Principles of Mechanical Measurements
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We have seen so far the important mechanical quantities, the measurement of mechanical quantities like displacement, velocity, acceleration, force and torque. From now onwards we are going to see some of the process variables, measurement of process variables like temperature, flow, pressure, like that. To start with we are now seeing the temperature measurement. Now the temperature is one of the four fundamental quantities along with length, time, mass and temperature. So the definition for temperature is it indicates the kinetic energy of atom or molecule of a body that kinetic energy decides temperature. So any standard for the temperature should be able to measure the kinetic energy. So such a method we don’t have, so the standard for the temperature is obtained from the fixed points of 6 elements.

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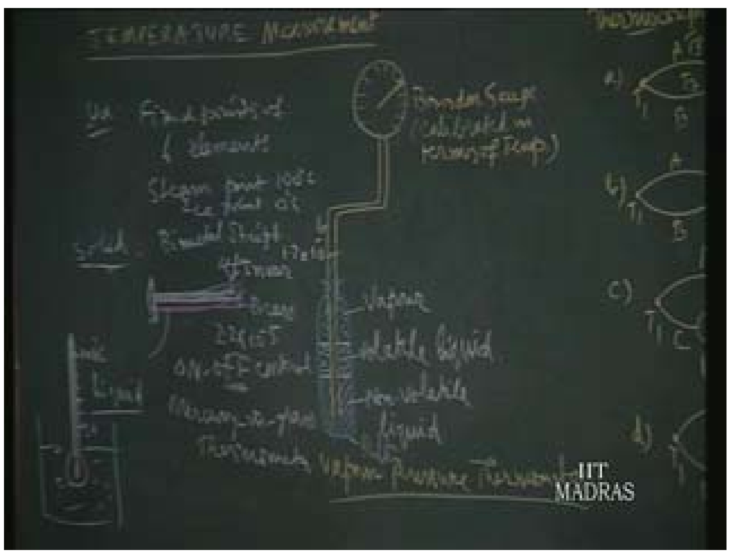

They are mentioned in any Clark's stable for example steam point 100 degree centigrade and ice point zero degree centigrade and melting point of gold, melting point of silver, melting point of sulfur. These six points are there so based on that any instrument is calibrated. So standard for temperature is the fixed points as defined any Clark's table one can refer the Clark's table. Now what is the importance of temperature? Temperature is a very important quantity in the sense it decides the state of any body, an inert body an inert matter. An inert matter can have three states solid, liquid or vapor and all these three states are decided by the temperature of that matter and not only the temperature affects any nonliving body, the health of any living body is decided by the temperature.

Also in many industries we find, for manufacture of some material or say the baby powder and you have to maintain the product at difference stages of the manufacturing, at different temperatures.

Not only at different temperature for constant durations, also a temperature cycle first half an hour one temperature, next second half an hour another temperature like that, the temperature cycle. So these have to be maintained properly so that we get the correct product as the output otherwise instead of powder you make get the solid at the end. So the temperature measurement is very important in all process industries and chemical industries at various points, temperature is measured and they are monitored and they are constantly watched by the operator and the signal is taken to the control room and it is displayed. Hence you find such an important parameter, we have got many literatures measurement about such important parameters even temperature measurement alone we have got books but here we are going to see the important aspects of temperature measurements as a completion of the material for this mechanical measurements.

Now for the purpose of the measurement of temperature we use the effect of temperature on the bodies. It changes the physical dimensions or volume of the body and electrical properties of the bodies or elements are changed, when temperature is changed and radiating capability of body or matter is again a function of temperature. By using these properties of matter or material, we are able to measure temperature. First and foremost one is say solid, expansion of the solid we are using in the form of bimetal strip. Still they are used in many of the refrigerators where you find two flat strips; one is made up of Inver other is made up of say copper or brass. This is a brass strip both of them are fixed together and then it is fixed at one end. This is a brass; Inver is a material it's a nickel steel alloy having a temperature coefficient of 1.7 into 10 to the power of minus 6. Whereas brass has got 2.2 into 10 to the power of minus 5. You find more or less brass has got ten times the expansion coefficient as Inver, so you find when the temperature increase naturally a brass will have more length expansion than Inver. So you will find when the temperature increase it bends like this.

So you find that is higher length will have the outer of the curve bending and now suppose if you have a switch point something like that then you will find this may be a power on the power line. So when the temperature increases it touches the contact point so power is carried to the compressor of a fridge. When the temperature comes down then it becomes flat and the temperature is cut out so it is on-off control, mainly they are used in on-off control. Such bimetallic strip that is what is made use of, the expansion of solid is made use of in measuring the temperature and controlling the… Measurement does not mean always exhibiting the value. Here it is measured and measurement is done by bending, when measuring means it bends this way or the other way and that is being made use of for control purposes. It's called either on or off, it will be in two positions, two position control. That is expansion of solid and now expansion of liquid we are using the mercury in glass thermometer. So we have a capillary in a glass material, it may be going up to here. So this is a glass column and at the bottom we have the bulb.

So you find the mercury is rising in the capillary so mercury is kept here. So it is a container, a small bulb and when whole thing is emerged in any bath then you find the mercury in this bulb expands and rises over the capillary column and this is being calibrated in terms of say 30 degree, this may be 100 degrees centigrade. So this is being calibrated, this calibration is done by using one or two fixed points so ice point is zero degree centigrade. So once you put ice and then mark wherever it sends at a zero and boil a water and then place it, this one and where it stops then you call it as hundred degree and divide equally the gap between zero and hundred into equal parts (Refer Slide Time: 09:40). That's how the thermometers are measured or being calibrated by using the fixed points.

So here what we are using? The expansion of the liquid is made use of in the mercury in glass thermometer and the vapour that is the physical dimension. The first principle is the temperature affects the matter in changing the dimensions. So that is the property what we are making use of in this instruments. So bimetallic strip, mercury Inver thermometer and third we have got vapor-pressure thermometer. Here we find this is a bulb which is immersed in the body or it is put in the furnace where we want to measure the temperature and the pre surface of the volatile liquid, the temperature at the pre surface this is the pre surface of the volatile liquid and that decides a vapour pressure. So you just immerse it up to this level and we find the evaporation of the pre surface builds enough pressure depending upon the temperature. That pressure build up is the function of temperature of the surroundings so you find the same pressure is transmitted through this liquid and it goes bourdon gauge, it's a pressure gauge.

So it measures the pressure of the vapour just above the volatile liquid and the whole tubing everything is build up with the non-volatile liquid, this is construction. So the pressure reading is now calibrated in terms of temperatures. This is the principle of vapor-pressure thermometers, these are often used in automobiles and cars where the radiator, water temperature is measured by a bulb like this, vapor-pressure thermometers and the meter is put in one of the dash board instruments for the driver to see whether the temperature of the radiator water is increased. If it has increased that means water quantity is reduced then we supposed to pour some more water into the circulating system. So for temperature measurement, the property the physical expansion of or physical expansion of the matter is made us of.

There is another version instead of this vapor-pressure thermometer, there is also liquid-pressure thermometers where only liquid is made use of that is the what are the volatile and non-volatile liquid, some chemical name you can refer the standard textbooks and the liquid-pressure thermometer, the whole volume is made of only one liquid, probably a mercury. Mercury also can be used, the bulb and this tubing and the bourdon gauge everything is filled up with the liquid. Now when it is immersed then the liquid try to expand but it is not allowed to expand because a constant volume. So you find to the extent of expansion of… (Refer Slide Time: 12:30). Then the compression is there and then it develops pressure.

Since it is a constant volume since there is no gap of expansion that much expansion results in a high pressure of the liquid. That pressure is rate in the bourdon gauge again but the problem in such liquid pressure thermometer is any intermediate temperature. So this may be T_1 and here if you have T_2 and T_3 and all these temperatures will contribute towards the pressure of the liquid. So whereas in vapor pressure thermometer and pre surface volatile liquid alone and the temperature of the pre surface of volatile liquid alone decides the pressure of the vapor. Any other temperature in between will because the evaporation it will be compressible, it will not affect the vapor pressure, any intermediate temperature will not affect the vapor pressure. Hence we find the vapor pressure thermometer is more accurate than liquid pressure thermometer, hence this vapor thermometer is often used.

If we are using liquid pressure thermometer then for the compensation we should take another tubing and this much expansion is given in the opposite direction. So that any error is compensated and it is given so it is little elaborate in construction and more costly. So that is regarding the dimensional change of matter by temperature variations, that is what we made use of. Now next one the electrical property that is thermo EMF.

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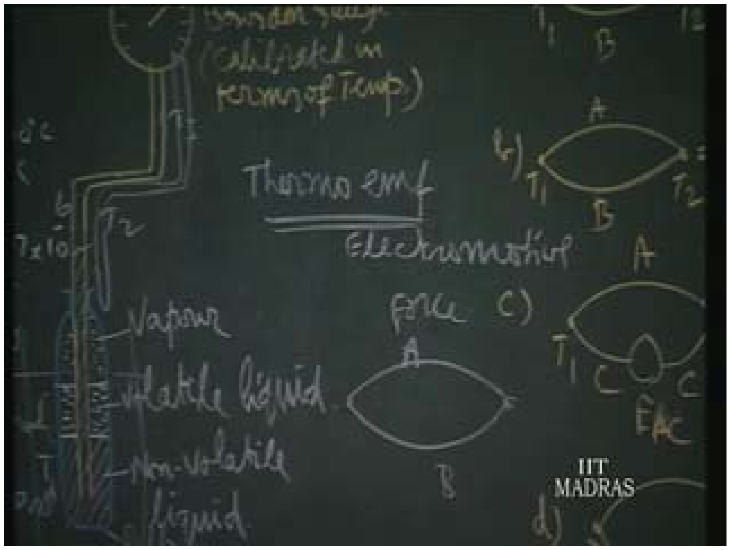

First we take thermo EMF that is EMF is electromotive force. That is we have two wires of homogeneous material wire A and wire B or matter A or element A and element B and they are joined together, it's made up of homogeneous material wire, two wires and the two junctions where the two ends of the material are connected together. This is one junction; this is other junction by building or soldering, by just strong twisting so that you find there is sufficient electrical contact. That is what is important, you get it by simple twisting or soldering or welding. So the two junctions when they are at two different temperatures T_1 and T_2 then what happens and EMF is developed in the circuit, made up of these two wires, wire A and B and that is called a seebeck effect.

The two thermocouple wires, when such material having these properties of developing EMF when the junctions are subjected to different temperatures such materials are called thermocouple materials and when two thermocouple material junctions are at different temperatures, an electromotive force is developed in this circuit, that is our seebeck effect. Later on this was found out nearly in the 19^{th} century, early part of 19^{th} century and later on Peltier and Thompson also found out some more thermal effect on this thermocouple wire that is Peltier. Peltier effect is when the current flows in the thermocouple circuit so current is flowing like this say current i flows. Once they are in the two different temperatures, there EMF developed that EMF developed divided by the total resistance of the wire gives rise the current flow in this circuit.

Due to current flow heat is absorbed and in the hot junction of course T_1 and T_2. Suppose T_1 is greater than T_2 then we say T_1 is the hot junction and T_2 is the cold junction. Due to current flow in the thermocouple wire, the heat is absorbed at the hot junction and heat is liberated at the cold junction. What is the effect? It is amounting to more or less a loading effect in the instrumentation. So now the T_1 is due to this current flow is reduced from T_1 to say some other T_1 dash because heat is removed due to current flow so it is reduced. Finally we are measuring the reduced temperature; it is exactly the loading effect so that is Peltier effect.

Then one more effect by Thompson, Thompson effect that is when the current flow and the heat flow. Now heat flows always from higher temperature to lower temperature so heat flows like this. Now you find in one wire, the heat flow and current flow are in the same direction that is in the wire B, in the wire A the current flow and heat flow are opposite in directions. So we find when the current flow and heat flow are in same direction, heat is liberated to the atmosphere that is the Thompson effect. Heat it liberated and in the wire where the current flow and heat flow are opposite, heat is absorbed from the atmosphere by the wire. So that is Thompson effect. So these are three effects that are happening in a thermocouple circuit. But in practice we are using some four laws in actual measurement of a temperature by using thermocouple. Those four laws are explained here. What are the four laws? That is empirical laws used in actual measurement of temperature by using thermocouples and they have to be understood, if at all we are going to make use of thermocouple. The first one is the intermediate temperature; so far we are talking about the junction temperatures.

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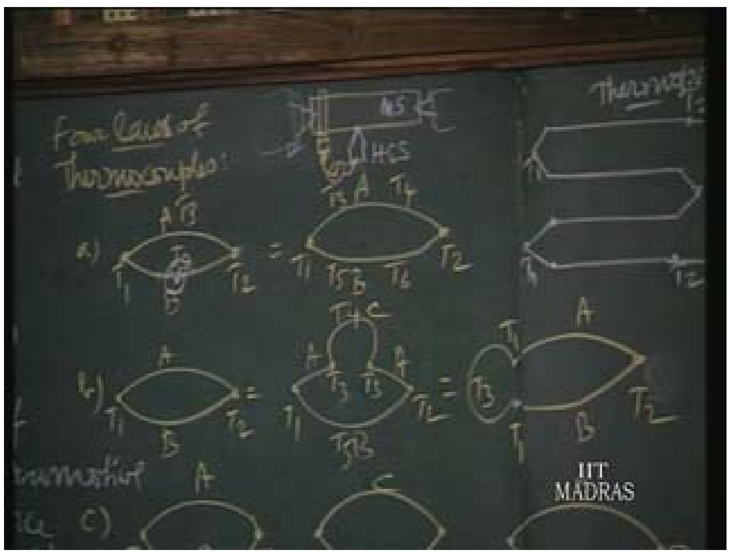

The voltage developed in such a thermal EMF or voltage developed in such a thermocouple wire is depending only on T_1 and T_2. That is why it is made more elaborate even when the intermediate temperature happens to be T_3 or T_3, T_4, T_5, T_6 something like that; you find that the voltage developed in the first circuit is same as the voltage developed in the second thermocouple circuit. That means intermediate temperatures of these two wires will not affect the EMF developed due to the temperature difference of T_1, T_2 in the two junctions. Intermediate temperature can be anything so that is the first law of thermocouple.

Second law states we can bring a third element because thermocouple circuit is made up of two elements, homogeneous element A and B. Now I am bringing third element C cutting the material A at these two points and connecting the third member C. Now here the voltage developed will not be affected if that is the important. If the two new junctions are at the same temperature. Now two new junctions are at T_3 and main junction temperatures are T_1 and T_2 but when you are bringing third material and these two junctions we are going to connect with the material A should be at the same temperature. This is the property what is made use of in the voltage measurement of the thermocouple circuit.

When you want to measure thermocouple circuit what we are doing? We insert a voltmeter, voltmeter mostly consists of copper wire and we find the two junctions we are making use is at the temperature of the atmospheric condition. Atmospheric temperature is the new junction temperatures, it's the same temperature. This condition is satisfied hence you find the voltage developed, thermo EMF developed in such circuits is no way affected in the earlier circuit where there is no such voltmeter. Also we find the law of intermediate temperature also holds good. The third material can be exposed to any temperature later, like this say T_4 it will not affect the EMF. Here you find this third material is connected at one of the two junctions here at the T_1 junction, the new material is connected. This is what is made use of in the measurement of cutting tool temperature in a lathe.

The lathe head stock and the tail stock is here and the material is turned in between these two head stock and tail stock. If tail stock is a moveable one and this is head stock which is being rotated and when we have the cutting tool somewhat like this, see this is the hot junction. This temperature is made, this is to be measured. Normally the cutting tool is made up of high speed steel, the material may be mild steel. So two different materials so it is analogous to two different elements and the cutting point is junction. Then away from the cutting point we take another slip ring, some somewhat like slip ring arrangement and we have the brass contact and with a spring loading and this also we take one point from there, between these two we connect a voltmeter and is analogous to this one.

This T_1 is the temperature that is this is at atmospheric temperature, this also atmospheric temperature away from the cutting tool, between these two new junctions we are connecting a voltmeter by suitable mechanism that is slip ring and brass is a new mechanism. That means at the atmospheric temperature we connect the voltmeter. That is T_1 is split and made to connect a voltmeter. This is circuit what is made use of in the temperature measurement of cutting tool in a lathe for example. So that is our second one. The third law states the calibration of the thermocouple elements and we have got number of elements exhibiting this thermo EMF property and then suppose 10 elements means then permutation combination, you may get a number of combination with 10 elements, hundreds of combinations with these 10 various elements and calibrating each pair is very laborious and time consuming job.

So what is done normally is each material is calibrated with platinum. Normally platinum is one material, all other materials each time is taken with the platinum, one thermocouple is made and that calibration. That is EMF developed under different temperatures, one cold junction temperature being zero degree centigrade ice point. With cold junction temperature as ice point all elements are calibrated with the platinum that chart is already available. If you want to combine any two elements then from these calibrated chart we can easily obtain the characteristic without doing actually the full calibration that is what is explained as the third law.

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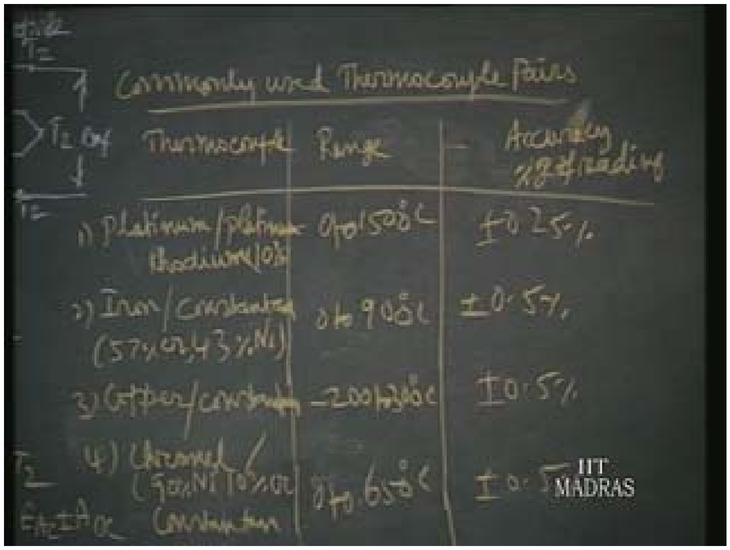

First you find the thermocouple is made up of material A and C and the voltage EMF developed is EAC, if you recall. Similarly if you have got material C and material B with the same temperature T1, T_2, hot junction, cold junction temperature and if you call the thermal EMF as EBC, the C material is common in both that is the same as platinum. Platinum is the common material. Then if you have a pair between A and B thermocouple pair that EMF developed for that same T_1 and T_2 is obtained, EAB is given either addition of these two voltages or the difference between these two voltages what is written here and whether plus or minus how to locate it, how to fix that plus or minus at least one temperature. That is having this T_2 as zero degree centigrade you have to have one temperature in own temperature T_1 and find that voltage, for that two temperature differences whether by adding you get this voltage or by the difference between this you get the voltage, you can check (Refer Slide Time: 25:44).

Once you checked for one reading later you need not do the calibration, simply obtain this calibration curve, from other points for calibration from these two standard charts. So that is the calibration procedure is made simple by the third law. The fourth law states the cold junction temperature need not be always zero degree centigrade, it can be any other temperature. Preferably the atmospheric temperature so that is explained like this. Suppose we have the thermocouple pair A and B, first the EMF developed between T_1 and T_2, T_1 is these two temperatures of the junctions. T_1 and T_2, T_2 is larger than T_2 if you call that voltage develops as E_{T1T2} and then the same pair when it measures between T_2 and T_3, the same thermocouple pair. If you call it E_{T2T3} then voltage developed in T_1 and T_3 will be equal to that is E_{T1T3} that is here T_1 this is T_3 this junction, same pair thermocouple pair. That is E_{T1T3} is equal to E_{T1T2} plus E_{T2T3}. That is mostly will find your T_2 is your atmospheric temperature.

So we measure having atmospheric temperature as the cold junction and then the T_3 is the higher temperature that voltage we measure it and from the chart for the A and B material combination you can get from T_1 to T_2 what is the voltage. Add these two voltages then you know the total EMF developed for a temperature difference of T_1 and T_3. So corresponding to the temperature, what is the temperature T_3 you can find out.

That is how the fourth law is made use of that is the cold junction temperature is not always zero degree centigrade, it can be any other temperature. These are the four laws normally used in actual practice and you find even though there are many material exhibiting the thermocouple property, in actual practice we find some 5 pairs 1, 2, 3, 4, 5 pairs. These are the 5 thermocouple pairs are often used in measurement.

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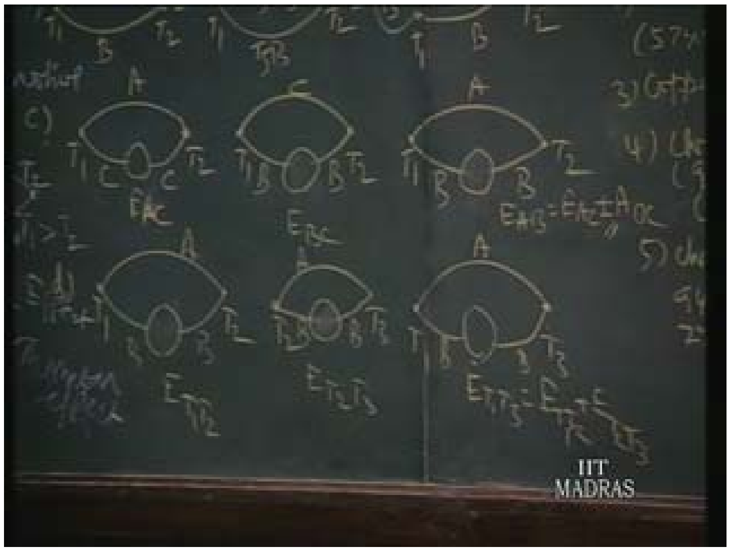

First one is platinum and platinum rhodium, wire A may be platinum, wire B is platinum rhodium alloy. I have given some percentage, this is 10% of the rhodium, 90% platinum and 10% rhodium then it is called platinum rhodium alloy. Such a percentage is made use of zero to 1500 degree centigrade and it is more accurate than the other pair, we find 0.25% of the reading. Among the available thermocouple pair this is least sensitive. That means for platinum rhodium for 1500 degree centigrade it develops a voltage of say about 15 millivolt that is what it develops from zero to 1500. The zero degree is cold junction temperature, 1500 degree is the hot junction temperature then it develops around 15 millivolt. Whereas we find the copper constantan and chromel alumel it develops around 1000 degrees (Refer Slide Time: 29:45). For 1000 degree centigrade difference it develops around 50 millivolt. The other one chromel constantan for 500 degree centigrade 50 millivolts. It is more sensitive; iron constantan develops at 750 degree centigrade as a 50 millivolt.

So you find from these characteristics the copper constantan has got measurement range of around 350, up to 350 alone it is made use of and it develops at that temperature around 15 millivolt. So these are some of the values for this important thermocouple pair and in this you find the least sensitivity we have got platinum/ platinum rhodium but it is having very high accuracy I mean higher accuracy than the other pair. It is because even in oxidizing atmosphere the platinum is the most inert material, it doesn't get contaminated whereas you find the copper constantan can be used only up to 300 degree centigrade, 300 or 350 that this range beyond that the copper gets oxidized. So we cannot that then the calibration is lost. It is supposed to be pure and homogeneous material so when it is contaminated beyond 300 degree or 350 degree centigrade then you cannot make use of it.

So it is a very least range and another important point is at higher temperatures say around 1000 degree centigrade and all or above that or around 1000 degree centigrade if there is inert atmosphere, I mean if there is some oxidizing atmosphere, the thermocouple wire absorbs the nearby materials. Normally we find the thermocouple wire is put in a protection tube somewhat like this and here we have the thermocouple wires. Thermocouple wire is taken like this, we have got a cover and then it is taken. So it is called production tube made up of iron. So it is to protect the junction otherwise you will find the, some fluid gas flowing. If you want to find the fluid gas temperature some dust and all may contaminate, may fall on the wire and it may get contaminated and it may change the calibration character. So it is in the pipeline so it is just inserted in pipeline and that is production tube and at say 1000 degree and all then you find this material absorb some of the material nearby in the vicinity if you have got any metal it is also absorbed.

So beyond 1000 degree centigrade we have to be careful that the wire doesn't get contaminated or when it absorbs such foreign material that calibration gets changed. So that is how the actual usage of thermocouple should be taken care of. We have seen that in thermocouple the output voltage in a single thermocouple is in terms of millivolt and it is common practice to increase sensitivity, a number of such thermocouples are joined together in series and then they are used as thermopile that is what is called thermopile.
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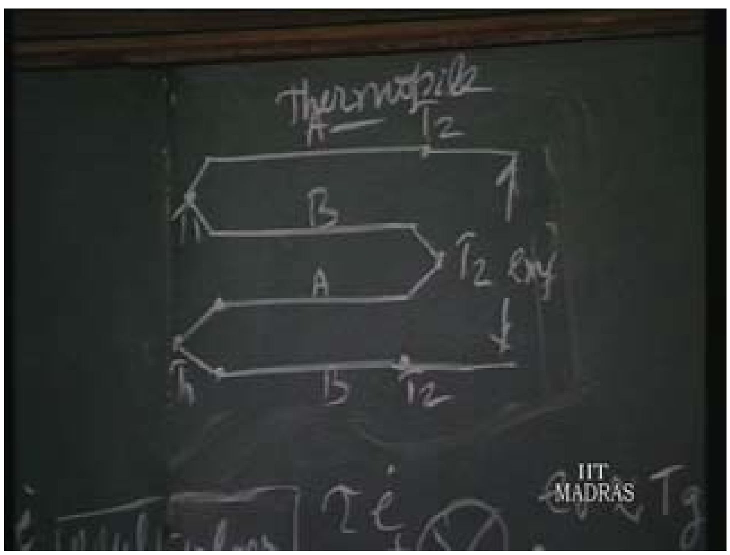

It contains more than one pair of thermocouple elements. Here we have got two such pairs and this is hot junction, the cold junction is say atmospheric temperature. So you have got two such junctions so the net voltage, net EMF output is twice the output for a single… (Refer Slide Time: 00:34:02). So this wire A, this is wire B so two pairs are used, this is hot junction actually it is only for clarity sake I have drawn apart but otherwise you will find these two things very near and they are put over a surface and between the atmospheric temperature and this you will have the difference, voltage is develop and that voltage will come, that is twice the voltage of single thermocouple element. Here I have shown only two, you can have 3, 4, 5 or 6 any such pairs can be connected in series in the same way and you will find 6 means 6 times the voltage of the single pair. So these are available and they are called thermopile, it is only number of thermocouple elements put together.

Naturally the thermocouple wire can be used only when the temperature of measurement is lower than the, I mean melting point of the one of the thermocouple wires, lower melting point of the, we have got two elements. One element will have a lower melting point so the measurement temperature should be less than that element, that is the limitation. Suppose the temperature is high, that one of the thermocouple wire may be melting under the temperature then you can adopt any one of these two following techniques.

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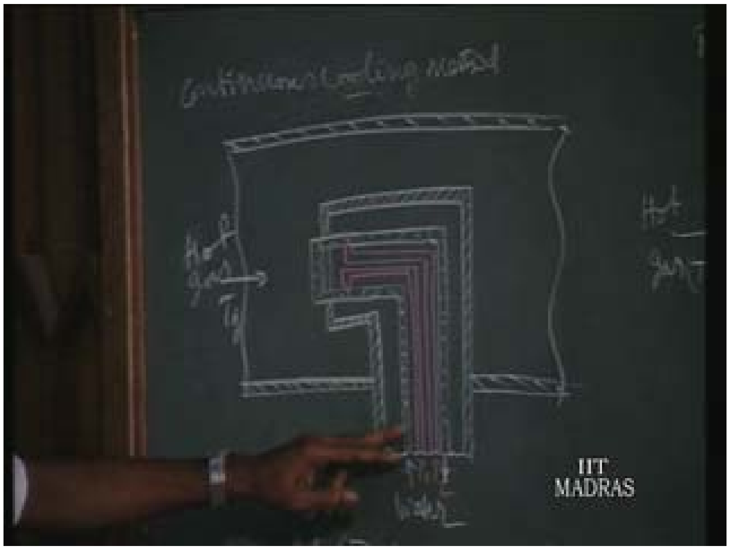

So measurement of higher temperatures higher than the melting point of one of the wires can be measured by adopting these two techniques, any one of these two techniques. That is called continuous cooling method; the other one is called pulse cooling method.

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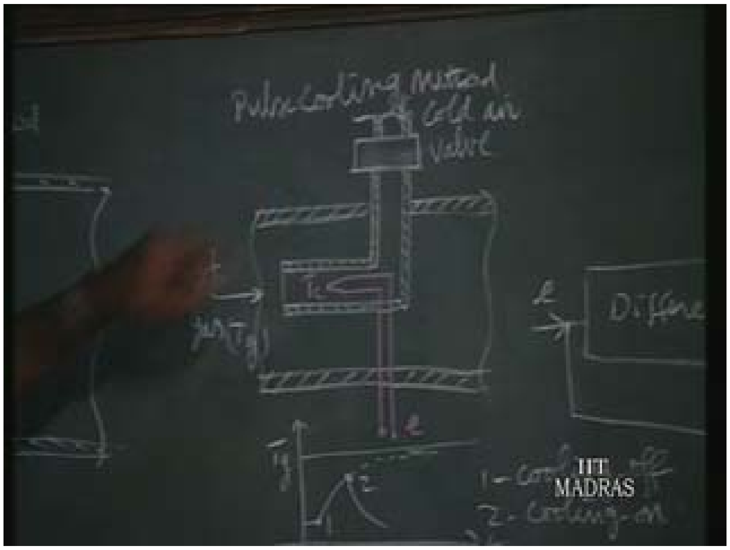

These are the two methods available. First the continuous cooling method, we have a pipeline carrying the water that is a part of its passage is exposed to the hot gas coming, this hot gas temperature TG is very large, and it may melt the thermocouple wire. So what is done is thermocouple wire is made use of to measure the inlet water temperature, water is coming here inlet water temperature at this point just before entry and later on the hot gas transmits the heat to the water in this area, cylindrical area of say area A, area A is the cylindrical area through which heat is flowing into water. So water gets heated up and coming out water from this section will be having higher temperature. So these two temperatures, inlet temperature before this heating shown and outlet temperature from the heating shown are measured by using the thermocouple wire. That is T_1 and T_2 which is very low value, so this is what is measured from this measured temperatures you can compute the hot gas temperature.

Once you know the heat conducted through this area A is equal to heat taken by the water. This is per second, so you find this mass flow rate of water per second and C_p is the ratio of the specific heat of water and T_2 is the high temperature of the water and the incoming temperature of water and A is the circular area through which the heat is conducted, h is heat transfer coefficient, heat transfer coefficient is having watt per that is joule per second joule per second or that is watt per meter square per degree centigrade per second. So that is how this kilogram per second and here also per second unit is there and T_g is the gas temperature, T_2 is the output temperature of water.

So that heat is conducted between temperature difference of T_g and T_2, so that is heat conduction that is equal to heat gain by the water flowing, they are equated. From this you can measure m is known by measurement and the T_1 and T_2 are measured by having the thermocouple and A and h and all constants available. So we know the unknown temperature T_g. This is the continuous cooling method and we have got another method called pulse cooling method, in this we have pipeline carrying the cold air and the hot air just in a pipeline thermocouple is situated. So normally the cold air is allowed by the wall and cold air is at a higher pressure it will be flowing from the inner pipe to the main pipe. So that you will find the thermocouple junction is always at the smaller temperature. That is this is the temperature, smaller temperature $T_{c1}$for example. It is much less than the hot gas temperature.

Suppose if you want to measure the hot gas temperature what you will do. Close the valve, immediately this hot gas will enter into this support pipe and the junction temperature will start rising. We know this is a first order instrument in a temperature measurement instrument first order instruments. So they follow this differential equation, tau is the time constant of the thermocouple element and rate of rise of the temperature plus the temperature that junction temperature is equal to T_g. this is the first order that is (tau D plus 1) x_o is equal to k times x_i, this is standard format. Here if you substitute for T_c is e by k, you can also instead of T_c you can write e and this is also you can write e because the voltage, the thermo EMF is proportional to T_c and here you can write kt_g. So you find it is a typical first order instrument.
So the temperature starts increasing exponentially, we know the equation is equation exponential equation. Output voltage is given exponential it is an exponential function. So it starts increasing. But before it reaches this gas and temperature at which one of the wires may melt, you again allow the cold air and here that point one cold air is cut and it starts rising before reaches melting point, we again opened the cold air so now cooling is on.

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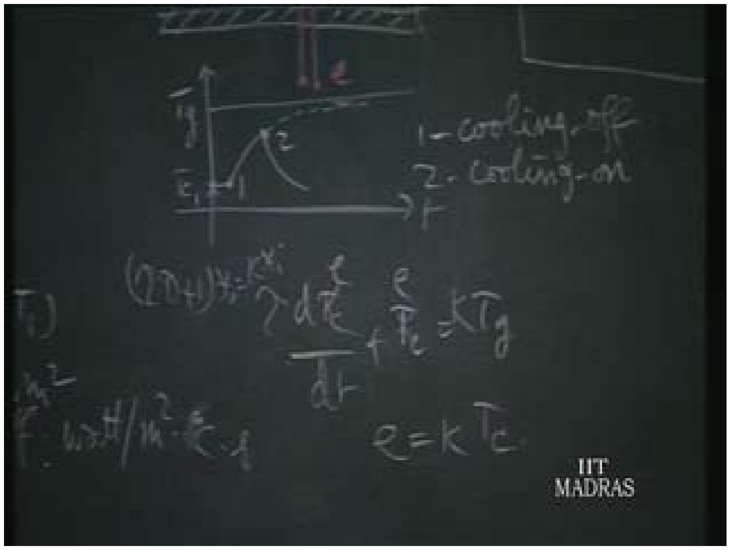

Then later on it starts reducing temperature but from these characteristics we can gauge, we can get this, using this equation we can find out the hot gas temperature. That is we realize this mathematic equation in this circuit that is e is proportional to T_c or de by dt, e we have got output voltage and through differentiator we get the e dash, that is multiplied by the tau.

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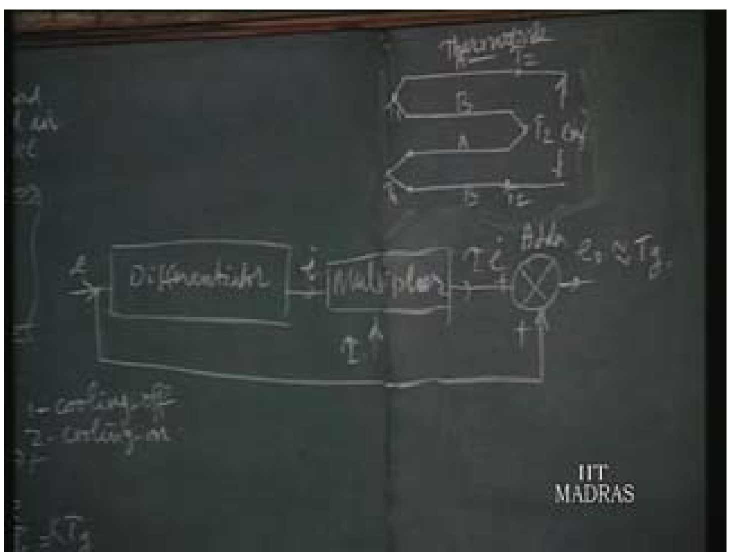

So proportional to the time constant of the circuit, of the thermocouple element multiply these two things and tau e dot plus the same e is taken. This is adder by adding these two quantities you will get e_o, that is tau e dot plus e that gives the proportionate quantity for the T_g, e_o is proportionate to T_g because k into T_g. So by having some known temperature you can find this e_o can be calibrated and later on you can use it for unknown temperature. So that is how the pulse cooling method is made use of to measure even higher temperature, higher than the melting point of one of the wires.