Principles of Mechanical Measurement
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Module - 10
Temperature Measurement
Lecture – 3
Introduction to pyrometers

Morning everyone. Today, we are going to finish up on our topic on this temperature measurement which is a part of our module 10 and we are going to end up with a week number 10 in during today's lecture. Now, you already had two lectures on this particular topic where we have discussed about 3 different approaches of temperature measurement, like if you remember during the first lecture on this particular week we have categorized the different methods of temperature measurement rolling into 5 categories.

Out of which the first two very common categories like the measurement based upon the exp volume expansion or change in geometric dimensions and also the change in gas or vapour pressure were discussed in the first lecture. Like under the former category we talked about two very common methods, the bimetallic straps or biometric strips and the liquid in glass thermometer. Whereas, in the second category we mostly talked about the pressure thermometer actually discussed I want to very briefly.

And in the previous lecture we discussed about the methods based upon some change in some electrical quantities, there we had 3 different kinds of methods which are extremely popular for industrial applications, like the RTD or resistance temperature detector, the thermistor and also thermocouples. As a quick recap in case of RTD we generally use some kind of metals and as the temperature changes the resistance of the metal also changes.

Now, if that sensor is forms a part of some kind of bridge circuit which is initially under balanced situation, then any change in the resistance will cause a deflection and so you have to put some effort to get it back to the null situation. So, we can operate the device in deflection mode or null mode both of them providing a way of measuring the change in the resistance and subsequently a change in the temperature. RTDS are very good devices; these are very stable in operation has a very large temperature range can easily go up to 800 to 1000 degree Celsius.

The other one is thermocouples which actually operate in opposite way to resistor or I should say RTDs in case of RTDs we have positive coeff temperature coefficient of resistance that is with increasing temperature resistance increases. Whereas, in case of thermistors commonly we have negative temperature coefficient that is with increase in temperature resistance decreases very very sharply.

The magnitude of the temperature coefficients can be one or two order higher if or thermistors compared to RTDs there by providing excellent option for identifying even very small change in temperature. We can also have our thermistors with positive temperature coefficient, there is generally our semiconductor type materials and again provides very high sensitivity. However, the problem with thermistors generally is a small much smaller temperature range.

And the third one that we have discussed is thermocouple probably the most common temperature measuring option in industries where we make use of the see beck effect through a temperature, through a couple of two dissimilar metals. One end of the couple is kept at the point very one that impression measurement, other end is kept at some other temperature generally a lower temperature.

So, the emf produced by this gives a measure of the corresponding temperature our thermocouples are very cheap device we can get a point measurement which is probably not possible with any of the other methods talked about. So, far and also they are generally quite rugged can cover a very decent temperature range; however, thermocouples generally require a cold junction compensation to get it accurate reading. As we move on today we shall be solving a few numerical problems first we in relation with all those electrical components.

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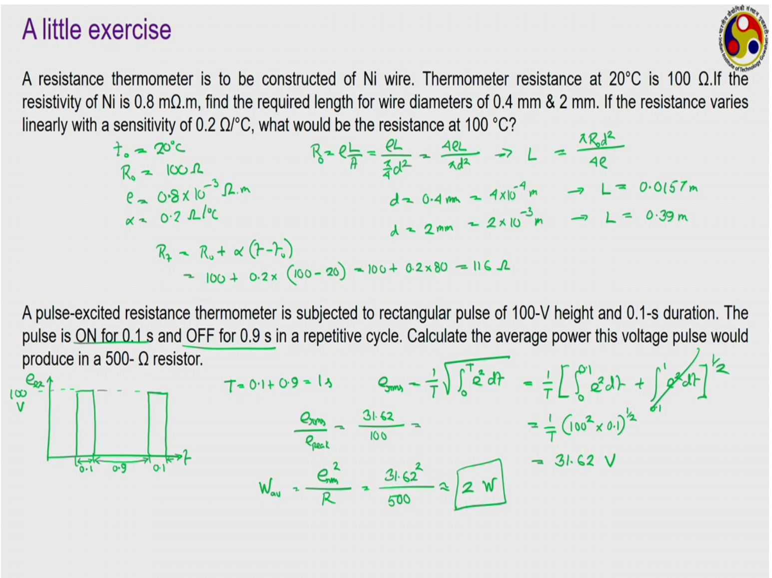

And the first problem there just read it out, here you are talking about a resistance thermometer it is to be constructed of nickel where thermal resistance at 20 degree Celsius a 100 ohm. If the resistivity of nickel is 0.8 milli ohm meter please be careful about the way I have written this here there are 2 ms on either side of ohm symbol the first one refers to milli. So, that is just a prefix 2 ohm whereas, the second one is meter there is a dot in between so be careful the way we are writing this.

So, it is 0.1 milli ohm per meter or so centimetre and we have to find the required length for wire diameters of 0.4 meter, 0.4 millimetre and 2 millimetre, then there is a second part I shall be coming back to that shortly. So, we have an resistance thermometer basically an RTD made of nickel. So, we have initial temperature say, we can write T naught to be equal to 20 degree Celsius and corresponding reference resistance is equal to 100 ohm. And the resistivity which commonly written as rho is given as 0.8 into 10 to the power minus 3 ohm meter.

Now, we have to calculate length of this resistor. Now, what is the definition of resistivity is actually a very simple question, at least for the first part we do not have to use any concept of temperature measurements, it is just the definition of resistivity. We know that as per the definition resistivity or sorry, the resistance R is written as rho L by A, that L is the length of the resistor and A is the cross section area or if we make use of the diameter then it is rho L divided by pi by 4 d square that is 4 rho L by pi d square or if we take length out, so we have pi R d square by 4 rho.

So, it is a very straightforward situation at least for the base case we can maybe writing R naught for this for the initial situation. So, R naught is given as 100s ohm resistivity is given as 0.8 into 10 to the power minus 3 ohm meter and the two different values of diameter given. So, if you put d equal to 0 0.4 millimetre that is 4 into 10 to the power minus 4 meter, then you can do the calculation. For the first case you are going to get a L equal to 0.0157 meter whereas, if we are putting d equal to 2 millimetre that is 2 into 10 to the power minus 3 meter, then we are going to have L equal to 0.39 meter.

So, you can see that with changing the value of this diameter how drastically the corresponding length required that changes and generally we always want the size of the sensor to be very small. So, that we can get quite local measurement and also the device bulk of the device is much smaller, so it is essential that we use where some very small diameter. Like in the first case where the diameter is just 0.4 millimetre only a 15 mm length is sufficient whereas, in the second case we need a much larger length about 39 centimetre which is significantly larger compared to the first case. However, the diameter is increased only 5 times so.

Now, go to the second part of the problem. It is said that either resistance varies linearly with a sensitivity of 0.2 ohm per degree Celsius. What would be the resistance at 100 degree Celsius? So, here we can make use of the simple relation for RTD, it is said that the resistance varies linearly with the sensitivity of this much. So, the change in resistance with temperature follows a linear relation which we can represent something like say R t is equal to R naught into 1 plus alpha into t minus t naught, where t naught is the reference temperature.

Now, in this case R naught is given as 100 of ohm and alpha which is the sensitivity that is given as 0.2 ohm per degree Celsius. So, actually I have written it wrong the relation, because sensitivity is given in terms of a ohm per degree Celsius, in that case this should be written as R t is equal to R naught plus alpha into t minus t naught, where t naught refers to the reference temperature R naught is the corresponding reference resistance. Actually we have used capital T to represent the temperature truly speaking we should have written small t because generally the symbol capital T we reserve for temperature values in Kelvin that is absolute temperature, but here we are talking about temperature in Celsius.

So, rest is quite simple we can easily choose to know to be equal to 20 degree Celsius and R corresponding R naught to be 100 ohm. So, if you pull the values then you are talking about a distance of 100 ohm plus sensitivity of 0.2 into we want to calculate for responding to 100 degree Celsius minus T naught is 20 degree Celsius, so if you put the numbers then you are getting 100 plus 0.2 into 80 that is 116 ohm. So, its change in temperature from 20 degree Celsius to 100 degree Celsius for this particular RTD that every stress is changing by 16 ohm which is quite significant. And that is a very simple situation in RTD; let us deal with another one.

Here our problem is slightly different; here we are talking about a pulse excited resonance thermometer. It is subjected to a rectangular pulse of 100 volt height and 0.1 second duration. The pulse is on for 0.1 second and off for 0.9 second in a repetitive cycle. Now, that is quite interesting. Here we are saying that the RTD is exposed to sometime varying voltage signal and the time varying signal is of the shape of our rectangular pulse; that means, the excitation voltage if we plot with respect to time say time on this axis and excitation voltage on these axis, then this excitation voltage will be of a shape like this. For a 0.1 second duration it is a constant value 100 volt, then for remaining 0.9 second there is nothing and, so this duration is 0 0.1 second. Then if we say up to this is 0.9 nothing during this period then again, another rectangular pulse appears and all which is again the same duration that is 0.1 second. And this particular height of each of these pulses is equal to 100 volt.

So, we are talking about a periodic signal having a time period capital T of 0.1 plus 0.9 that is one second out of this for 0.1 second do we have a constant voltage signal of 100 volt and nothing for the problem any 0.9 second. So, we have to calculate the average power this voltage pulse would produce near 500 ohm resistor. So, the resistance is 500 ohm and we have to calculate the average power corresponding to this signal again it is not strictly a question related to RTD, but this is more related application of any resistance based devices. Whenever, you are talking about a periodic signal then instead of working with any values we have to calculate the corresponding rms voltage. Now, what can we that your rms value in this case? So, e rms can be equal to 1 upon time period into root over of integral 0 to T your e dt. Or I should say e square dt because they are taking rms.

Now, this integration can be divided into two parts that is 0 to 0.1 e square dt plus 0.1 to 1 e square dt whole to the power half. Now, for 0.1 to 1 the signal is off. So, this part cancels out and during the first part 0 to 0.1 the signal is on, let me a constant value of 100 volt. So, e square is a constant during that part, so it becomes a very simple situation 1 by T into 100 square into 0.1 and T is equal to 100 of course, whole to the power half. So, if we calculate the value your rms voltage is going to be coming as 31.62 volt. Quite often may not be in this problem, but we may be generally is interested in knowing this ratio of e rms to e peak of the periodic signal. Here the rms value is 31.62 volt and your peak voltage is 100 volt. So, you can get the corresponding ratio.

But our objective is not to get this ratio rather we want to calculate the average power. Once you know the rms voltage the average power calculation is very easy because your corresponding average power will be just e rms square divided by resistance. So, 31.62 square divided by you are having a 500 ohm resistor and corresponding value will roughly be equal to 2 watt which is going to be your solution. So, these are simple situations with RTDs.

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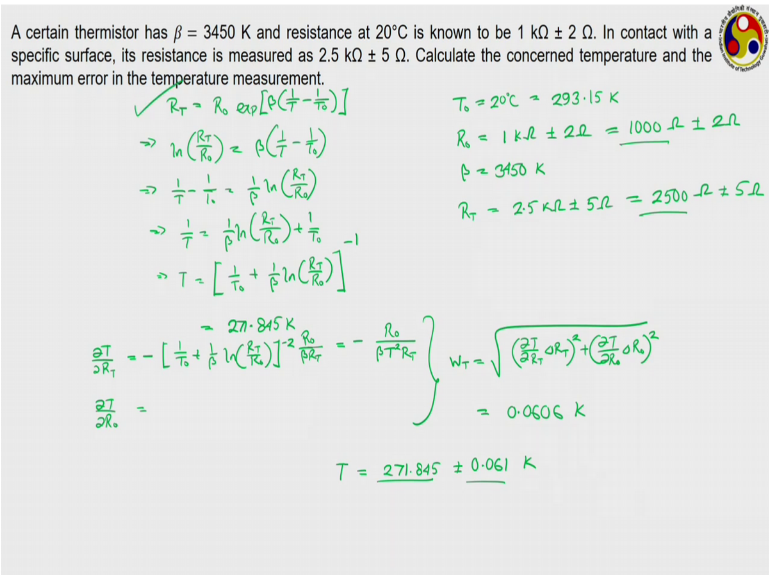

Let us now move to a problem involving thermistors. Here our question is just carefully read it out; we are talking about the thermistor having a beta equal to 3450 Kelvin and resistance at 20 degree Celsius is known to be 1 kilo ohm plus minus 2 ohm. So, there is an uncertainty involved at the reference temperature of 20 degree Celsius the corresponding reference resistance value is 1 kilo ohm with an uncertainty of 2 ohm.

So, now, for an RTD what is the relation with temperature? We know that for RTD the temperature relation is given us R T equal to R naught into exponential beta into 1 by T minus, 1 by T naught or log of R T by R naught is equal to beta into 1 upon T minus 1 upon T naught. So, if we want to express this or in terms of temperature, then we are going to get 1 upon T minus 1 upon T naught is equal to 1 by beta into ln R T upon R naught that is 1 upon T is equal to I guess we derived this thing in the last class, but I do not have it with me, so I am just getting a direct relation in terms of temperature. Or T is equal to 1 upon T naught plus 1 upon beta into ln R T upon R naught whole to the power minus 1. We could have represented in any other ways also but now I look at the problem.

Here it is given that your reference temperature T naught is 20 degree Celsius or in this problem it is better to convert this to SI units, so it is 293.15 Kelvin. Corresponding reference resistance value is 1 kilo ohm plus minus 2 ohm or 1000 ohm plus minus 2 ohm. It is and the beta value is given as 3450 Kelvin. It is in contact to the specific surface its resistance measured to be 2.5 kilo ohm with an uncertainty of plus minus 5 ohms. So, this plus minus 5 ohm is coming as uncertainty during the modified resistance measurement and you have to calculate the constant temperature and the maximum error that is uncertainty in this temperature measurement. So, where you are talking about an R T value of 2.5 kilo ohm plus minus 5 ohm or 2500 ohm plus minus 5 ohm. So, to find the value of the temperature the nominal value we have to put the nominal values here that you have to put R naught equal to 1000 ohm and R T equal to 2.5 kilo ohm or 2500 ohm in this particular phase relation and if we pull that the value of the temperature is going to come as 271.845 Kelvin.

Remember here T naught and is used in Kelvin, beta is given and R T and R naught we have used in the nominal values 1000 and 2500 respectively or I should say R T 2500 and R naught is 1000 ohm because we have to calculate the nominal value of the temperature

Now, you have to calculate the uncertainty. Just think about in the very first week how we have learned of calculating the uncertainty the same principle you have to make use of here. We have uncertainty involved in a measurement of beta. No, not in a measurement of beta, but we have uncertainty involved in the value of R T and R naught, not in the value of beta and T naught. So, we have to calculate then the corresponding sensitivities that is dou T dou R T. How much will be that? If you calculate this, so it is going to be minus 1 into this whole thing 1 by T naught plus 1 upon beta ln R T by R naught whole to the power minus 2 into if we go inside this now, into 1 upon beta into R naught by R T or we can probably write this one as minus R naught by beta T square R. So, corresponding value you can calculate similarly dou T dou R naught you can differentiate with respect to R naught and get the corresponding calculation for this.

So, once you get both the calculations done then the total uncertainty involved will be equal to the root of dou T dou R T into the uncertainty involved in R T measurement whole square plus rho T dou R naught into uncertainty involved in R naught measurement whole square. In this particular problem I just have the final value which is 0606 Kelvin. So, the final temperature that we are going to get that is actually going to come as 271.845 plus minus 0.061 Kelvin. This is nominal value and this is the uncertainty involved in this for the given thermistor.

Again, the we are just using this particular concept of thermistor rest of the power problem you already know from you your earlier discussions.

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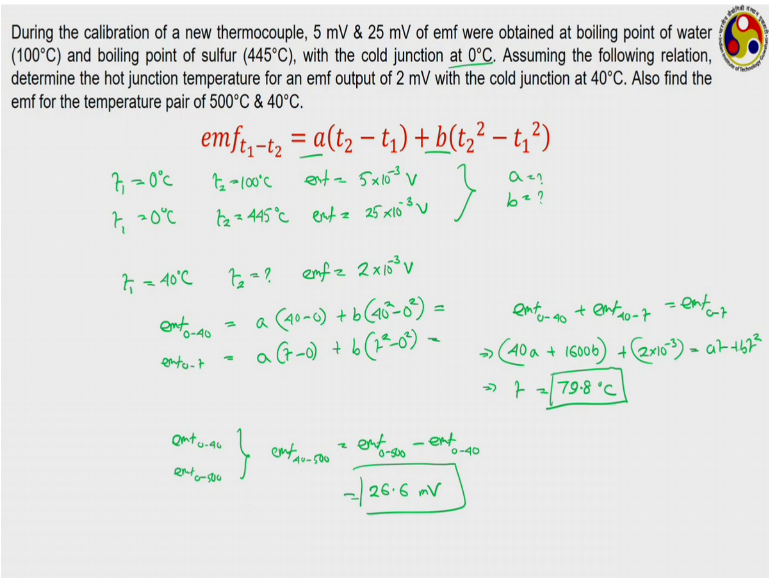

And finally, we shall be rounding off with a small problem on the use of thermocouples. During the calibration of a new thermocouple 5 milli volt and 25 milli volt of emf were obtained at boiling point of water and boiling point of sulphur, with the cold junction at 0 degree Celsius.

So, we are talking about the calibration of a thermocouple. And during the calibration process the cold junction is maintained at this particular temperature and the hot junction is taken in contact with two standard temperatures one is boiling point of water which is 100 degree Celsius and other is a boiling point of sulphur which is 445 degree Celsius and corresponding emf have been measured. So, assuming this following relation we have to determine the hot junction temperature for an emf output of 2 milli volt with the cold junction at 40 degree Celsius.

So, before proceeding let us try to make use of the given relation and identify the corresponding value of this constant coefficients a and b. So, in the first case your t 1 the cold junction temperature is 0 degree Celsius. Here it is also given these temperatures are in Celsius all this, t 1 and t 2 are in Celsius otherwise you should have converted in Kelvin, but for the given relation is specifically mentioned that the values of t 1 and t 2 are in Celsius.

So, for the first problem t 1 or for the first calibration point t 1 is equal to 0 degree Celsius, t 2 equal to 100 degree Celsius, and corresponding emf is equal to 5 into 10 to the power minus 3 volt. During the second calibration our t 1 is equal to 0 degree Celsius, t 2 equal to the boiling point of sulphur which is 4 for 5 degree Celsius and emf is equal to 25 milli volt that is 25 into 10 to the power minus 3 volt. So, you can combine this to get the values of a and v. We can get some numbers correspond to a and v being. I do not have the value, so I am not writing it here you can easily solve it by putting the values of t 1 and t 2 and get the corresponding two equations.

Now, using this relation you have to calculate the hot junction temperature for an emf output of 2 milli volt with the cold junction at 40 degree Celsius, this is the second situation we have, our third situation I should say t 1 is given as 40 degree Celsius, t 2 is unknown the one that we have to find and the emf is mentioned to be 2 into 10 to the power minus 3 volt. Now, the question is the calibrations that are that we are done corresponding to the value of 0 degree Celsius, then how can we make use of this? We could have directly obtained the value, but there is a better way of doing this that is, I hope you remember the laws of thermocouple that we have discussed in the previous lecture here. We shall be using the laws of the intermediate temperature.

See the emf corresponding to 0 to 40, we can easily calculate by putting the values of a into 40 minus 0 plus b into 40 square minus 0 square is equal to something you will be getting based upon the values of a and b. And in the second case emf corresponding to 0 to some unknown temperature t, that will be a into t minus 0 plus b into t square minus 0 square against something you are going to get.

Now, what we know from our previous discussion and from the laws of thermocouples. Then emf corresponding to 0 to 40 plus emf is corresponding to 40 to some t should be equal to emf corresponding to 0 to t. Here emf corresponding to 4 0 to 40 to t is given, so if you put those values emf 0 to 40 for R notation it is 40 a plus 1600 b plus emf transparent 40 to T that is given as 2 into 10 to the power minus 3 that will be equal to 80 plus bt square, as a and b values already you have calculated here so putting this you are going to get the value of t. And in this case, t is going to be coming as 79.8 degree Celsius. Remember here we are using t as Celsius only because the relation and the given relation specifically states that the t is in Celsius. So, this is the hot junction temperature.

For the second case it is mentioned that you have to find the emf for a temperature period of 500 and 40 degree Celsius. Again, we can follow the same procedure. For emf corresponding to 0 to 40 can be calculated, emf corresponding to 0 to 500 can be calculated, then emf corresponding to 40 to 500 will be equal to emf corresponding to 0 to 500 minus, emf corresponding to 0 to 40 and that is going to give you the result. The answer that you are going to get in this problem is 26.6 milli volt So, you can do the calculation get the values of a and b and putting them, you can try to find these two values. So, these are certain example problems related to the electrical thermometers which are very common in applications and you know I am sure you will be using this not only in early about race, but later on also when you join the industries.

Let us quickly discuss about a few more temperature measuring options before I close on this particular topic.

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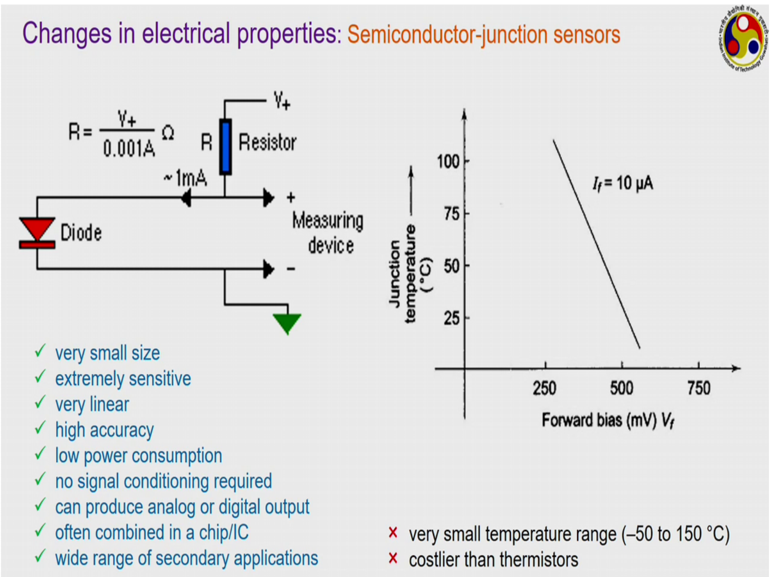

And among electrical properties or changes in electrical property based measuring devices we have discussed about 3 of 3 the RTD and thermistors which uses the principle of resistance change with temperature whereas, we have also discussed our thermocouple which makes use of the see beck effect. However, there is a 4th option also thermistor commonly is called bulk semiconductor sensors whether is something known as the junction semiconductor sensor or semiconductor junction sensors, these are nothing but diodes.

As we know from your knowledge about physics that as a temperature changes the performance of diode also changes, both during the forward bias and reverse bias and the voltage output from diode keeps on changing. Just the same principle is used, so we can make use of a very simple diode take it in contact with the surface where you want the temperature measurement and by noting the corresponding change in temperature which is generally very very linear you can easily get the, change in voltage I should say we can easily get a measurement of the corresponding temperature of the surface.

It has several advantages like it is very very small in size. You know how small a diode can be, so these are small devices. They are extremely sensitive to small changing temperatures. And deployed very linear output, something like this during forward like in shown here as the temperature is dropping the corresponding the voltages also keeps on increasing. High accuracy we can get from them almost comparable to the thermocouples or even better than the thermocouples sometimes. Low power consumption, particularly if you compare this one to RTD and thermistors the power consumption is quite low. No signal conditioning required like in case of thermocouples. We can use this one in analogue circuits to get analogue output also we can use them to produce digital outputs or even sometimes logic outputs are like something just like yes and no kind of outputs also can be produced from them.

They are often combined in a cheap or IC to get multiple operations done parallelly using the same circuitry. And we can have a wide range of secondary application of such kind of devices. Several control application switching kind of applications, sensing, some surrounding temperature, warning systems all of them can have this kind of junction semiconductor based sensors. But there is one big disadvantage that is ice temperature range is very small only about minus 50 to o150 degree Celsius and they are generally costlier than the thermocouples. Despite having low power consumption they can be much more costlier compared to thermocouples and thermistors both.

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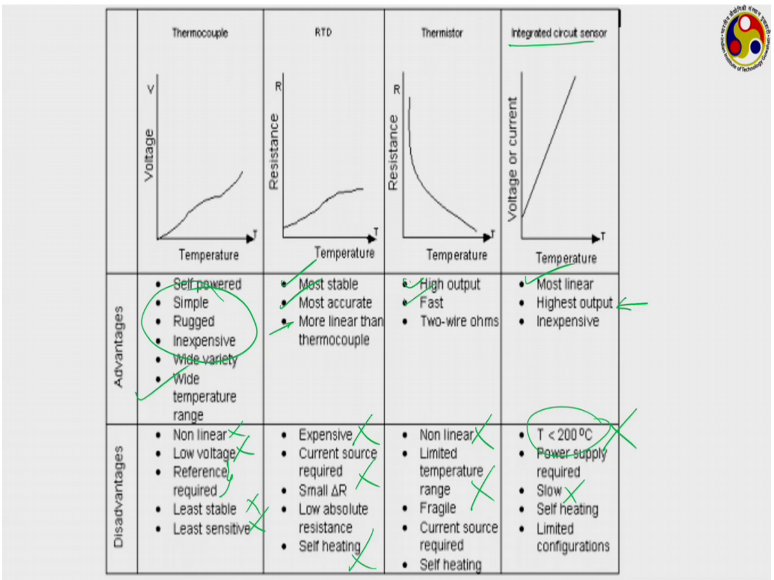

So, these are change electrical property based devices. This is a summary of the 4 that we have talked about. Just their advantages and disadvantages are listed here and also the voltage versus temperature plots are shown. As you can see that the integrated circuits based sensors or the one just I just talked about the junction semiconductor sensors are giving very very linear output that is why they are the most linear kind of device. However, the most stable output and most accurate operation we can also we can generally get from the RTD, but the output from RTD are generally quite small. In magnitude, we often have to go for some kind of amplification; whereas in case of thermistor, we get the high output probably for a given change in temperature thermistor gives the highest output mostly.

Also, thermistors are generally much faster compared to the other one. Actually, it is mentioned that ICS based devices also give the highest output, but thermistor is also comparable in them. Definitely they are much greater in magnitude come for the thermic of compared to the thermocouples and RTD.

Thermocouples have several disadvantages like non-linearity is one disadvantage, voltage output is quite low, they are much less stable and less sensitive compared to RTD, we need a reference temperature; however, their biggest advantage is the simplicity inexpensiveness and ruggedness. And also, they can give very high temperature range particularly if you compare with thermistors or IC based sensors that is if we compare them with semiconductor based devices they gave a very wide range.

RTD also can give a very wide range of can pro help in wide range operation, particularly considering that their operation or output is very more linear compared to thermocouples and also compared to thermistors, but their problem is they are expensive we need a current source and self heating problem. I i square loss that can be significant particularly the lead versus loss also can be quite significant to the RTD. Thermistors the problem is the non-linearity in the output and the limited temperature range, and also their fragile nature and the self heating related issue quite similar to RTD, but their advantages are this high output and extremely fast response. Particularly, if you want to use in some kind of feedback circuits or some kind con temperature control of application thermistors, can be very good option.

And IC based sensors their advantage or their very linear output and highest a linear output and also highest output and very inexpensive comparable thermocouples sometimes even cheaper than thermocouples. Their problem is this particular temperature range, and the requirement of power supply and they are quite slow probably the slowest among all 4.

So, each of them has their own idea of application. Like if we are looking for an option for long term operation very stable of output and very accurate output, we should go for RTD. Whereas, if you are looking for some kind of control application fast output probably thermistors are better option at least as long as you are and the low temperature zone. Thermocouples can cover a very high temp operating temperature zone, so if you are looking for applications which are quite rough and you have a large temperature span and you want to measure temperature at several points, thermocouples are ideal compared to RTDs. And if though you, specifically need a very linear output at low cost then IC based sensor or valve one of the junction semiconductor sensors probably are the better option.

So, with this we move on to the next category where we shall be talking about the use of emitted radiation from bodies for temperature measurement. Now, we know that when you want to measure the temperature of a surface using say an expansion based device like a liquid in glass thermometer, we have to take the thermometer in contact with that surface at least the bulb of the thermometer also preferably a significant portion of the stem of the thermometer and should be in contact with the surface, where do you want a temperature measurement. And then the thermometer itself will take some time to respond slowly acquiring heat from the corresponding surface or losing heat to the surface if it is at a lower temperature and then the liquid column will keep on moving into the capillary tube settling down after certain period of time.

So, we have to bring the thermocouple the important part is we have to bring the thermometer in contact with the surface and also you have to wait for some time. What about the electrical base sensors? The same issue still persist, for electrical base sensors or for pressure thermometer we have to bring the sensor part in contact with the surface, the rest of the component rest of the components can be a distance apart particularly if we are using a significantly long lead wire in case of RTDs or thermocouples or if you are using a long capillary tube in case of pressure thermometers you can go for some sort of distant measurement or remote measurement, but still some part needs to be in contact with the surface.

But now if that is not possible then what will happen? Like think about if we want to measure the temperature of the stars, the temperature of the sun which is the closest star or the star closest to our planet at least then how can we measure the temperature of that. Or maybe something which is within your grasp, but still you may not have an option of measuring that temperature like say how can measure the temperature of the fire inside a combustion chamber or a furnace. Quite often the combustion chambers can have temperature of 2000 Kelvin or higher than that and none of the known materials can sustain that level of temperature for a prolonged duration of time. And that is why we cannot use any of the discussed methods first such level of temperature measurement. We have to necessitate an option for remote temperature measurement, truly remove temperature measurement where every part of the device will be away from the measuring zone or the measurement zone.

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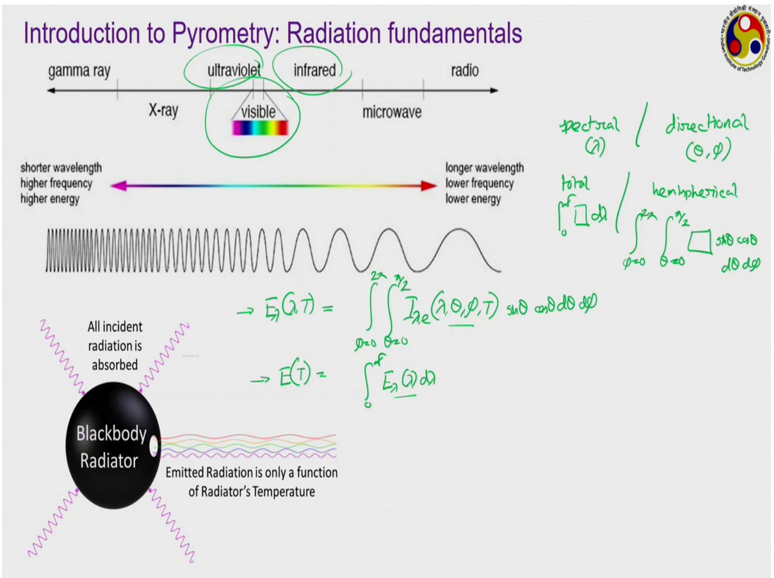

And that is why and that is where the radiation based devices which are commonly called pyrometer they comes into picture. We know that anybody at a temperature higher than absolute 0 emits some radiation depending upon its own temperature level. The temperature level of emission depends upon the or I should say the level of emission the wavelength of emission depends upon the temperature of the source. The radiation waves can be classified in several categories depending on the magnitude of wavelength. Like for extremely small wavelength we can have ultra-violets whereas if we move to longer wavelengths or shorter frequencies then we shall be having X-rays, then UV rays, then we have a very small visible spectrum brand and then comes infrareds which are much longer wavelengths and lower frequency signals compared to the ultraviolet swans or X-rays.

Now, exactly which kind of radiation a body is going to emit that depends on the temperature of the body. Like the most ideal one that we can have is a black body which emits radiation. Independent of the wavelength of the corresponding radiation rather whatever emission that comes out of a black body is a sole function of the corresponding temperature only. Similarly, any radiation falling on a black surface that gets totally absorbed.

Now, whenever you are talking about radiation generally two terms comes into picture, radiation is dependent on temperature, radiation emitting from a surface is dependent on the direction, and also it depends on the wavelength. So, accordingly we use the term spectral and directional. Spectral refers to the dependence on wavelength whereas; directional dependence directional indicates the dependence on. The direction if we are working in a spherical coordinate system then it depends on the value of theta (Refer Time: 38:10).

In corresponding to spectral we have another term which is called total. Total refers to integrated over all possible wavelengths from 0 to infinity as waves or electromagnetic waves can have wavelengths ranging from 0 to infinity and so once we integrate correct corresponding spectral quantity over the entire spectrum what we get that is called the total.

Similarly, if we integrate over all possible directions then what we get that is called hemispherical because then we are talking about integration over along all possible rays of a hemisphere where our integration will be phi equal to 0 to 2 pi, 0 angle theta equal to 0 to pi by 2, then corresponding quantity sine theta cos theta d theta d phi. These are very standard proofs you can refer to any standard heat transfer work to get the origin of this particular relation. But hemispherical refers to emissions going in all possible directions over an hemisphere.

Now, if I lambda e refers to the intensity of emission coming out of a surface with a wavelength of lambda then this is generally spectral directional variation because it depends on lambda, theta, and phi, or to be more specific it also depends on the temperature of the surface. So, this is a spectral and directional quantity where we has we heard we have the dependence of the wavelength and also dependence on the all possible directions.

Now, if we integrate this over all possible directions that is phi equal to 0 to 2 pi, theta equal to 0 to pi by 2 sine theta cos theta d theta d phi. Then what we get? That we generally indicates, e lambda function of lambda which is we call the spectral emissive power or I should say the spectral hemispherical emissive power because here we have we are talking about emissions of one particular wavelength, but going into all possible directions over a hemisphere.

And now, once we integrate this one over all possible wavelengths then what we get is the total emissive power. Actually, it should be a function of temperature and this is also a function of temperature, because theta phi dependence goes off once we do the integration and lambda dependence goes on once we do this second integration. So, this is spectral emissive power or spectral hemispherical emissive power, this is total hemispherical emissive power, that is a total amount of radiation that can be emitted from the surface of a body maintain a temperature T.

When you are talking about a blackbody that is for a given temperature that is the maximum emission that we can get from this circular surface, but the emissive power that keeps on varying is the temperature of the surface. If we plot that then we are going to get a curve like this. Here we have the wavelength lambda on one side and spectral emissive power or e lambda be that is why I just talked about that is on the other side.

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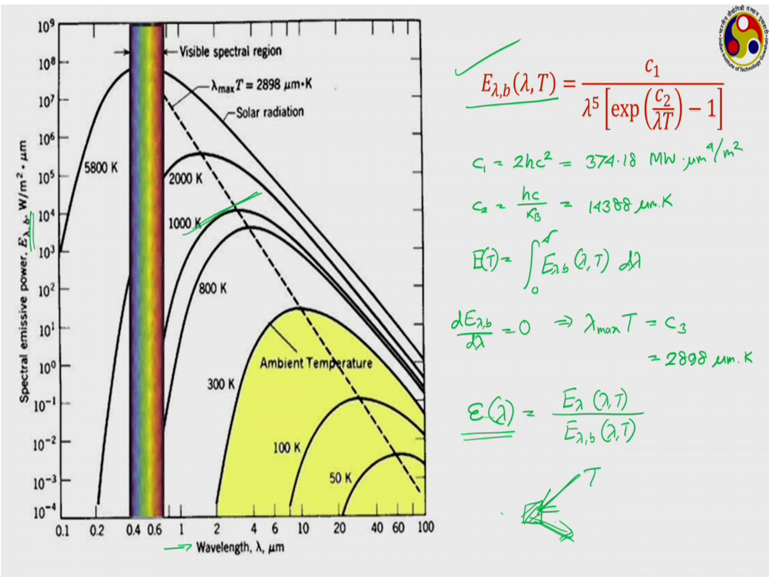

Now, depending on the temperature of the source you can see that each of them is taking some parabolic kind of shape. For lower temperature the wavelength is also quite low, but as the temperature keeps on increasing corresponding wavelength increases and beyond 1000 Kelvin the change is also quite significant, but for lower temperatures probably the change is much more dominant. And this particular relation is given by this, where on the left hand side we have that the spectral hemispherical emissive power which is given a very relation like this.

Here c 1 and c 2 are constants, c 1 is equal to 2 hc square and the value is generally 374.1 8 megawatt micrometre to the power 4 by metre square, where h is the planks constant. I hope you can remember that the planks constant general is presently sets the new standard for measurement of mass, small c refers to the velocity of light in vacuum and c 2 is hc by K B, where again h and c are respectively plank constant and the velocity of light in vacuum and K B is the Boltzmann constant and the value of c 2 is 14388 micro meter Kelvin. Be careful here, we are writing this unit micrometers of writing meters because wavelengths are always very small often in the range of micrometres. So, c 1 and c 2 are given.

Now, if we want to know the value of total emissive power from this surface then it will be equal to integrated over 0 to infinity and this total hemispherical emissive power is a function of temperature. Now, for a given temperature of the surface if we are our interest is to calculate where we get the maximum value of this emissive power of corresponding to which wavelength at least then we have to differentiate this expression with respect to lambda with t remaining constant and equate that to 0 if we create that.

Then we get the very well celebrated relation known as the Maxwell's displacement law or it is called the Wiens displacement law, where the first one is the this particular one is a Plank's relation. Whereas, what we are writing here is called the winds displacement law where the for a given temperature the product of the temperature and corresponding maximum corresponding through wavelength at which we get the maximum spectral emissive power that is a constant and the value of the c 3 is 2898 micrometer Kelvin. So, this sets up the basis for the temperature measurement using the radiation based devices.

We know that as a temperature of the surface keeps on changing corresponding emissive power will also keep on changing. And for it will of course, depends on the wavelength, so if we can analyze the wavelength for a surface then we can also or I should say the analyze the wavelength corresponding to the emission coming from a surface we can also calculate the corresponding temperature of the surface. But the relations that I have written here this relations can are available or these relations are valid for black bodies, but in practicalism we are talking about real surface then you have to define something known as the emissivity.

Emissivity is given as the spectral emissive power for a real surface divided by the spectral emissive power of a black body or I should say the spectral hemispherical emissivity is defined as spectral hemispherical emissive power for a real surface divided by the spectral hemispherical emissive power of a black body. Estimation of this epsilon is very important for any real radiation based measurement.

Now, the principle is that whenever a surface is emitting certain radiation then we shall be using some kind of detector which is going to sense that radiation. Now, energy is coming to this particular sensor in the form of radiation accordingly temperature increases, but it will also lose energy to the surrounding in the form of its own emission and there may be convection from the surrounding air if there is anything at all.

If there is no convection or conduction heat losses then it will also keep on emitting depending on its own temperature accordingly there will be change in the temperature of the sensor, and after some time it will reach certain equilibrium position or equilibrium temperature. And under which condition the emission coming from the source and the emission coming going out of this particular body should be equal to each other, so that the temperature will be maintained constant. So, then applying an energy balance we can easily sense the temperature of this sense temperature of this particular source. As we are continuously measuring the temperature of this particular body using any of the method that we talked about till now, right, thermistors.

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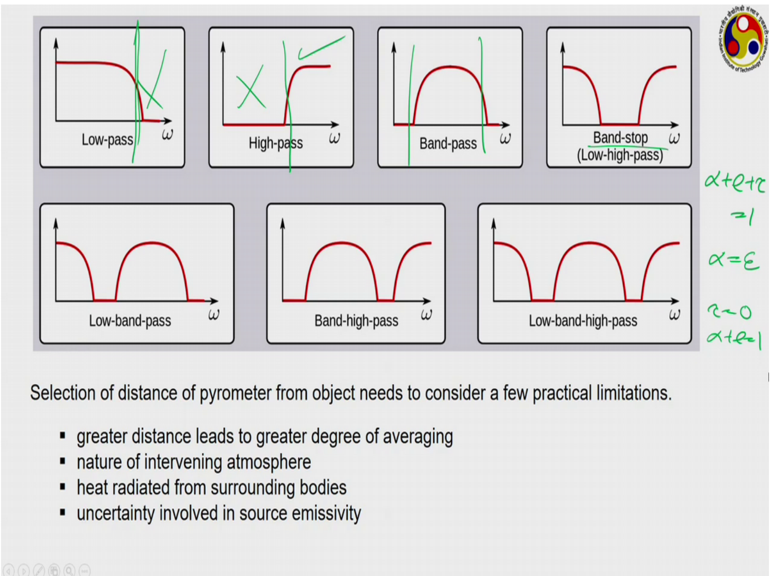

For the perp, for this purpose we generally depending on which wavelength we are interested in, we can use different kinds of filters like shown here, if our interest is low frequencies then we is low pass filter where the freq wavelength corresponding to lower corresponding to low into wavelength they are allowed to pass, but those having higher wavelength they are not allowed to pass. Similarly, for high pass filter those are having high roles are allowed to pass, but low wavelengths are not allowed to pass. We can also have a band first thing where well only within a range of wavelengths the waves are allowed to pass or the opposite of this in the form of this band stop and several combination of this there are different materials which represents varying levels of absorptivity depending on their configuration.

We know that whenever emission falls on a surface or I should say irradiation falls on a surface the irradiated energy can have 3 different phase. It can get absorbed in a surface, it can get reflected from the surface or it can just transmitted to the surface. Accordingly, we can write alpha plus rho plus tau is equal to 1, where alpha refers to the absorptivity that is the fraction of the irradiated energy which gets absorbed by the surface, rho is reflectivity it represents the fraction of energy. It gets reflected and tau is a transmittivity which represents the fraction corresponding to transmission. There for a perfectly black surface we generally have all alpha equal to epsilon which is called the Kirchhoff's law, that is emissivity and absorptivity are equal for practical. Practical surfaces like if you are talking about an opaque surface in that case tau is equal to 0, so that alpha plus rho is equal to 1.

And accordingly which wavelength it is going to, but the values of both this alpha and rho that varies with the wavelength. So, depending on which wavelength we are going to talk about accordingly we can select different kinds of filters. Like pyrex, pyrex glass generally allow radiations of within wave range of 0.3 to something like 2.7 micron to pass through and blocks everything else. So, if our interest is low frequency or sorry lower smaller wavelength then this one can be a good filter option whereas, calcium fluoride generally allows wavelength in the range of 0.3 to 10 micron to pass through, so it can be a high pass kind of filter it conduct as a high pass filter.

Now, the selection of the pyrometer from or I should say the selection of distance pyrometer from the object needs to be considered if you if you need to consider a few practical limitations. We know that pyrometers can give you remote temperature sensing because as we are sensing radiation, so theoretically speaking the radiation that is coming from the source and falling on your sensor that is in that is independent or not changed by the medium which is in between. However, there can be several other factors which can decide this distance. Like the greater the distance more degree of averaging we have to go for because the emission coming from the source get scattered in all possible directions there by only a small fraction may reach your sensor, so you have to go for some kind of averaging.

The nature of interfering atmosphere while we generally considered the atmosphere to be non-participating; but presence of certain gases, like carbon dioxide or water vapor that they can observe significant amount of radiation. Also, the presence of dust or moisture particles can lead to reflection from this from the medium itself. So, if such kind of participating media is present then a significant portion of the radiated or the initial irradiation coming from the source may get lost. The heat radiated from the surrounding what is also can affect your reading because your sensor often is not able to recognize the difference between the emission coming from the actual source and the emission coming from some unwanted surrounding object. Uncertainty involving the, source of source emissivity is a big factor as I have just mentioned, so that we need to have a proper idea always.

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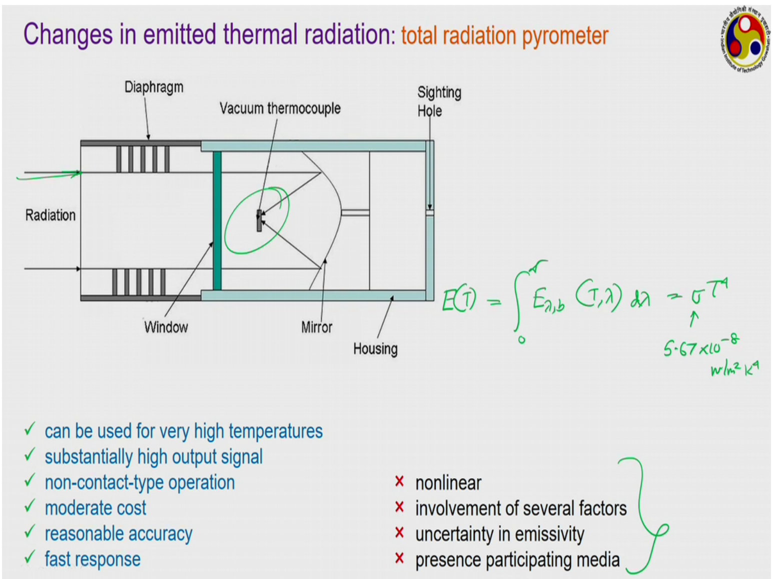

These are just some kind of common radiation measuring instruments. The first one is a total radiation pyrometer which is something like a total measurement measure overall wavelength there is no filter used emissions of all wavelengths are allowed to come.

So, as the radiation enters from this side it generally gets reflected by a mirror. The mirror is adjusted such that it all the emissions are allowed to meet in a particular focus. And we keep some thermocouple or some other kind of temperature measuring device there to measure the temperature of temperature at this point, and then using the energy balance we can easily get the temperature at this particular location. Total radiation pyrometer or any such kind of radiation pyrometer has a host of advantages like can be used for very high temperature we can easily go for 2000 or 3000 degree Celsius or even beyond that because we are talking about a temperature balance. So, never assume that the temperature of this thermocouple is going to be equal to the temperature of the source; it will be much lower than this because it is receiving only a small portion of energy, but as you are using the energy balance, so accordingly its temperature will be an indicator of the source temperature.

Substantially, high output signal we can get here which was a problem in case of thermocouples etc. Non-conductive type operation which is the biggest advantage for any kind of parameters, moderate cost, reasonably accurate, these are and quite fast response, at least faster compared to the liquid in glass kind of thermometers or sometimes the RTD s even. But the problem is non-linear response because the total emissive power energy or emissive power that is coming out of a surface is not linearly dependent on its temperature. Like in the previous slide I have written the relation for e lambda b using the planks relation.

Now, if our interest is to know the total emissive power we know that this one is a function of temperature and the wavelength. Now, if we integrate this one over 0 to infinity that is all possible wavelengths then the result that you are going to get that generally is some constant into T to the power 4. What is this relation known as? These are well celebrated Stephen Boltzmann relation and the sigma is Stephen Boltzmann constant whose value is 5.67 into 10 to the power minus 8 watt per meter square Kelvin to the power 4.

So, the emission emissive power coming from a body is actually proportional to the 4th power of temperature. Therefore, as the temperature changes emissive power can change significantly and thereby providing highly non-linear response. There are several factors involved as we have mentioned surrounding radiation from the surrounding sources can also affect your perfect the performance uncertainty in emissivity is a problem in any kind of pyrometers and presence of participating media. Again, all these actually are problem for any kind of radiation based pyrometers.

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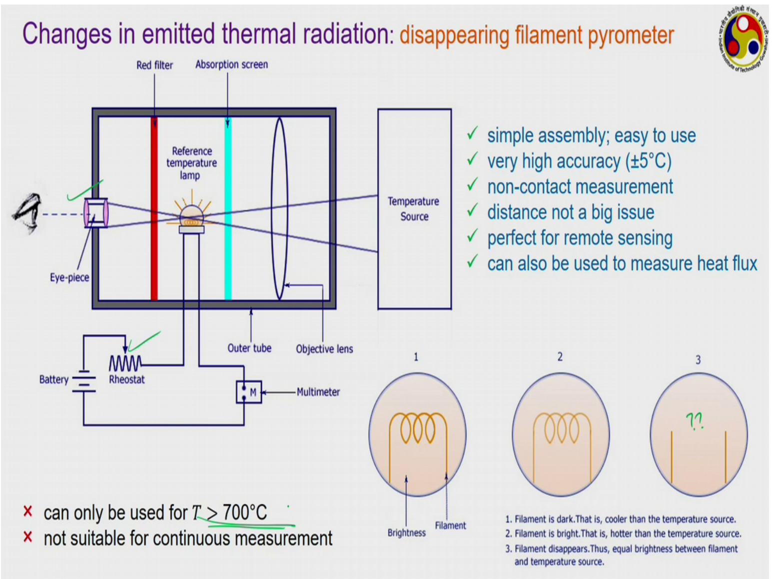

Next one is an optical pyrometer which is also commonly known as the disappearing filament pyrometer. It is a very interesting situation, here we have one bulb filament, the temp from the temperature source whatever emission is coming using some kind of lens that is allowed to focus at the filament specifically at the filament and then using this eye piece observer gives a focus on the filament. The eye piece is generally adjusted so that the filament and the temperature source they are seen on the same line.

Now, the temperature of the filament can be changed by changing the setting of this rheostat. So, accordingly the emission from this filament can also be modified, we can easily increase this one or decrease this one. Our idea of the observation here it is a purely observation based device. So, our idea is something like this, when the filament is visible in compared to the main source then the filament temperature must be lower than the temperature of the source. When the filament is appearing lighter compared to the source then it must be at a higher temperature because it is emitting more white light or whiter emitting more from the white restriction on the visible spectrum. So, it must be a temperature higher than the source. And if both temperatures are exactly equal then as you can see the where is the filament. Where is the filament here? The filament has vanished or disappeared. So, the temperature at which this particular observation is done that temperature should be equal to the temperature of the source. So, this is called a disappearing filament pyrometer or vanishing filament pyrometer.

It offers advantages of the simple assembly and very easy use, can go for very high accuracy within plus minus 5 degree Celsius it can predict which is actually quite creditable because we are measuring something in the range of 1000 or 2000 degrees Celsius or even higher. Non-conduct measurement, distance is not an issue for this and this is perfect for remote sensing, like most of the other pyrometers. And we can also use this one to measure the heat flux again by applying an energy balance.

But problem is that as we are looking for some kind of visible emission from the filament itself, so we need to go for very high temperatures. Filament can emit some light only when the temperature of the filament goes above 700 degree Celsius. So, we have to breach this particular temperature range to of make use of this disappearing filament pyrometer and it is not suitable for continuous measurement. But this is a kind of optical pyrometer and it has particularly when we go beyond this particular temperature range it is a very useful one from measurement point of view and finally, ok.

Before I go to the next device exactly how we calculate for this optical pyrometer?

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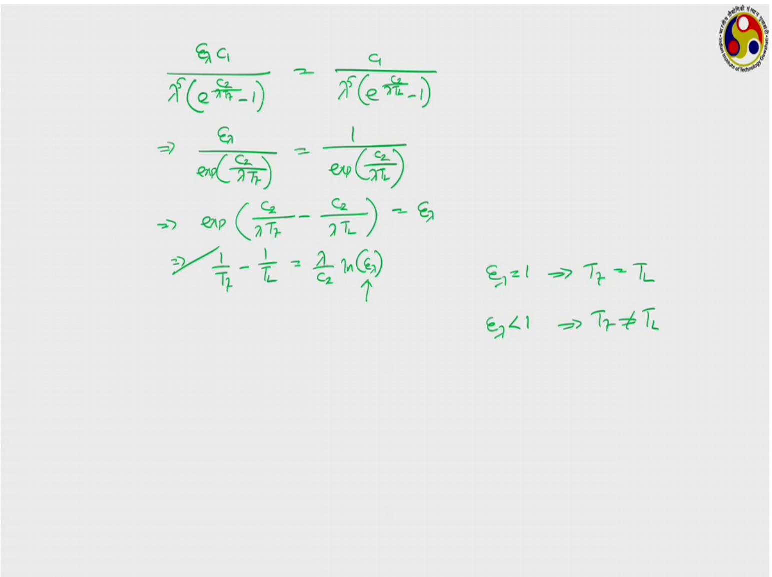

We know that the emission coming from the source can be given as epsilon lambda by c 1 into lambda to the power 5 into exponential of c 2 by lambda into temperature of the source that is a target temperature minus 1 will be equal to for the filament, filament can be assumed to be a blackbody because the way it behaves. So, its emissivity is equal to 1 by lambda to the power 5 to exponential c 2 divided by lambda into T for the lamp or filament, 1.

Now, when the temperature is lower, lower means as long as the temperature is lower than 4000 degree Celsius this exponent is too large compared to 1. So, that the 1 can be ignored. So, we have if epsilon lambda divided by exponential of c 2 by lambda into the target temperature is equal to 1 divided by exponential of c 2 divided by lambda T L. So, if you combine this, so we have exponential of c 2 by lambda T target temperature minus c 2 by lambda T lamp is equal to epsilon lambda which is 1 upon target temperature minus 1 upon lamp temperature is equal to lambda upon c 2 ln epsilon lambda.

Here we need to have a proper estimate of this epsilon lambda, lambda is the wavelength corresponding to which we are doing this experiment c 2 know the value of c 2 as I have given earlier. So, lamp temperature is the one that we are measuring when we are dealing with a black surface epsilon lambda is 0 giving T t is equal to T L. When epsilon lambda sorry, epsilon lambda is 1 for a black surface; when epsilon lambda is less than one that is we are dealing with a real surface, then T t and T L they are not equal then this particular relation provides a way of connecting the value of target temperature. So, this is an example of how we do the calculation in case of any pyrometers.

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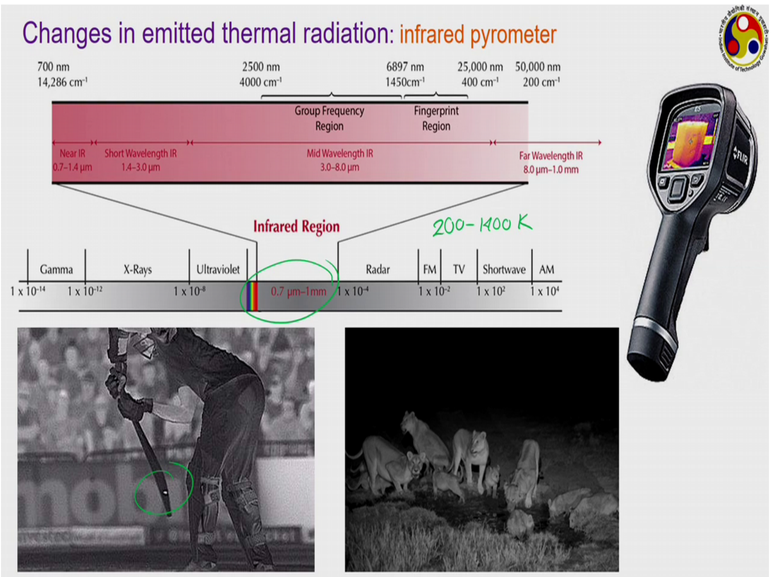

And finally, I am going to finish with the infrared parameter. Infrared pyrometry is an option which provides us to measure quite not lower temperature. Actually, when the term pyrometer we use we used to go for very high temperatures only in the range of 500 600 degree Celsius or even higher a few thousand degree Celsius. But this infrared pyrometry which is the one that allowed us to come to much lower temperature level because in case of infrared we are talking about this particular wavelength range 0.7 micron to 1 millimetres and the this corresponds to a source temperature of only about 100 to 1400th Kelvin. So, we are talking about a temperature range of 200 to 1400th Kelvin.

So, using this infrared temperature you can easily make use of in fact, you can easily get temperature values quite close to the normal ambient temperatures or something below that 700 degree Celsius limit that we have seen in case of optical pyrometers. The working principle remains the same only difference is that here you are using the infrared spectrum of light.

Infrared cameras or infrared image guns are quite popular very easily available in the market and they have you must have seen several applications of this. This is just a standard feature, but applications have you seen this picture? Those who are interested in cricket definitely have seen this, where they call it hot spot or something where as the ball strikes the bat or any other part of the batsman they generally detect that by this white mark [vocalized-noise. This physically when the ball strikes a particular portion there is a because of the momentum transfer it is small change in temperature its temperature increases by a few degrees and the infrared camera is able to detect that particular one it is an application.

This is another application the night vision cameras which is very common in case of animal safari or several other applications, in army applications. These are all those funky shows that comes on television for ghost hunting or they all make use of the night vision cameras which are basically nothing but the infrared cameras. And infrared camera, you use the term camera, but actually that is a pyrometer because the objective is to get temperature values over a particular spectrum.

So, that takes us to the end of this particular module where we have talked about the measurement of temperature following different principles. We started with the laws of thermodynamics particularly the zeroth and second law of thermodynamics to define the scale of the thermodynamic temperature scale.

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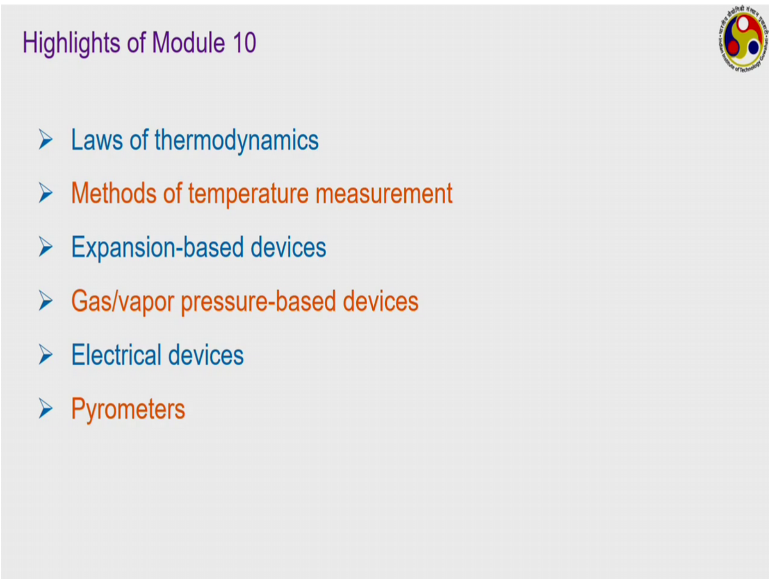

Then we categorize the temperature measuring options into 5 different categories, out of which we have discussed about the expansion based devices in the form of liquid in glass thermometer and bimetallic strips. Then we talked about the gas vapor pressure based devices in the form of pressure thermometer. Then we discussed 4 different types of electrical devices which all are very common like the RTDs, thermocouples, thermistors and diode based sensors or IC based sensors. And then we talked about the pyrometers, there can be wide range of pyrometers like optical pyrometers, total radiation pyrometer or infinite pyrometer depending on the range of wavelength that you are dealing with.

So, that is the end of this 10th module. I hope you have got some idea about the most popular methods of measuring the temperature. Please try to solve the assignments because I have already solved quite a few example problems in this during the course of today's lecture, and also the previous lecture and I am sure you'll be able to solve the example problems or assignment problems. So, if you have any query please keep on posting in the forum.

Thank you very much.