Transducers For Instrumentation
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Lecture - 07
Thermal Sensors: RTDs and Thermistors

Hello, welcome to the course Transducers for Instrumentation. Last lecture we discussed a special type of temperature sensor which is thermocouple in which we had two materials to in fact, two different materials which join them together and the voltage build up across the cold junction is linearly proportional to the temperature gradient. So, there we are using a multimeter or a voltmeter to measure the voltage directly from the thermocouples. Now, today we are going to discuss another type of thermal sensor which is RTD or we call it the Resistance Temperature Detectors in or RTD in short. So, Humphrey Davy showed that the resistivity of a metal shows a proportional temperature dependence means the electrical resistivity or R is equal to R naught which is the base resistance of that material plus alpha into delta T. So, the electrical resistance of a material is proportional to the temperature gradient which we apply and if there is a change in the temperature of this material there is a proportional change in the electrical resistance and R naught is the base resistance which is a fixed value and William Simmons they demonstrated that the use of platinum as a element in a resistance thermometer.

So, he used the platinum wire as an element to make RTD. Why platinum is specially used because it can withstand high temperatures you can use the platinum wire to measure very high values of temperatures it can withstand without melting and still maintaining excellent stability even at those high temperature. As a noble metal it shows limited susceptibility to contamination this platinum you can put inside a chamber which is filled of some gas or some ah reactive liquid this platinum does not react with the environment or that particular gas or liquid and it does not contaminate the fluid inside. So, platinum is a very noble material to use as a RTD though this design produces a very stable element the thermal contact is very poor.

So, the construction of a resistance temperature detector or RTD is we take a wire of platinum and we just wound it on a glass rod or something like this we take we take a glass ah glass rod and we wound a platinum wire on this rod and this is what our RTD is. This produce a very stable element the thermal contact is very poor. So, when we make this kind of sensor how do we have a proper contact of this assembly with a heated body let us say which is circular in nature. So, a very small portion of this assembly let us say this portion only gets in contact with the heated body. It limits the thermal contact area which gives us different kind of errors in the measurement.

So, this is the limitation of this kind of design which results in a slow thermal response time the fragility of the structure also limits it multiple laboratory environments. So, this type of assembly it can give you RTD sensor, but it is very limited to multiple laboratory situations. So, now we switch to thin film RTDs or the metal film RTDs. So, the concept is same we have electrical resistance which is proportional to delta T the electrical resistance is proportional to the temperature. To make a electrical resistance we need to have a two terminal element and in between there is a certain length of this material we want to use it as a electrical resistor.

Instead of having a long wire now we deposit a very thin film of the material on a substrate typically let us say platinum or glass metal glass serif film is deposited or screened onto a small flat ceramic substrate typically silicon. So, let us say we have one substrate on top of it we deposit a very thin film may be a few micron thick only and then we pattern it using photolithography there are certain fabrication steps involved in this we etch out the unwanted area unwanted film what we deposited and we pattern a serpentine like structure which is our resistance now. So, we deposit a thin film and using photolithography we make this kind of structure. Now we have two terminals here one is this is terminal 1 this is terminal 2 and this entire length is my resistor I can connect these two terminals to my multimeter and measure the resistance of this wire. Now the size of these RTDs which we make using these thin film this is very small.

So, this film RTD of a substantial reduction in assembly time because this can be done in a very scalable manner. So, it reduce the assembly time and has further advantage of increased resistance for a given size because the thickness of film is very small it means that to have a higher value of resistance we can go further thin down the thin film and we save the material. Now even if we are using the platinum which is very costly material the amount of platinum I am using in depositing this thin film is very small. So, I can go for very expensive metals and still make the sensors very cheap. So, this is one advantage of this kind of fabrication.

Due to this manufacturing technology the device size itself is small which means it can respond quickly to small change in temperature. This we discussed earlier in lecture if we have a very small sensor the thermal capacity of the sensor is very small. So, by making a sensor very small it can rise to that body temperature in a very small time. It just need a very small amount of thermal energy and it can pick up the temperature exactly to the sensing the body the heated body and it can give the response very fast. So, the response time of RTDs when they are made using thin film that thermal the response time is very small.

These are some metals and their resistivity in ohm per cm or the circular mill foot. Let us for example, we have gold, silver, copper, platinum, tungsten, nickel and these are the typical resistivities. So, depending upon the application where we want to have the value of resistance which is fixed by application we can choose any of the metal from this table. This we can note the all metal produce a positive change in resistance for a positive change in temperature. When the temperature is rising the resistance of these metals this always rises.

So, this R is actually R naught plus alpha delta T where this term is positive with temperature rise the resistance actually goes high. Though in RTDs gold and silver are rarely used as RTD elements because of their lower resistivity. It is not because of the cost of these metals they are not used because of the low resistivity because the very low value of resistance it is very difficult to measure those resistances. We need a certain resistivity to make resistances and the resistance values typically in ohm to kilo ohm range is easy to measure comparable to 0.1 ohm or few milli ohm of resistivity resistance this is very difficult to measure.

So, gold and silver are rarely used. Tungsten has a very relatively high resistivity, but this is reserved for very high temperature applications because it is extremely brittle this metal is extremely brittle and difficult to work. So, it has very high resistivity, but we use this metal only for very high temperature measurements. Copper is also used occasionally as an RTD element it is low resistivity forces the elements to be longer because if the resistivity is lower we need to have a longer wire to have certain resistance in ohm or kilo ohm range. Otherwise, for small size sensor the resistance of the copper will be in milli ohm will be very difficult to measure, but its linearity and very low cost makes it an economical alternative.

Copper is still used because of the good linearity and very low cost its upper temperature limit is only 120 degree C after that the copper metal actually does not respond very well to temperature gradients. The most common RTDs are made up of platinum nickel or nickel alloys these are the materials which commonly used for RTD fabrication though the these metals are costly, but because we are using very thin film of these materials the cost of the material comes down and we can still use these expensive metals. The economical nickel derivative wires are used over a limited temperature range they are quite non-linear and tend to drift with time for measurement integrity platinum is the obvious choice. So, now we come to how do we do the measurement using these RTDs we have these RTDs which are fabricated using thin film they are very small in size. Now, how do we take measurement of temperature using these RTDs.

So, the common values of resistance for a platinum RTD range from 10 ohm to several 1000 ohms these are the typical resistance values of RTD. 10 to let us say 50 kilo ohm standard temperature coefficient of platinum wire is alpha which is 0.00385 it means for a 1 degree change in the temperature the resistance of platinum wire is 0.00385 ohm. For a 100 ohm wire this corresponds to 0.00385 ohm. For a 100 ohm wire this corresponds to

0.00385 ohm per degree c at 0 degree c. Now, we take this resistance value which is 0.00385 ohm and we have to calculate the resistance value of the platinum wire.

So, this resistance value is 0.00385 ohm and at 0 degree c. Now, we take this RTD which is fabricated using platinum wires or the platinum metal this is our RTD and here we are exposing it to temperature TS or the TB which is body temperature and here is my instrument connected which is measuring this change in the electrical resistance. Now, this instrument which may be a multimeter this meter is connected to this RTD through these lead wires these extension wires these are called lead wires which also has its own resistance. Let us say 5 ohm is the resistance of this one such lead wire.

So, 5 ohm here and 5 ohm here. So, total is exactly 100 ohm of RTD plus 2 into 5 ohm because of the lead wire. So, actually we have a RTD of 100 ohm, but effectively when we join this using lead wires the total resistance is not 100 ohm which is now 100 plus 10 ohm which is 110 ohm. So, because of these extra lead wires now my meter is not reading 100 ohm, but it is actually reading 110 ohm. So, this measurement wires leads to the sensor may be several ohms or even tens of ohms depending upon the value of these lead wires this reading can be even more degraded.

So, a 10 ohm lead impedance implies 10 over 0.385 almost 26 degree centigrade error in the measurement these lead wires can produce. So, this is the problem when we have a sensor we want to connect it to a measuring unit using some lead wires these lead wires also has electrical resistance. So, one classical method of this error is using the bridge the wheat stone bridge we have this is the bridge we have let us say R 1, R 3, R 2, R 4 and here this is RTD which is acting as R 2. Now, this is the conventional way of removing this error this is the conventional way where this RTD is exposed to that body temperature which is from outside and all the other resistance is are not exposed.

This RTD is made of platinum it will give a linear change in the resistance when subject to this TB and this we can detect using this bridge, but when we expose this RTD to some temperature we need to keep it separate from the other assemblies or the other resistances because these resistance also has some temperature dependency. So, still we connect this RTD which is far away from the whole assembly this is whole assembly we do not want to expose to different temperature only this RTD is taken away using these lead wires and this area is exposed to the temperature which is TB which is some higher temperature. Now, because of this extra lead wire we have lead wires we still have some resistances of these lead wires. So, this is the extra lead wires which we have here which causes the error in the measurement. So, what we do we take this kind of assembly where we have this RTD these are the lead wires and we take measurement at this point only and we connect extra lead wire here on the other side of this measurement to compensate for this extra lead wire.

Let us say this is our lead wire, our lead so these are also our lead which we connect on the other arm of bead stone bridge to remove this error and we take measurement between these two points. So, this is four lead connection for resistance connection and we put dummy lead wires in the measurement to reduce the error, but it increases some cost because of this extra wires and we can completely correct for this resistance error using this bead stone bridge. So, this is what actually we are doing in the this bead stone bridge example we are doing a four point measurement instead of having a two point measurement. So, let us discuss what this four point resistance measurement is or sometime we call it the Kelvin connection. So, this type of four point measurement is done for precise resistance measurement.

So, up to now we know two probe method and the drawback of this two probe method is error due to contact resistance. So, we have for example, this is the resistance which we are trying to measure this is a resistance and how do we measure the resistance we apply a certain known voltage and we measure the current and then resistance is nothing but V upon I we apply a known voltage and we measure the current. So, this is the voltage V which we apply here accordingly there will be a current flowing into this which is I let us say it is flowing from here to here and this will produce a voltage between these two points which you can measure using voltmeter this is the voltage you are applying here this is the known voltage V e let us say. So, the problem here is this resistance is when material of this resistance which is in connection with these lead wires which is used to connect these instruments to this resistance whenever there is a junction here all the junction has some contact resistance. So, let us say we take metal one and metal two we join them together it is not like they do not have a contact resistance and this contact resistance is very much different than the resistance of material one and resistance of material two it is not same.

So, the contact resistance depends on the materials and this is always there. So, if we see this setup microscopically we have a resistance here which we are going to measure but we have certain contact resistance here and we have at this junction wherever there is a junction we have these contact resistance let us say RC and this is in series with this resistance or Rl the load resistance. So, actual resistance here is Rl plus two times RC. So, this two times RC is an extra resistance coming from the contact resistance which produces the error when I am connecting a voltage source voltage across it there is a current flowing this current depends on not only the Rl but as on the RC as well because RC also in series with Rl. So, this current is proportional to Rl plus two times RC which is the error the contact resistance and this inaccurate value of current i is giving me the error in the resistance the R calculation from this formula this is this has error because of this extra term twice RC.

So, the contact resistance in this assembly is giving me error but now the contact resistance is something which we cannot remove whatever material we choose material one and material two they will always have some contact resistance. So, this we cannot remove but the what Kelvin connection is this contact resistance is giving me extra voltage drop or it is affecting the current only because if there is a current flowing inside this if we do not have a current flowing into the contact resistance then it does not impact the value of voltage. So, this is the typical assembly of four point Kelvin connection we have the resistance here where we connect the voltage from outside here in the from the external two probes which are carrying all the currents the current is flowing from this side to this side and we have contact resistance here RC and some current is flowing which we can monitor from here. Now, voltmeter instead of connecting at across these two probes we have separate probe for measuring this potential and this potential is a high impedance potentiometer the high current need not to flow in this in this setup this current is not very high it is very small in magnitude. So, if we have contact resistance here as well but there is no current flowing into these RC's these are not going to impact any voltage difference and the actual voltage we are measuring between this and this.

So, between these two probes we are actually measuring the resistance and which we can again scale to the full length of this resistance value. So, this is the four point or the four probe method which is also called Kelvin resistance we have two probes for supplying current and again two probe for measuring the voltage or we call it the inner probes. So, these inner probes does not draw any current hence the contact resistance does not impact measurements. So, this RC is always there contact resistance between two metals these are always there but the current is not flowing so it does not impact the voltage reading. So, this is the Kelvin connection and this is the Kelvin connection we generally use in RC.

So, RTD measurements so we have this RTD element we excite this externally and across this we measure the voltage V_{out} and we measure the resistance of these RTDs. So, this is four terminal lead resistance correction and voltmeter we use with the high input impedance and no current flows in the voltage connections this current is very negligible or we can write 0 because of this there is no problem of contact resistance. Now resistance to temperature conversion this RTD is a more linear device than the thermocouple but it still requires some curve fitting the CVD equation or this Schoenleer-Wern-Duisen equation is used to approximate the RTD curve which is given here RT equal to R naught plus R naught alpha T minus delta T upon 100 minus 1. So, this is the complete equation where we have RT which is resistance at temperature T R naught is the resistance at 0 degree C which is a fixed value alpha is the temperature coefficient for that particular metal delta is typically 1.49 for platinum and beta is typically 0 for T greater than 0 or it is 0.11 for T less than 0. The exact values of coefficient alpha beta and delta are determined by testing the RTD at four different temperature and solving the resulting equation. These coefficients alpha beta and delta these are typically measured when we do some calibration of this developed RTD. Calibration is something what we when we fabricate a sensor then we apply certain input known inputs to the sensor and the output is known. So, we calibrate the output of the sensor and find out all the coefficients alpha beta and delta. So, after this we come to the third type of thermal sensor which is thermistors.

A thermistor is a semiconductor made by mixture of metallic oxides such as oxides of manganese, nickel, cobalt, copper and uranium. So, this thermistor unlike the RTD it is a mixture. However, in RTD we discussed a pure metal which has resistance proportional to temperature. Thermistor is not a pure metal it is a mixture of multiple mixtures and depending upon what you mix you can have more than two materials to mix with depending upon the mixture and the and it contains output characteristic of thermistor changes. Thermistors may have negative temperature coefficients means the electrical equation for resistance can be R equal to R naught minus alpha T.

This can be a negative temperature coefficients or we call it NTC in short. So, this is the typical characteristic of thermistor where we can have negative temperature coefficients. It means if the temperature is rising the resistance of thermistor can go down. So, this temperature goes up but the resistance of thermistor can go down unlike the RTD where it always goes high. This resistance versus temperature graph we can plot RTD's and thermistors on the same graph.

We see RTD is always increasing linearly in the temperature of the thermistor and it is increasing in the temperature of the thermistor. So, this is the temperature of the thermistor and this is the temperature of the thermistor. For thermistor graph we see RTD is always increasing linear graph where the temperature always rises with temperature with this resistance is always rising with respect to the temperature. For thermistor we can have multiple curves depending upon the mixture we use we can have different different characteristic. For example, we have this graph for a particular thermistor one where we have positive temperature coefficient for most of the temperature range and we have negative temperature coefficient for a small range.

This can be our thermistor two where we have mostly the negative temperature coefficient depending upon the mixture we use. So, we have positive temperature coefficients as well as negative temperature coefficients in the same thermistor. For example, this thermistor in this temperature range this is NTC the negative temperature coefficient and from here to this range this shows a positive temperature coefficient. So, the same thermistor for different range of temperature it can show a PTC or an NTC. However, the very unique characteristic of thermistor is if we see the slope here of this graph the RTD slope is very linear and the slope is not very high, but if we see this thermistor graph here in this range from 40 to 50 degree the graph is very sharply rising in this temperature range only.

So, in this temperature range of the graph is very sharp it means the slope of this graph is very high and the slope of the graph is the sensitivity of a sensor. It means the sensor will produce a very sharp output for a very small change in the input at the input measurement which is temperature. So, it is 1 degree temperature rise will give a very high output or change in the resistance. So, for a very short range of temperature the thermistor output is very high and the sensitivity is very high. So, these thermistors are very much useful when you have a very narrow band narrow range of temperature, but you want to precisely measure the temperature.

The thermistor model is given by this equation which is basic equation log natural S equal to A naught plus A 1 upon T plus A 2 upon T square where S is the measured resistance and the simple model to first order approximation is log S equal to A plus beta M upon T or you can solve it to have this equation which is the temperature. Beta M is the metallic characteristics, T naught is the reference temperature and S naught is the reference temperature. A higher value of beta is desired to have a high sensitivity if the beta is increasing then the graph actually this has more and more slope. Sensitivity is given by S equal to minus beta upon T square which is the equation for sensitivity and the modified this model is T equal to A plus B log natural R upon R naught. These are the equations which we use to model these thermistors though we know that the thermistor is a non-linear device.

So, we do some sort of curve fitting to have this exact match and we use these models to accurately model the thermistors. The manufacturing process of thermistor is very different than other sensors. The thermistors for thermistor fabrication we start with two or more semiconductor powders we have two or more different semiconductor powders this we mix together with a binder. Binder is something like something kind of a glue sort of thing we put all these mixtures in this binder to form a slurry. Small drop of the slurry are formed over the lead wires dried and put in a sintering furnace.

So, for example, we make a mixture of two different two or more different semiconductor powders make it like a paste. Now, we take two lead wires this is one this is two lead wires we dip this whole these two wires into this mixture and take it out. So, when we take it out a small amount of slurry will be on the end of this thing joining these both of these two lead wires together. This droplet will be formed here and this is our sensor we take it out and then we dry it and put into a sintering furnace. During sintering the metal metallic oxide shrunk into the lead wires and formed the electrical connection.

So, this is the electrical connection which is formed during sintering. This bead we call this droplet the bead this bead is then isolated using some glass or some coating we put on it. So, that it does not react with the environment. So, these are sealed by coating them with glass and then this glass coating improves the stability by eliminating water absorption this should not be exposed to the humidity or water in the air. The resistance of the thermistor may vary from a few ohm to several kilo ohm that depends on the mixture we use.

The thermistor size is very small when we dip these lead wires and take it out the amount of slurry which making a droplet is very small. So, when we have a very small sensor then we get two advantages one is the very small time constant and ease of access to small surface. We have a very small sensor. So, we can have a very fast and very fast time constant. So, we can have a very fast response of this sensor and we can even measure the temperature of a very small object as well.

So, these are the two advantage by having a small size sensor. A silicon with varying amount of boron impurities can have either a positive or negative temperature coefficient of resistance. So, if we have silicon which is very commonly used semiconductor if we have boron impurities changing upon the quantity of this boron in the silicon this whole assembly can show a positive as well as negative temperature coefficient for different values of boron. Germanium doped with arsenic gallium is used for cryogenic temperatures. So, this is another thermistor. The linearity of thermistors is a interesting property a thermistor is a non-linear device unlike RTD or thermocouple those two temperature sensors are linear in nature the output voltage generated in thermocouple is linear to temperature.

Similarly, the resistance change in RTD is linear to temperature change. The thermistor here is a non-linear device if we change 1 degree centigrade of temperature the output depends on where we are on that curve. If the sensitivity is very high in that range it will show a very high response very sharp change in the resistance if the curve is flatter in that particular temperature range the output will not be so high. So, this is a non-linear device. However, in certain applications one resistance can be added in parallel to thermistor to improve the linearity.

So, having a high sensitivity means we have a non-linearity in the device. So, sometime we can sacrifice some sensitivity of the sensor, but we want to improve on the linearity. So, what we do we add a external resistance in series with this thermistor and that extra resistance is linear in nature. So, we can somehow linearize the total output of this whole assembly. The sensitivity of this sensor is very thermistor is very high therefore, the change in resistance resulting from a temperature change is much higher.

Then the small change in resistance of the lead wire. So, if we have a lead wire connecting this thermistor the resistance change in thermistor will be much higher compared to change in the lead wire. So, we do not have much of a lead wire problem here. Hence, this error resulting from lead wire can usually small enough to be neglected for thermistor. So, let us take one example of thermistors we have a 10 kilo ohm NTC thermistors this is a 10 kilo ohm NTC thermistor which is negative temperature coefficients. So, we have a temperature change with beta equal to 3500 determine the thermistor resistance at T equal to 30 and 50 degree also determine the relative sensitivity in ohm per degree centigrade room temperature is 25 degree.

So, answer is minus 210 ohm per degree centigrade. And we know the formula from earlier slide the sensitivity is equal to minus beta upon T square. So, these are all the thermal sensors we discussed which are conventional three sensors like thermocouple RTDs and thermistors. When we make a complete system using these thermistors or these thermal sensors these network or these systems there is a analogy between electrical and thermal networks that we can see. For example, we have this thermal network which is nothing but a electronic PCB we have a board here on top of this we have a semiconductor IC and this semiconductor IC is doing some processing and we are feeding it some voltage from outside this IC is generating some heat this heat is need to be removed from this IC.

So, that it can work properly. So, what we put we put on top of this a heat sink which look like this which is a aluminum heat sink aluminum heat sink this heat sink has its own thermal resistance. So, we have this assembly and this heat sink to improve the contact area we put some glue or epoxy in between and we have this ceramic casing of IC which is sitting here this is IC and on the bottom we have PCB. So, this is a thermal network. However, we can make electrical kind of network using the thermal resistances where we have this junction temperature instead of having the junction voltage we can now have a junction temperature which is here which is generating all this heat junction and this heat is flowing to surroundings which is air which is here and which is here through the board. So, this temperature can flow from the top through this heat sink or from the bottom through this PCB.

So, we have two paths from this junction to the air which is this is path one and this is path two and this is path two this is heated junction. So, this junction is connected to the case of this IC and which has its thermal resistance which is R package this case is connected to the sink using some interface material which can be the epoxy o r glue which has its own thermal resistance. So, this case is connected to sink through that thermal resistance and then this sink is connected to the air which is flowing in the fins through this air which is flowing through this R heat sink which is the thermal resistance of heat sink. So, this heat is flowing from T junction to T air through this thermal resistance network this is one path second path is this thermal junction is connected to this board junction and this board junction is connected to air using intermediate these resistances this can be bond wires or solder balls and this resistance may be some FR4 substrate. Which has its own thermal resistance so we can see a thermal network is exactly behaving like a electrical network we have a node a high voltage junction here.

So, instead of high voltage we have a high t emperature junction here and the environment which is the air or the fixed temperature which we can consider as a reference node or we can assume let us say this is 0. So, if we assume this 0 degree and this is 25 degrees C the heat is going to flow from this node to 0 degree with here this is also 0 degree. So, heat will flow this side and this side through this thermal resistances. So, we see that though it is a thermal network the calculation of this thermal network is very similar to the electrical networks how we solve these using Kirchhoff's law. So, there is a correlation between these electrical and thermal parameters for example, we have in electrical systems we have V equal to I into R the voltage equal to current into the resistance which is our Ohm's law for thermal network we have delta T equal to P into RTH which is delta T is the temperature difference instead of the potential difference we have temperature difference instead of current we have power dissipation in what and instead of electrical resistances we have thermal resistances.

So, all these electrical parameters has some similar parameters in thermal networks for example, voltage difference is analogous to the temperature difference electrical capacitance is analogous to thermal capacitance. So, these thermal networks can also be solved just like an electrical network.

So, this is all for today.

Thank you.