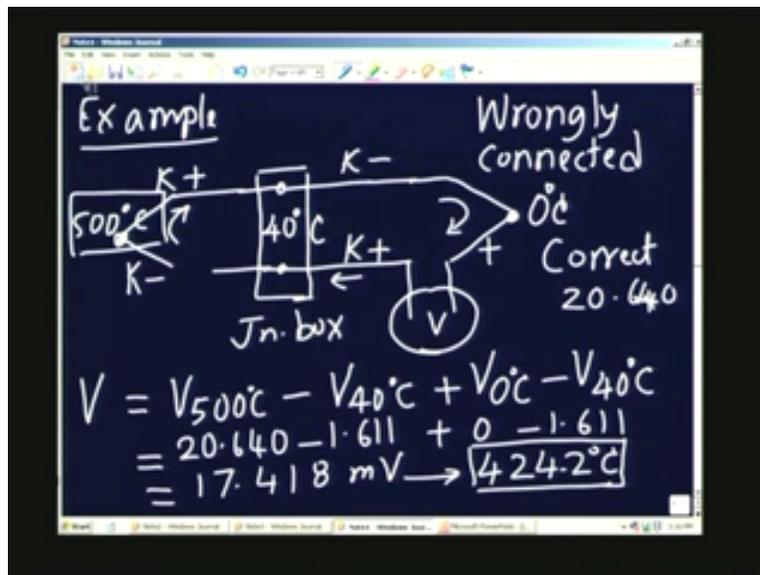
What has been done is again we are using the K-type thermocouple. The following circuit has been made. This is second example for today. So, we have the measuring junction at 500 degree and we are going to use extension wires to connect it to the outside. So what has happened is, this is K-type positive, this is K-type negative and extension wires are connected to a block junction box. We have already discussed the use of the junction box which is maintained at 40 degree centigrade. And what happened is, by mistake the negative element has to be connected to the positive terminals and the

positive element to the negative terminal, and I am measuring the output here, this is the ice point and all are connected like this.

So the mistake is that, the positive and the negative elements have been switched at the junction box. So, this is the wrong connection and we would like to find out what is the consequence of such a mistake. For this, we can find out what is the voltage read by the voltmeter. We can go around the circuit. We will see that V corresponds to 500 due to the hot junction. This is from plus to minus, I am going from this direction or you can go in the other direction, it does not matter how you are going.

So for the 500 degree I will get a positive voltage, let us say. Then I will get a negative voltage correspond to 40 degree. So actually I am going the other way. This should give you positive and then I am going from positive to negative here. Here I am going from negative to positive and positive to negative. I will get minus V_{40} all with respect to 0 degree because we are going to use the same table, then from negative to positive again. So this will be plus V corresponding to 0 degree Celsius, so we are going like this. And here again we are going in this direction positive to negative, so it will be minus V at 40 degree Celsius.

Now, we can put the values here: 500 degree the value from the table is "20.640, this is 1.611 all in millivolts, this will be 0 and this again 1.611. This gives a value of 17.418 millivolts. Just remember that what was intended is that, K plus should have been connected to K plus here and K minus to K minus here. Then everything would have been alright. If it were the case, these two would cancel each other and I would get V_{500}. So what I should have got?

The correct reading or the correct value is 20.64 corresponding to 500 degree, but what we have got is 17.418 and if you were to convert these to a temperature, because this is what I would read, I would not be obtaining this 17.418. By calculation like this what I would get directly is the reading from the voltmeter, this should be the reading, and if I convert this reading to the temperature it will correspond to 424.2 degree Celsius. What we wanted to measure is 500 and what we are inferring is 424, so you see that there is a very large error. So if I were to convert connect it properly, I should do like this.
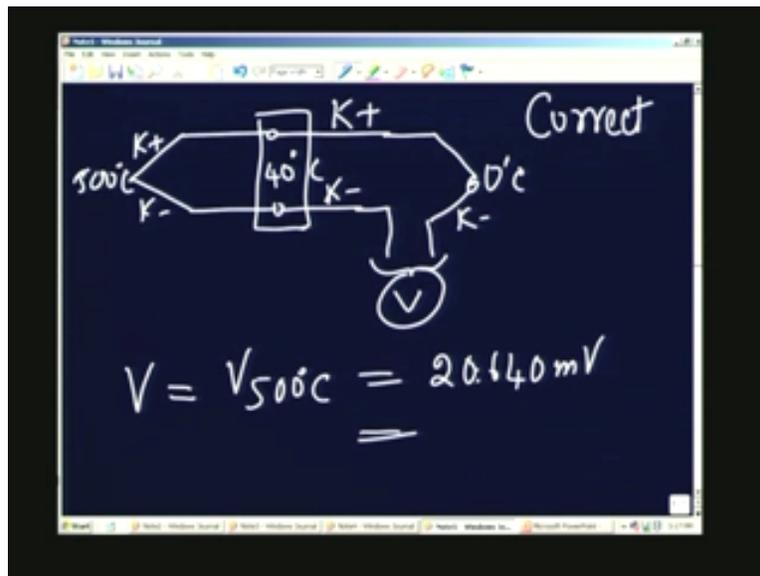
This is K plus, this is K minus is at 500 degree Celsius and this is the junction box which may be at 40 degree, K plus here and this goes to 0 degree ice point and this is K minus, this is also K minus and I will be measuring the voltage here. This is the correct arrangement. In this case the voltage reading would be equal to V at 500 degree, corresponding to that it will be 20.640 millivolt. So a mistake in connecting the wrong terminals could lead to a large error as we have seen from this example. You saw the large error 500, 424 almost 75 degree or 76 degree error is there. So the error is because of the wrong connection which has been made. So I will take one simpler example.

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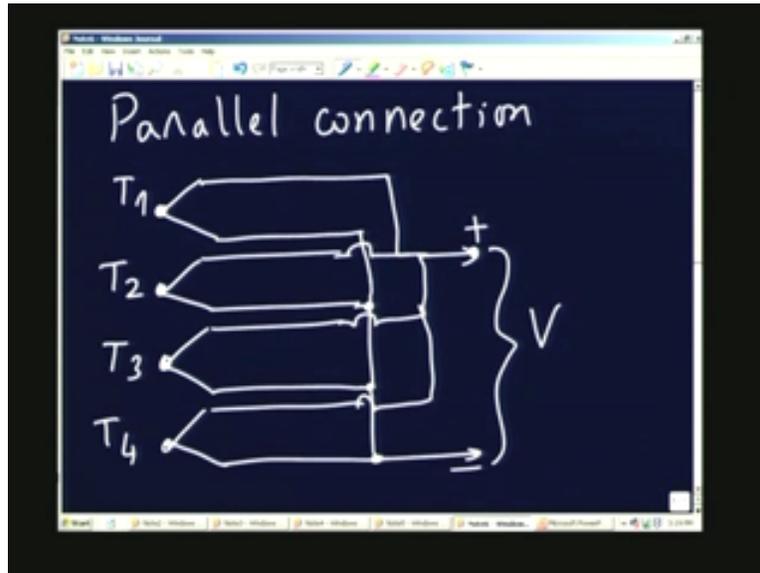
Suppose we connect a large number of thermocouples in parallel, let us just look at the arrangement. So I will call it the parallel connection. Suppose I have a junction here, let junction one, junction two, junction three, junction four. So these are the wires, I have taken four junctions. I am going to connect all the negative terminals, all the positives and all the negatives I have connected. So I am going to measure the output across this.

If you see here what is happening. Suppose this is at temperature T_1, this is at temperature T_2, this is at temperature T_3 and this is at temperature T_4, the output is now, not the output for a single thermocouple but it is something which is going to be due to that all the four thermocouples are connected to the terminal plus or terminal minus now in parallel. If the temperatures are all the same, if T_1 equal to T_2 equal to T_3 equal to T_4, I will simply get the value of one of those temperatures T_1 or the T_2 or the T_3 or the T_4.

However, if one of them is bigger than the other and so on, now you can see for example this makes a circuit. It is actually circuits now. It is in fact not an open circuit which we would like to have. A thermocouple is used in the open circuit mode but here they are following some loops, you can see that some loops are formed and because of that, currents will flow and therefore what will happen is that the output voltage will be only one value which will correspond to the mean value of the temperature, mean of the four temperatures, because the currents are going to flow, it will be equivalent to

whatever we are going to measure is equal to the mean of the four temperatures.

Sometimes T_1, T_2, T_3, T_4 may be temperatures at four different points within a material and I would like to find out what is the average temperature in the material. Of course these may be very close to each other, T_1 may be 30 degree, T_2 may be 31, T_3 may be 29 and T_4 may be 28 and so on. So what will happen is, if I connect like this, I will directly get the average temperatures averaged over the 4 thermocouples. In this case it can be more or less than this.

In the other case earlier, we had a thermopile where they were all connected in series and in that case the voltages were adding, here the voltages are all going to average out. So the voltage averaging means the temperature which is going to be indicated is the average of the 4 temperatures. Sometimes deliberately we connect the thermocouples so that we can directly measure the average temperature without going through the calculation of different temperatures T_1, T_2, T_3, T_4 separately and then adding together and dividing by 4 to get the mean. You can do it directly by connecting in this particular parallel fashion. So with these examples, I will go back to the slides where we were talking about the things we are going to cover in the present lecture

So we have looked at examples 12 and 13 which were worked out on the board. Now I am going to look at what are the things which are involved when you want to measure the temperature at a surface inside a solid and of a flowing fluid. The reason why I want to do this is to indicate the way we are going to do that physically, what is the method we are going to use and secondly, what are the sources of error in such measurements. That is also important to us. These errors we are going to talk about are systematic errors which occur because of some specific reasons and in fact we will try to identify the reasons why these errors occur and will try to find out if you can give some idea about how to calculate this or how to estimate these errors. So let me take the examples one by one.

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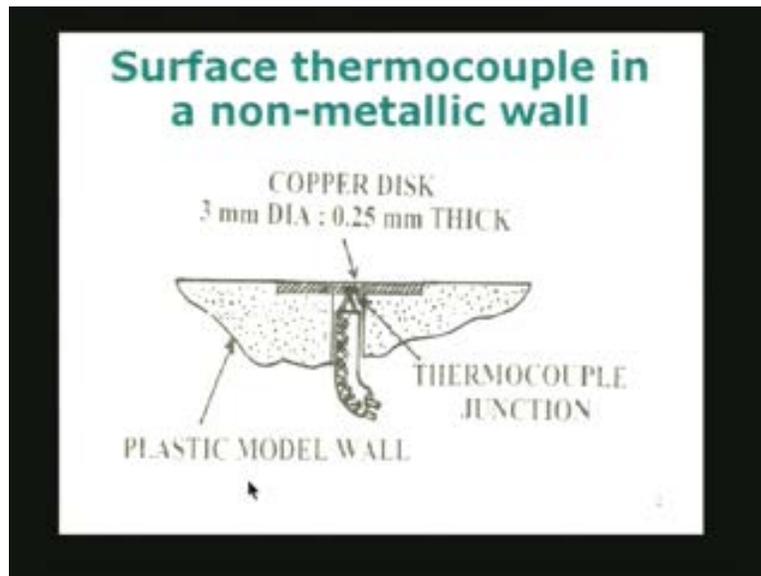
We would like to measure the temperature of a surface. In the slide I am showing a body which is made up of a material, which is a plastic material possibly not a very good conductor of heat. The nature of the material is going to a play a role. That is why what we have done is in order to measure the surface temperature I have used a copper disk which is embedded on the surface and the copper disk is a very thin copper sheet of point 25 millimeter thick and the diameter is roughly 3 millimeter. It is like a button which has been embedded on the surface, flush mounted on the surface.

So what I am trying to do is, to measure instead of measuring the temperature of the plastic model wall, I have just introduced a button which is going to be the object whose temperature I am going to measure. And I have an embedded thermocouple which is introduced from the bottom as you can see here, so I have the thermocouple coming here and possibly inside this copper disk, I can make a small hole and embed the thermocouple junction inside the hole. And the thermocouple is taken out from the bottom and the junction is somewhere within the copper disk and because the copper disk or the copper material has got a very high thermal conductivity, it is possible or it is expected that the temperature is more or less uniform throughout copper button or copper disk.

A second point with respect to this copper disk is, suppose we have a fluid which is flowing over the surface on the top here, it will move past the copper disk and it will be in good contact with the copper disk and because

copper disk is a very good conductor the amount of heat transferred if there is a temperature difference between the fluid and the surface is risible, effective heat transfer can take place so that we expect if the velocity is big enough the difference in temperature of the fluid and the surface will be very small.

So we expect, in fact the temperature which we measure can be used as a measure of the effectiveness of the heat transfer which is taking place from the medium to this surface. So, the copper disk is getting heated from the top if the temperature of the fluid is different from the temperature of the surface. And possibly there can be some amount of heat loss due to the thermocouple which is connected to the bottom.

The thermocouple consists of two wires as we know and the wires are highly thermally conducting, and they will conduct away some of the heat which is from the copper disk. Therefore we expect the temperature of the fluid to be higher than the temperature of the copper disk which will be higher than the temperature of the thermocouple embedded inside. So we expect some kind of a temperature variation from this side to the other side. In fact the error in the temperature measured in this particular case can be calculated based on some of the thermal quantities. We will take it up a little later. We will give the appropriate formula.

What are the variables which will play an important role?
The surface area of the copper disk will play an important role and the larger the surface area of the copper disk the better is the heat transfer from the fluid to the copper disk and therefore you can reduce the error by having a large copper disk here and by using very thin wires for the thermocouple which is attached to the bottom.

The second example I am going to take is the temperature measurement within a solid by using a thermocouple. So the solid material is shown here at the bottom and the temperature is going to be measured by using a thermocouple which is inserted into a blind hole.

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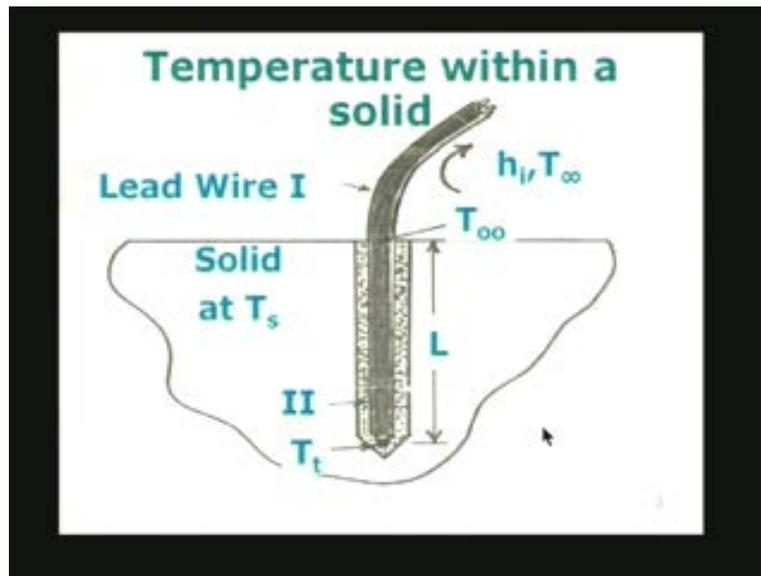
So I have long blind hole, a deep blind hole whose length is L and the thermocouple is embedded up to that depth. The thermocouple is actually here at the bottom of this well and between the thermocouple and the side walls of the drilled hole I can use some kind of a packing material which is a good thermal conductor. So we can use some material which conducts heat effectively so that there is a good thermal contact between the thermocouple and the walls of the hole drilled into the material.

Now we will see how it is going to affect the measurement of temperature? And of course the lead wire has to be taken out because there is no other go. The thermocouple is taken out and it is probably exposed to an ambient at T infinity that is shown here and may be some amount of convertive heat transfer is taking place between the outside of the lead wire and the ambient.

Some of you who have done your course in heat transfer earlier would be able to follow some of the arguments and others who do not have a background in heat transfer may have to wait till a later stage when you study heat transfer to understand some of the things which we are going to talk about now. What I will do here is to give the basic ideas without bringing in too much of mathematics and then finally I will give some of the results simply without proof which can be used to calculate some of these errors.

So the idea is just to give a physical background about the heat transfer phenomena which is taking place, find out what are the appropriate formulae and stop there. We need not go ahead and discuss how to derive this formula. We will just use a very user approach instead of using the approach of some body who wants to learn about it in detail. We would like to get a working knowledge of how to calculate these errors instead of going deep into the subject itself.

So, the lead wire is outside and it may be connected to a voltmeter far away. And the heat transfer or heat transfer through this lead wire can be modeled, this I will take up little later. And therefore what will happen again is, if the temperature of the solid is T_s which is greater than T infinity, it is T_s is greater than T infinity, of course if T_s is less than T infinity, all the heat transfer will be in the other opposite direction. So, solid is T_s.

I want to measure the temperature of solid but when I embed the thermocouple and put it here, I am going to measure the temperature indicated by thermocouple which if there is a heat loss through the thermocouple it means that T_t will be less than T_s. So the difference between T_s and T_t is in fact the systematic error in the measurement in this particular instillation. So now if you look at this sketch I have drawn a deep hole and used some material of high thermal conductivity, so that there will be a good thermal contact between the solid and thermocouple wire which is going through the hole so that I want to make the temperature difference between T_s and T_t as small as possible, this can be done by the following.

One is, have a very good thermal contact between the cable and the hole which is drilled it is solid. Number 2, have a very deep hole L which is very large when compared to the diameter of the wire. If you do that, you can actually reduce the temperature error T_s minus T_t. If indeed, it is possible to send it to a very deep hole, then you might even be able to eliminate the difference between T_s and T_t. And also see to it that the outside is not exposed to a very high heat transfer coefficient because that is also not good for this. So there are three temperatures I have shown here; T_s, T_t and there is a T_{00} which is the temperature at this plane where the thermocouple is just coming out. And this temperature will be less than T_t, T_{00} will be less than T_t, T_t will be less than T_s and T infinity will be again less than T_{00}. Therefore there is heat transfer coming from the solid, entering through the sides of the hole, going through the thermocouple and again eventually going to the ambient.

So whenever you have heat transfer taking place from a region of high temperature to low temperature there will be gradients and these gradients manifest as an error because what I am going to measure is T_t which is what is going to be indicated by the thermocouple voltage which I measured. Therefore T_s minus T_t will be the error in the temperature in this particular instillation. The next case is the case of measuring the temperature of the fluid which is flowing inside a duct or a pipe or a tube.

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Many times what happens is that we do not want to have a direct contact between the thermal sensor or thermocouple or any other temperature sensor and the fluid which is flowing inside. A typical example could be a tube or a pipe carrying steam at high pressure, you would not like to have any direct contact between the steam and the thermocouple material, you would like to have no leakages whatsoever, therefore necessarily we will have to introduce what is called a thermometer well.

Thermometer well is something like what is shown here, a well made of an annulus, a tube which is inserted into the medium, the fluid is flowing like this at a temperature T_f and the thermometer value is ticking right into the into the tube in a direction perpendicular to the flow. The fluid is flowing in a direction which is indicated by this arrow. The well is kept in this direction, again there is a depth of immersion this L the length of the well is called depth of immersion and you can see that the thermocouple is attached

to the bottom of the well and it is taken out and is connected to the external circuit. And the well itself is made usually of some material like brass or steel. It could be even be copper, aluminum or any material one can think of. The choice of the material depends on many factors which will be taken up little later, we will talk about it.

The idea is, the well must be able to separate the fluid out or prevent the fluid from direct contact with the thermometer. It should be strong enough so that there are no leakages there is no chance of any rupture of the well and so on. So it will have an inner diameter of d_i as shown here and the outer diameter is d_0. And let us look at the heat transfer mechanism. The fluid which is at a temperature, let us say higher the ambient temperature and the temperature of the wall which is shown as T_w, it is actually going to flow pass this well and it is going to dump some heat into the well if the well is at a temperature lower than the fluid temperature. So again we are talking about some temperature gradients being existing in this.

So why do the temperature gradients exist, because the well is connected to the wall of the tube or the wall of the duct and if the wall of the duct is at a temperature different from the fluid temperature, let us say in this case less than the fluid temperature, obviously there is a temperature gradient along the length of the well. So there is a temperature variation from here to here and in fact I have shown the T subscript t as the temperature of the bottom of the well which is what is being measured by the thermometer or the thermocouple, and as you approach the wall of the duct the temperature will become equal to T_w. Therefore there is a thermal gradient along the length. So the thermal gradient along the length gives rise to some amount of heat transfer from the fluid through the well to the outside, or to the wall of the duct and therefore there will be a difference in temperature between T_f and T_t and that is the thermometric error in this particular case.

Again as we saw in the previous case of solid material, the length of the immersion is going to play an important role. The other things which are going play an important role are the physical size that is d_i and d_0 and also the thermal conductivity of the material of the well. These are going to be of important parameters. That means the physical dimensions d_i and d_0 which are geometric parameters, the length of immersion is also a geometric parameter and then we have the thermal conductivity material of the well. And of course when a fluid is flowing normal to a cylinder like this the well appears as a cylinder. As far as the fluid is concerned there will be exchange

of heat because of the flow flowing fluid and the effectiveness of the heat transfer mechanism is determined by the velocity of the fluid through the Reynolds number.

So, we are actually looking for some relationship that exists between the Reynolds number of the fluid flowing positive and the effective heat transfer coefficient in this particular application. And then thirdly, the thermometer well may have an emissivity of surface equal to epsilon. So some amount of heat transfer may also take place the radiation from the surface of the well to the wall of the duct. So the thermometric error T_f minus T_t which is the error will depend on various parameters which go in to the particular problem. And we shall look at it later on how this is exactly going to be done. So in the previous case I mentioned that the length of the immersion is going to be an important parameter. The maximum length of immersion of course could be limited to about, at the most it could be going from one end to the other end. That may not be the best thing to do. It may be going from there, let us say some where in the middle of the tube at the middle of the duct. Therefore, in order to increase or have larger values for L possible, we can immerse in a direction different from the normal direction we look here.

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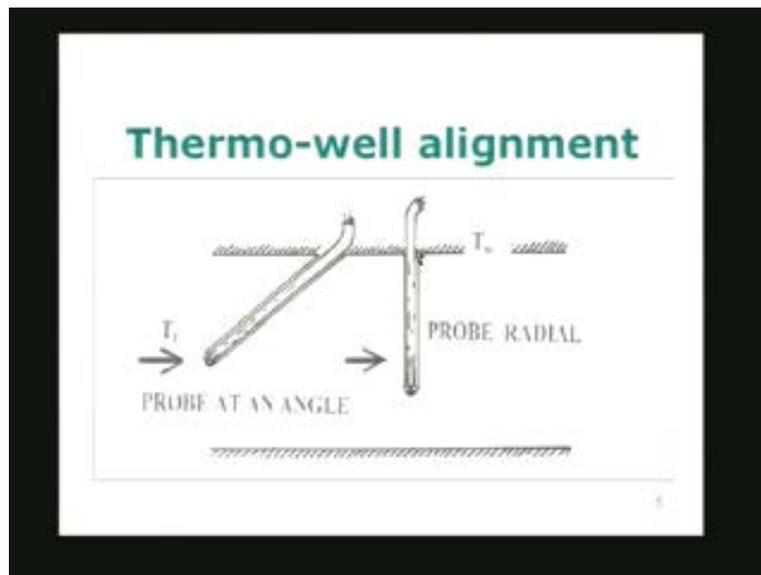
So thermo well alignment can be changed. It can be in the vertical fashion like this. The flow is taking place from left to right, the probe is radial, if it is a tube or it could be at an angle to this thing or it could be also like it comes

like this and then takes a turn and it could be like that. So in fact I would like to show what other possibilities are there.

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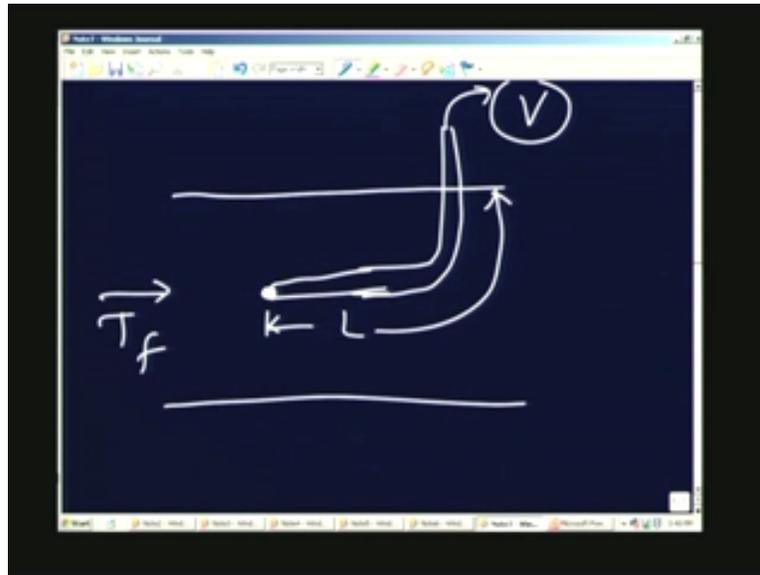
So you have the tube which is carrying the fluid whose temperature I would like to measure. I can actually make the probe like this. That means that the length of the probe effectively is this length. So if I make it long in this direction and then with a 90 degree bend here,so the output is going to be measured there. This is connected to the voltmeter and I have a very long wire. So, the length of the immersion is an important parameter which is going to be playing an important role in determining the size of the error and therefore there is one thing which we are going to look at.

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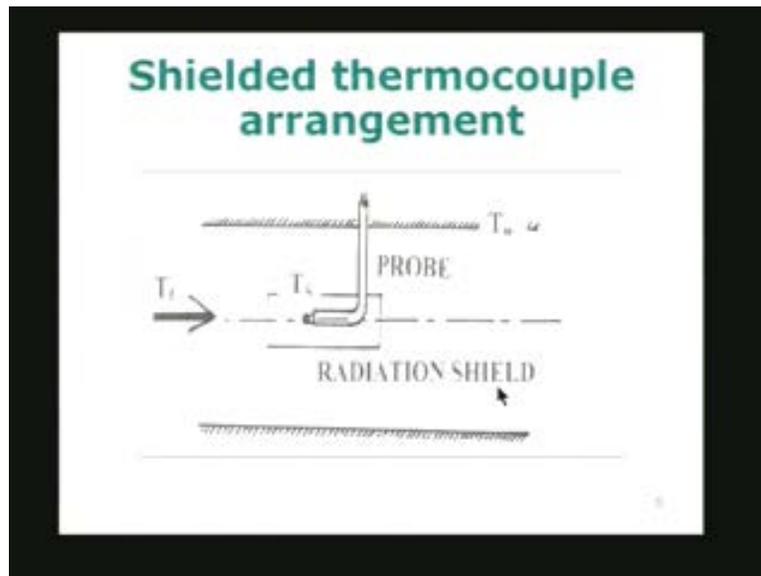
Actually, we have shown a probe in that particular fashion. Here I am looking at shielding to reduce the amount of radiation which takes place from the thermocouple or the probe to the walls. In this case suppose the fluid is at a high temperature, the wall is at the temperature lower than the T_f. If I have the bare thermocouple or the probe alone without the shield which is shown here, the temperature of the probe will be intermediate between T_f and T_w such that the amount of heat transfer from the fluid to the probe, if it is equal to the heat transfer from the probe to the wall that will be the equilibrium condition and the temperature of the probe will take up such a value that this equilibrium is achieved.

Suppose the temperature is high enough that radiation is important and if you remember radiation is proportional to the 4th power of temperature. If I surround this probe with a shield which is usually a metallic cylinder, which is made up highly polished material, so that it has got low emissivity. The probe is not in direct view of the wall. It is actually going to view only the shield and therefore it is going to have heat transfer, the heat transfer is going to take place from the probe to the shield and the shield outside will of course have heat transfer taking place to the walls of the duct which is at the lower value.

At the same time, both the probe as well as the shield is in convective contact or contact with the hot fluid. So there will be some heat transfer from

the fluid to the shield also. So what will happen in this case is that if you have a radiation shield surrounding this probe, the temperature of the shield which will be in between the value of the fluid temperature and the wall temperature will be the effective background temperature for the probe and therefore the amount of radiation, heat transfer from the probe to the shield will be smaller than if the shield where not there it would have been between the radiation probe and the wall of the tube. Therefore you are going to reduce the radiation error by having a surrounding shield like this.

Sometimes a shield is also made in the form of a nozzle, a converging diverging nozzle so that the fluid which is entering and going past the probe is made to go at a velocity much higher than the velocity prevailing the in the duct itself. So, if you remember the basic heat transfer ideas, if the fluid velocity increases it is the efficiency of the heat transfer between the fluid and the surface also increases, and therefore if I increase the velocity by having a small shield cum some arrangement which is going to make the velocity go up in the form of an internal nozzle arrangement, then I will have a high velocity stream flowing past the thermocouple probe and therefore the heat transfer by convection is improved because of the shield and heat loss by radiation is decreased and therefore we expect the temperature of the probe to be much closer to the temperature of the fluid and therefore the error in temperature which is going to be present is going to be reduced. So shielded thermocouple arrangement is recommended for high temperature applications where you want to measure the temperature of a high temperature stream.

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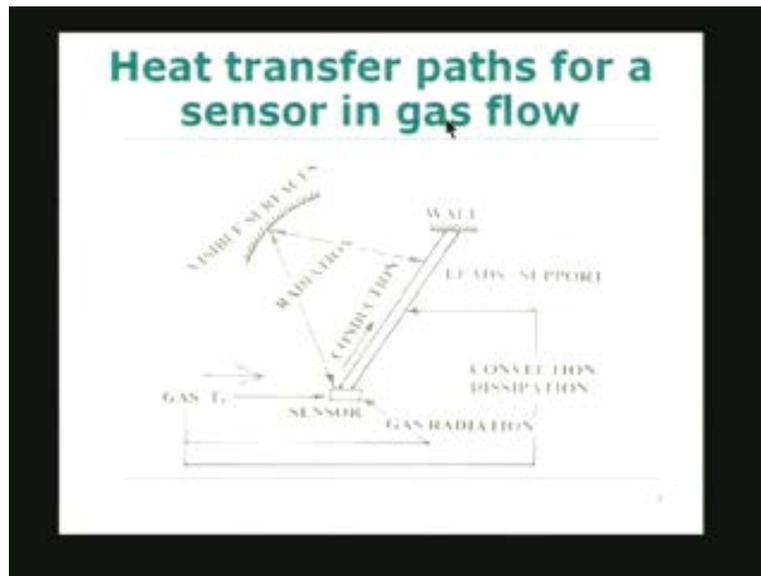
So now we will try to summarize the observations we have made in the previous cases by considering all the different passes for heat transfer in an arrangement where we want to measure the temperature of a flowing gas stream. The sensor is the central thing and it is connected to the walls by a lead or some support arrangement. The probe consists of, in fact the leads or whatever support arrangement we have, plus the sensor at the tip of that probe. The gas which is going to flow in the tube or in the application, is going to flow past the sensor and therefore there may be some amount of heat transfer from the gas to the sensor through convection because there is a direct contact between the medium and the surface and it may also be by radiation from the gas. If it is a very high temperature gas some amount of gas radiation may also be involved.

As far as the sensor is concerned, it is now if it were to get heat transfer only from the gas and there are no loss mechanism, then quickly it will achieve a temperature equal to the temperature of the gas and there is no error at all in this application. However, because of the gas the sensor has to be connected to a wall through leads of a support arrangement, some amount of conduction loss is going to take place or for example, if you have thermocouple wires, the wire themselves will conduct some amount of heat away from the junction and the junction will be at a lower temperature if there were because of this conduction error. Therefore, conduction is one

mechanism which is going to be a loss mechanism as far as the sensor is concerned. Some amount of heat loss takes place by conducting.

Then, again it may be in viewing some surfaces which are cool or cold compared to the gas temperature. Therefore some amount of radiation loss may take place. And in fact as I have shown here some amount of conduction heat transfer may take place is leads and the leads themselves may lose heat by radiation to the surroundings. And again of course, there is convection directly from the gas also to the leads because leads in support are also in contact with the gas which is flowing. Therefore the error in the measurement of the temperature which is a specific or systematic error will depend on the effectiveness of the heat transfer mechanism between the gas and the sensor as compared to the effectiveness of the heat transfer mechanism from the sensor to all the other things which is in physical contact. So the equilibration or equilibrium will be achieved when the amount of heat transferred from the gas to the sensor is exactly balanced by the heat loses through various means such as the conduction error, the radiation error and so on. So a calculation of the errors will require an understanding of these phenomena or this process which are going to take place and therefore we can identify the sources of errors in temperature measurement as I have done here.

One source of error is a sensor interference with the process. That means because we have put a probe into the stream whose temperature I want to measure, some heat transfer process is going to take place. In this case for example, conduction error in surface temperature measurement, for example, conduction through the lead wires of the thermocouple attached to the back of that copper stub. That copper button had a thermocouple which will adjust the bottom and the wires could take away some heat by conduction from the surface. So, conduction error in surface temperature measurement is one example where a sensor interferes with the process by actually taking away some heat.

In some cases sensor may interfere with the process as well as other environments. This is where the radiation error comes to the picture. It takes away heat by conduction possibly and then it loses heat by radiation also, therefore radiation error is a typical example where there is an interference between the process as well other modes of heat transfer. That means, other environment means other modes of heat transfer.

While measuring temperature of moving fluids convection and conduction processes interact and therefore they lead to the systematic error. In case of high speed flow which is involved in aerospace applications, viscous dissipation effects may also be important. That means the conversion of kinetic energy of the fluid to internal energy and when kinetic energy is converted to internal energy because of viscous forces, the heat,the temperature will go up. The fluid will actually heat up very close to the probe because the probe is in a region where the boundary layer is going to be present right next to the probe and the high speed flow is going to decelerate the rate up to the flow next to the surface and because of large velocity gradients which are present near the probe surface there may be significant amount of heating.

Therefore, in high speed applications this may be a very important error which has to be taken into account. But in the normal practice, for example air condition ducts carry conditioned air or hot water applications where you have hot water flowing through a fluid through a tube in a heat exchanger application for example, these viscous effects are not important and we may be only involved in accounting for convection and conduction errors and to some extent may be radiation errors in some extreme cases.

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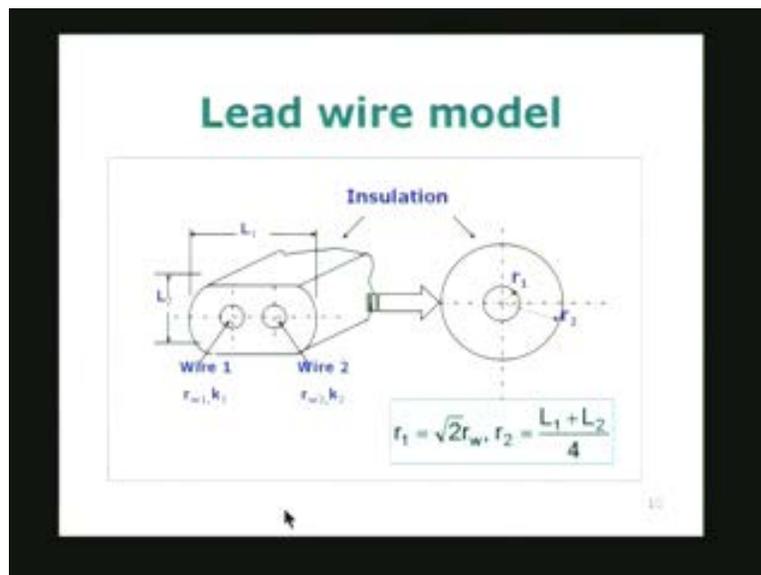
So in order to probe further into the mechanism of heat transfer and also to understand how to calculate, we will propose some way of looking at this whole process.

The first one I am going to consider is the conduction error through the wires and it can be easily modeled and the model requires two things; one is the modeling of the lead wire what exactly it means we will see in a moment and then the second one is the process of the heat loss or heat transfer through the conduction. So there are two aspects to this problem; one is to model the lead wire and then the second one is to model the heat transfer process. We will try to explain this physically in this lecture and then will continue in the next lecture from there onwards.

So the lead wire model, what it tries to do is to look at this complicated thing here. A thermocouple consisting of two wires; wire number 1, for example, it may be K-type in which case this may be chromel wire and this may be alumel wire,or it may be a T-type thermocouple. So you know the two materials for the corresponding one. So, this may be copper and this may be copper constantan, for example, and the wire 1 and wire 2 normally they have the same diameter wires so r_{w1} and r_{w2} have written for generality but they can be the same equal to r_w and the two materials obviously have two different thermal conductivities. So thermal properties of the two materials are different and k_1 and k_2. And these two wires are laid parallel to each other at a certain distance between them so that there is no physical contact along the lengths of the wire between these two materials and it is surrounded by an insulation whose thermal conductivity may be k_i for example. And the insulation will have major dimension L_1 and minor dimension equal to L_2. So what I am going to do is I am going to look for an equivalent single wire model.
An equivalent single wire model would replace this arrangement at the left, we chose the actual arrangement by a single wire of radius equal to r_1 surrounded by a single cylindrical annulus which is an insulating layer of radius equal to r_2.

Therefore what is the equivalence?How do we do that one? And the principle is very important. The area of cross section of the two wires we know and if they are of the same area of cross section, is the same radius, the area of cross section pi r_{w1} square or equal to pi r_{w2} square. So the requirement is that the area of cross section must be actually the thermal conductivity, area of product must be the same when you take this

arrangement and compare it to this arrangement. So k_1 a_1 plus k_2 a_2 equal to k, a product for this. So if k_1 and k_2 ,so if a_1 and a_2 are the same it becomes a into k_1 plus k_2 where a is the radius the area of cross section each wire. So a into k_1 plus k_2 is equal to the effective thermal conductivity area of product for this wire.

So if you assume that k_1 plus k_2 is taken out, the area of cross section being the same, there is twice the area here, and so what I will do is, I will take the r_1 equal to the square root of $2r_w$, that will give the same area of cross section and for the insulation layer the r_2 will be effectively L_1 plus L_2 divided by 4. This is what is supposed to model this insulation. This is simply a model. That means that we are trying to estimate the error in temperature measured because of conduction and it is adequate to make a model of this type because the error itself is assumed to be a small in any application and we are trying to account for it by an approximate calculation proceeded.

If we want to actually do a very realistic job of the whole thing it becomes the difficult process and usually it is not warranted for most of the applications.

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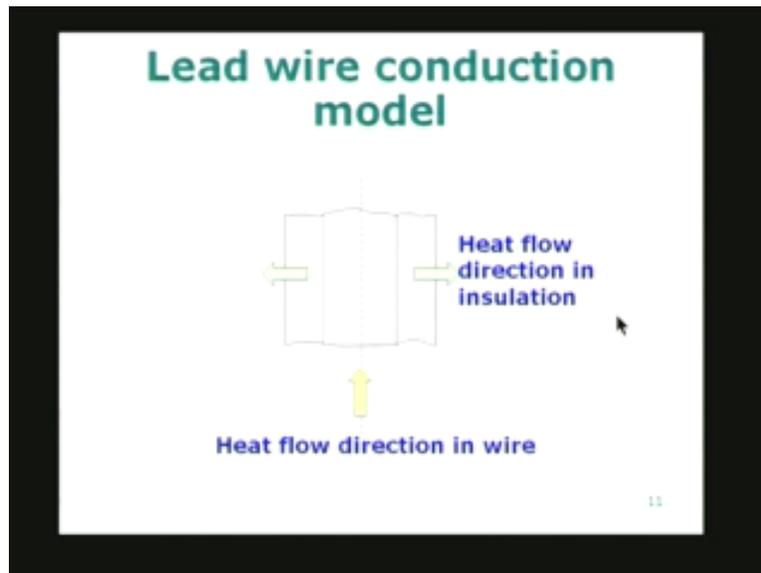
The second part to this model is the heat transfer model. So the assumption we are going to make as far as the lead wire conduction model is concerned

is that now I have written a longitudinal cross section of the wire. So I have a wire in the middle, a solid cylinder here surrounded by an insulation layer. So the second assumption I will make is that, the heat transfer in the wire is in the axial direction while the heat flow in the insulation surrounding it is in the radial direction. The reason why this kind of an assumption is valid or acceptable is that the thermal conductivity of the material of the wire is usually high compared to the thermal conductivity of material of the insulation. And therefore the heat transfer, the axial direction in the wire is much more significant compared to heat transfer in the axial direction in the insulation wire.

Therefore I can ignore the heat transfer in the axial direction in the insulation and assume only heat transfer in the radial direction. That is because the temperature of wire is different from the ambient and the heat transfer in the radial direction is due to heat transfer through this insulation layer plus heat transfer from the surface due to convection from the surface to the ambient. And in fact what we can will do, which we will show in the next lecture is to look at an effective resistance to heat transfer from the surface of the wire to the ambient. So we will model the heat transfer in the lead wire or heat conduction in the lead wire by axial conduction of the wire followed by a radial conduction in the insulation layer. So the analysis which we are going to present in the next lecture because it is now not enough time in this lecture, will be to model the heat transfer which is essentially axial in the wire and radial in the insulation by an one dimensional analysis.

This one dimensional analysis is similar to the fin analysis which is made in heat transfer applications and therefore what we will do is we will not give all the mathematical details, we will directly borrow the results from fin theory or fin equation model, and we will just show how the thermometric error due to the conduction in the lead wires can be modeled easily by fin analysis. So we will borrow the results from heat transfer theory and then we will try to use it and probably demonstrate it by taking simple examples. Thank you.