Principles of Mechanical Measurement
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Module – 10
Temperature Measurement
Lecture - 3
Expansion – based devices

Hello friends. Welcome to week number 10, where we are going to talk about probably the most common parameter that you can think about in any engineering application that is the temperature, and we are going to discuss about different methods of measuring the temperature. In fact, why only engineering, if we just forget engineering or forget science, if you just think about our normal day-to-day life or just think about the normal life of any common individual who does not have any relation with any kind of technical field, still he knows about the concept of temperature or at least he definitely makes use of the concept of temperature in some of his daily activities.

Like you definitely can remember that when you are a kid, the your parents may be your father or mother with a very worried look is putting up a small plastic below your armpit or below the tongue, just to check your body temperature, just to ensure whether you have fever or not. Or say the people who cook in our houses, the entire idea of cooking is just to heat the food stuff to a particular temperature, and maintain that temperature over a particular period of time to ensure that your food is properly cooked.

Things like about a pressure cooker there. The entire idea of pressure cooker is to increase the pressure inside the container, so that we can maintain a higher saturation temperature inside that. As the pressure increases, saturation temperature of water also increases. Like under common atmospheric condition, the saturation temperature of water is about 100 degree Celsius, whereas when you when you can make the pressure double, the temperature saturation temperature is approximately 120 degree Celsius. So, the entire idea of pressure cooker is to increase the pressure inside, so that we can maintain a higher temperature, and therefore we can boil the foods in a better way.

So, this way we can always make use of temperature or the concept of temperature in every day-to-day activities of ours. And that is why this is probably the most sought after parameter, most discussed or most employed parameter in any kind of human activities or I should say this is probably the second most sought after parameter, because time has to be the most sought after parameter that we have to make use of everyone needs to know about the concept of time for anything he or she wants to do, but then comes the temperature.

And that is why probably intentionally, you have kept this module towards the later part of this course, when you have already finished discussion about topics like pressure or flow or displacement etcetera. Mostly because you may already be knowing a few of the ways of measuring temperature, but I am sure I can introduce also several other ways of temperature measurement which will definitely be new, and you will definitely find that interesting.

Now, the before we will start, I would like to go for some initial discussion. Like we have been doing in all the previous modules, like in the topic of flow measurement, we started with some basic concepts of fluid mechanics, develop the analyst equation, because that is something that we made use of in the subsequent or discussions. In case of force measurement, we started with the discussion on the Newton's second law of motion or Newton's laws of motion. Similarly, we have to define the topic pressure, before we started pressure measurement. So, we shall be following the same approach here instead of directly jumping to any kind of instrument.

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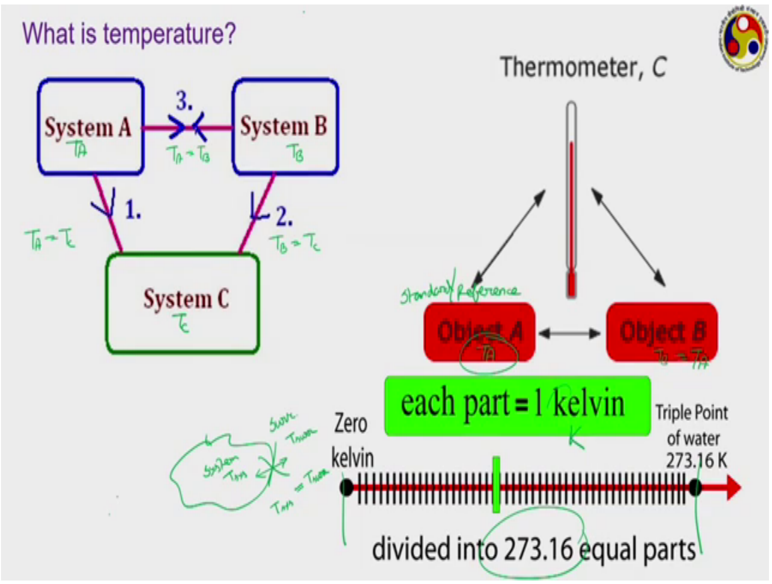

And that is why the first question that I would like to ask you is what is temperature? You definitely know what the temperature is, but can you define it. Because, the most commonly we define temperature is something like this is this feels hotter than the other one, and that is why it definitely is at a temperature higher than the other one.

Like suppose if I provide you two sticks, one this one, another this one. And if I ask you which one is at a higher temperature, probably we will try to just sense which one is feeling one more than the other. If this one is feeling one more than, you may be saying, that this is at a higher temperature than the other. But, that is a purely relative way of defining temperature and not a quantity one at all, because it may well happen that both may be at the same temperature, but one just feels warmer or cooler than the other.

Like you know very common example in a cold winter night, if you keep one metal stick, and one wooden stick outside throughout the night, and then in the morning if you touch them, then the metal one definitely feels much cooler compared to other one, despite both being at the same temperature. Both are exposed to the same environment for same duration of time, and therefore they must be at the same temperature.

However, the metal has an ability to transfer heat to your body much quicker or I should say in this case absorb heat from your body much quicker compared to the wooden one, and that is why that feels much cooler compared to the other despite the being at the same temperature.

Therefore, this relative way of defining temperature is not the perfect one, we must find a proper technical definition of temperature or at least some kind of scientific base based upon which we can define temperature. And that is not possible from any other laws of physics, rather we can define it only when we make use of the concept of the zeroth law of thermodynamics, I am sure you know about the zeroth law, but still I am repeating this one here to clarify the concept of temperature.

So, from the concept of zeroth law, we know that suppose I am taking three systems here like shown system a, b, and c. So, if our two systems will say a and c are in thermal equilibrium with each other, and similarly b and c are also separately in thermal equilibrium with each other, then a and b also has to be in thermal equilibrium into each other.

Now, what do you mean by thermal equilibrium, thermal equilibrium means there is no heat transfer that is taking place between the two systems or if I take just a single system like this, so this is your system, and outside the system you have the surrounding, because you know from thermodynamic point of view anything outside the boundary of a system is surrounding. And now if the system and surrounding are at the different temperature, let us say the system temperature is T sys, the surrounding temperature is T surr.

Now, if the system temperature and the surrounding temperature they are not equal, then there will be some kind of energy exchange between them, and that energy exchange we call the heat transfer, because heat is defined as the form of energy which can cross the boundary of a system only because of a temperature difference between system and surrounding.

Now, when these two those two temperatures are equal or I should say the system is in thermal equilibrium with the surrounding, then there will be no heat transfer at all. So, the concept of thermal equilibrium is related to whether there is any heat transfer taking place or not. There can be some other kind of energy-energy interaction between system and surrounding or even in terms of this example, there may be let us say the system C is the surrounding, and system A is the system.

Then if there can be some other kind of energy interaction, like work interaction or mass interaction, but the there if they are at thermal equilibrium, then there will be no heat interaction between them. Similarly, when B and C are in thermal equilibrium, then there will be no heat interaction between them.

Now, zeroth law says that if A and C are in thermal equilibrium, and B and C are also in thermal equilibrium. Then A and C must be also in thermal equilibrium, that is instead of taking A and B separately in contact with C. If we take A and B in contact with each other, then there will be no heat transfer between them, because they are at perfect thermal equilibrium. And when that is possible, I have already mentioned that is possible, only when this system and surrounding or in this case system A and B are at the same temperature.

So, then how we can define temperature, temperature is a property which defines whether these two systems are in thermal equilibrium in the or not or in a way you can say that one system A and B are in thermal equilibrium, then the property which is equal between A and B is temperature. So, if the temperature of system A is T A, and that of C is T C, then they will be in thermal equilibrium only when T A is equal to T C, so that there is no heat transfer.

Similarly, if the temperature of B is T B, then B and C can be in thermal equilibrium, only when T B is equal to T C. Now, when yes both T A and T B are equal to T C, so T A and T B are must be equal to each other that is temperature. So, temperature is the property, which must be equal between two systems or maybe between a system, and it is surrounding in order to have a thermal equilibrium between them, so that there is no heat transfer at all. So, this is the zeroth law of thermodynamics, which defines the concept of temperature.

Now, instead of considering three different systems A, B, and C, if we replace this C with it with a device which is separately in thermal equilibrium both with A and B, then that provides us a way of measuring the temperature. And that is the entire idea of thermometric, which is where we have object a or system A, and system B, and the C is a thermometer which is actually temperature measuring device.

Now, here I would like to clarify one term, the term thermometer does not refer to only that glass tube that you kept on using from or you kept on seeing from your childhood. Thermometer refers to any device which can measure temperature, so that glass tube that is that mercury filled capillary tube that is only one of the examples of a thermometer which have a specific name, and we shall be talking about that later on today. But, thermometer the term thermometer refers to any temperature measuring instrument.

Now, let us replace the system C with the thermometer, then if A and C are in thermal equilibrium, and separately B and C are also in thermal equilibrium, then A and B must be added separate must be at the same temperature. Now, if we know the temperature of this object a T A, but you do not know the temperature of T B, then what we are going to do? If that if we take the thermometer C in contact with temperature A, and the reading that we are getting that we are defining as this T A.

Now, if we take this in contact with its object B or system B, and if we get the same reading, then the temperature of this one must be equal to T A, so that is the idea where this A acts as the standard or you can say acts as the reference, where B is the subject of measurement, and thermometer is the measuring tool. So, the entire idea of the thermometry starts with this zeroth law of thermodynamics.

Now, what is the unit of temperature, there are several scales of temperature, but the SI unit of temperature, you know is Kelvin. Kelvin is defined as actually this graphics has a little bit of error, this should not be small kid has to be capital K, because that unit of temperature is called Kelvin or SI unit of temperature is called Kelvin to honor the great scientist lord Kelvin, and that so this K has to be capital one.

Now, the unit for temperature is Kelvin, which is defined as the distance between the absolute 0, and the triple point of water by twenty 273.16 number of equal parts, then the division or each subdivision is called 1 Kelvin that is triple point of water which is an universal constant is given the value of 273.16 Kelvin and absolute 0 is given a value of 0 Kelvin. And correspondingly, whatever you are getting that is 273.16 Kelvin.

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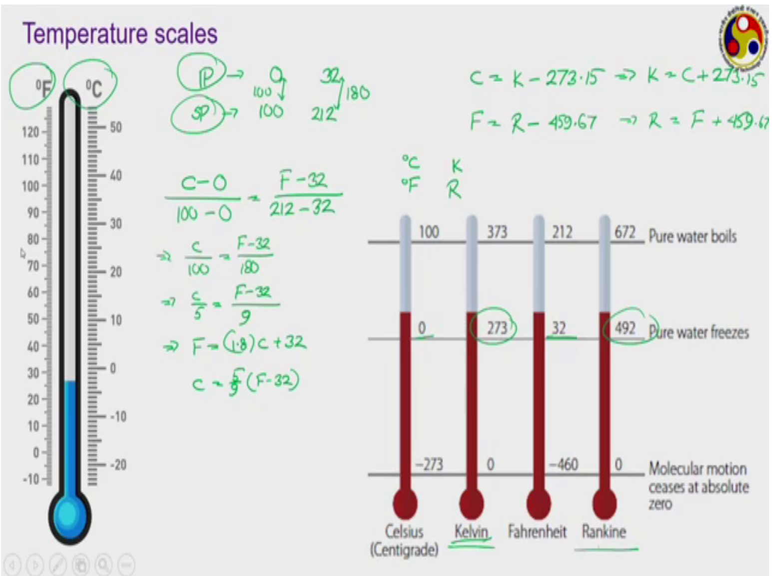

We shall, but there is not the only scale, there are several other scales also. Like the very common one Celsius and Fahrenheit scales. The term Celsius scale is based upon the name of its inventor, the French technician or this Celsius, whereas the Fahrenheit scale is in the name of the German inventor Gabriel Fahrenheit, who were the persons to propose this more or less at the same time or around the same decade in early 19 century.

Now, both these two temperature scales has something in common. In both cases, we need to specify two standard reference point that is why, they are often called two point temperature scale. We need to specify the reference value or some value at two points. And the common choice for these two points are one is called the ice point, ice point refers to the point at which or the temperature at which under atmospheric condition water starts to condense or in the reverse, we can say the steam starts to melt. So, in Celsius scale ice point or the melting point of water is given a value of 0 Horize in Fahrenheit scale, let us given a value of 32.

Similarly, the second point is called the steam point. Steam point refers to the temperature at which normal water or I should say water under atmospheric condition starts to boil or the liquid to vapor phase conversion for water under atmospheric condition starts that temperature is called steam point. Now, in Celsius scale, we call the steam point as 100, and in Fahrenheit scale, we call that 212. So, in Celsius scale the distance between the ice point and steam point is 100 units, whereas in Fahrenheit scale, the distance is 180 units.

So, what we do in either scale, we specify the ice point and the steam point with the corresponding values, and then the distance between these two that is 100 unit in case of Celsius scale, and 180 units of Fahrenheit scale, they are given equal divisions. We hardly go for calibration at some intermediate temperatures like we hardly take any reading at 20 degree Celsius, 40 degree Celsius or maybe 100 degree Fahrenheit, we rather just make equal divisions which may always not be true depending upon what kind of scale you are using.

Now, one thing you have to remember here, the choice of these values are completely based upon us that is the value of 100 specified to the normal boiling point of water or saturation temperature of water and 100 degree Celsius that under atmospheric condition that is our choice. We could have easily called that 1000, there is a nothing to stop us or you can easily define a new temperature scale, and give it your name.

And where you are going to specify the you may specify the ice point to be given a value of 100, and the steam point to be given a value of 0. And you are coming in the opposite direction means as the temperature increases, the value will decrease in this. There is no harm in that this will again be a perfectly correct thermodynamic temperature scale as long as you can make equal division between the two. But, this all these are two point temperature scale. There is also something called the single point temperature scale, but I shall be coming back to that later on.

When the idea of two point temperature scale, I repeat is to specify two reference point, and the common choice for reference points are the ice point and steam point. And in every temperature two point temperature scale; these two are given some values. And all the intermediate values or all the inter intermediate range is divided into equal subdivisions. The Celsius scale earlier used to be called the centigrade scale, because we are using the value 100 the some resembles to that, but from 1948 onwards the term centigrade has been dropped, and we use only the term Celsius.

Fahrenheit scale probably, you have what is the one, we were introduced to entry or introduced for the first time, because the medical thermometers which we use commonly for measuring the body temperature are generally given in Fahrenheit scale, where the standard body human body temperature is around 98.4 degree Fahrenheit, whereas the range is commonly a specified something like 92 to 110 degree Fahrenheit or maybe 95 to 100 degree Fahrenheit. Generally, below 94, 95 degree Fahrenheit and above 106 degrees Fahrenheit, it may become fertile for human body. In Celsius scale as it is shown this degree Celsius is the unit, but in case of finite scale it is degree Fahrenheit.

Now, how we can develop a relation between them, something a very school level stuff. As we are taking equal division between them, so you can go for a linear interpolation. So, in case of Celsius scale, if any temperature is given as C, then C minus the ice point temperature that is 0 divided by steam point temperature 100 minus ice point temperature that will be equal to if the corresponding temperature in Fahrenheit scale minus corresponding steam point value or sorry ice point value which is 32 divided by steam point value 212 minus ice point value or in the denominator, you can also visualize this one to be the number of divisions.

So, it becomes C by 100, because there are 100 divisions between the ice point and steam point in Celsius scale is equal to F minus 32 by 180, as there are 180 divisions in case of Fahrenheit scale or if we simplify, it becomes C by 5 is equal to F minus 32 by 9 a very well-known relation which you must have used earlier or any value in Fahrenheit scale, therefore Celsius being much more common nowadays.

So, if we want to measure any Fahrenheit value, then F will be equal to 1.8 times C plus 32 or if our interested in the C value, then C will be is equal to 5 by 9 into F minus 32. So, this way we can convert between either scales. But, Celsius and finite scales are not the only one, there are also absolute temperature scales which are which can be visualized as extension of these scales only, however practically speaking there different temperature scales.

If we extend this one to include two more scales, where we have the Kelvin which can be visualized as an absolute temperature scaled absolute temperature extension of Celsius, whereas we can have Rankine, which is the absolute extension of the Fahrenheit. So, in case of Celsius scale the as I have mentioned the ice point is 0, and that is 32 in case of Fahrenheit scale that is given as the value of 273 or to be more precise 273.15 in case of Kelvin. And 492 or to be more species, it is 491.67 in case of Rankine scale. And then corresponding the remaining extension, we can do in both higher side and lower side.

So, if we want to derive a relation between Kelvin and Celsius scale, any reading in Celsius scale will be the corresponding value in Kelvin scale minus 273.15 or the value in Kelvin scale will be equal to C plus 273.15. Similarly, any value in Fahrenheit scale will be equal to our corresponding in value Rankine scale minus 459.67 or the value in Rankine scale will be value in Fahrenheit scale plus 459.67. Actually, is Kelvin and Rankine scales are called single point temperature scale, why they are calls that that we shall be discussing shortly. But, whenever you are talking about in single point temperature scale, generally the degree symbol is dropped. Like two point temperature scales, we use the units as degree Celsius and degree Fahrenheit.

However, in case of single point temperature scales or absolute temperature scale, we use only K to denote designate Kelvin, and only R to designate Rankine. So, these are the most common temperature scales that we can think of however as I have mentioned, you can easily define any two point temperature scale by choosing your own values of ice point and steam point, your own values at ice point and steam point, and then taking equal number of divisions in between two. Then subsequently you can extend in either direction that is below the ice point or above the steam point just following the same pattern of the subdivisions.

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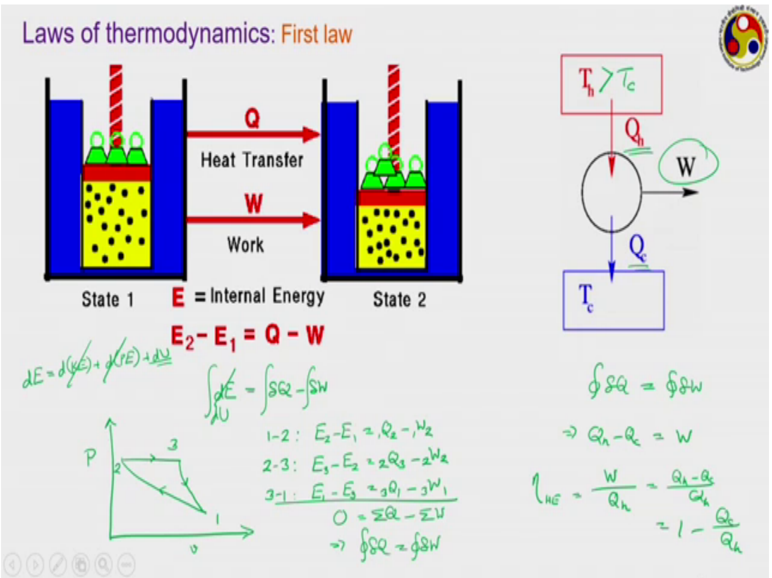

Now, we started with the zeroth law of thermodynamics, let us extend a bit more in terms of thermodynamics. And let us talk about the first law of thermodynamics. Now, first law of thermodynamics tells that the change in internal energy of any system, during a particular process depends on the net introduction will gain system and surrounding.

If Q is the amount of net heat interaction, and W is the amount of network interaction is taking place, then corresponding change in internal energy will be will be the summation of these two with the direction being taken into account or in differentially, we generally write in differential way we generally write dE that is change in energy of the system during an infinitely small process will be equal to del Q minus del W, where del Q is the amount of heat transfer to the system, during this infinitely small process. And del W is amount of work done by the system that is work transfer from system to our surrounding, during the same process.

And this is during a particular process, if you want to analyze a system, then we have to do this for an entire system, and sum all of them up like think about a particular cycle, let us plot that on any property diagram. Let us say we take a pv diagram. So, we pick up any standard process; let us say our process initially starts with a compression process starting from 0.1, and going to 0.2 which is at a much higher pressure and low volume. Then we have a constant pressure that is isobaric expansion process, during is pressuring is constant where volume increases to 3. And then we have another process, during which the systems comes back from 3 to 1.

So, now if we want to apply the first law of thermodynamics on this particular process, then integrating this particular relation over each of the processes, we can write during process 1 to 2, we can write E 2 minus E 1 is equal to Q 1 2 minus W 1 2 or Q 1 to refers the amount of heat interaction that is the amount of heat transferred to the system, during this process 1 to 2. And W 1 2 refers the amount of work done by the system, during this process.

If the direction of heat transfer work transfer are opposite to the one that we are considering, then you have to put a minus sign. During process 2 to 3, you have E 3 minus E 2 is equal to Q 2 3 minus W 2 3. And then during 3 to 1, you have E 1 minus E 3 is equal to Q 3 1 minus W 3 1. Now, if we add all of them up, then you have 0 on this side is equal to summation of all these Q's minus summation of W's or you know we generally conventionally write them as cyclic integral del Q is equal to cyclic integral of del W that is net heat transfer to the system over a cycle is equal to net work done by the system over the same cycle, as E that is energy is a property.

Here mind you this E or energy actually is the talks about the total energy content of the system, we generally has three counterparts, two macroscopic part, and one microscopic part. Macroscopic part in the form of change in kinetic energy plus change in potential energy, these are the two ways system energy can change from a crucible point of view plus we have the internal energy which is a summation of all possible microscopic forms of energy.

Practical cases, these two may be extremely small compared to this one. In that case, you can replace this dE with dU. But, mind you this is possible, only when the changes in kinetic and potential energies are negligibly small compared to the change in internal energy or to be more specific you are talking about a stationary system. Stationary means, there is no change in kinetic or potential energies.

Now, in this first law of thermodynamics never talks anything about the temperature, it just talks about the heat and work interaction. But, that gives us one useful relation that we are going to make use of very shortly that is the concept of a heat engine. A heat engine talks about a system working over a cycle, during one part of the cycle it is drawing Q h amount of heat from a high temperature reservoir T h.

During another part, it is rejecting Q c amount of it to a low temperature reservoir kept at T c here, T h is greater than T c. And during another part, it is producing this work output W such a configuration is called a heat engine, when it is taking heat from a high temperature reservoir, converting a part of that to work output, and rejecting the rest to a low temperature reservoir.

Now, if we apply the form of the first law of thermodynamics on this cycle, then you have just seen that cyclic integral of del Q is equal to cyclic integral of del W. Now, there are two heat interactions shown here. So, accordingly, we can write Q h minus Q c, because Q h is added to the system that is positive, Q c is going away from the system, so that is negative as per our sign convention is equal to del W. There is only working one work interaction is shown which is being done by the system, so it is positive, so that is equal to W.

Now, if we want to define an efficiency of this heat engine. Efficiency is defined as work output divided by amount of heat added to get this work done. So, using the previous relation from first law, it is Q h minus Q c upon Q h that is 1 minus Q c upon Q h. So, the efficiency of heat engine can be derived just from the knowledge of these two temperatures without bothering about that I am sorry just from the knowledge of these two heat interaction Q h and Q c without bothering about the values of this temperature T h and T c. This one we can make use of in conjunction with the second law of thermodynamics.

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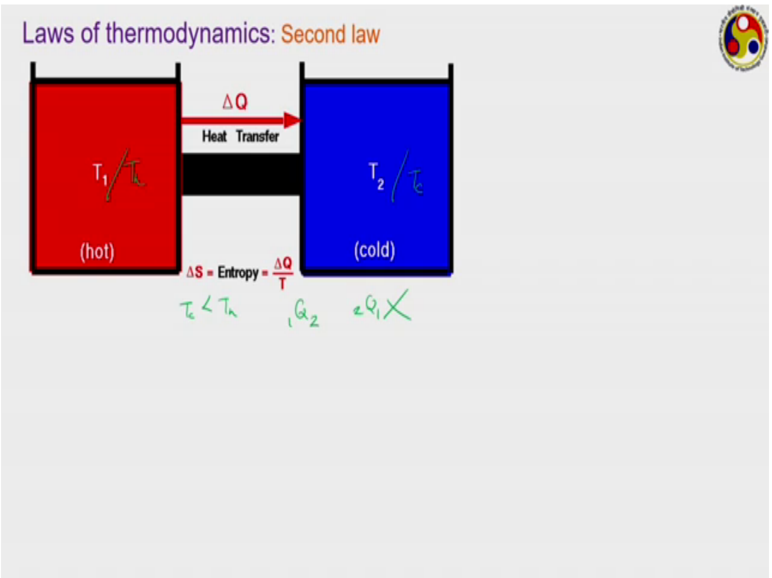

Now, second law of thermodynamics, and there are several statements possible from this, but there are two very popular statement, and out of which we are going to take the one that is generally called the more fundamental which is the Clausius statement.

According to the Clausius statement, it is impossible to transfer heat from a high temperature reservoir to a low temperature or sorry as per the Clausius statement, it is impossible for a cyclic device to transfer heat from a low temperature reservoir to a high temperature reservoir without any other effect that is without leaving any other mark on the surrounding, it is impossible to transfer heat from a low temperature body to a high temperature body over a cycle. During a particular process, it definitely is possible. But, when we talk about a cycle, it is not possible.

Like shown in this particular case, you have two bodies at temperature T 1 or maybe we take temperature T h just to be consistent in the previous slide. Every temperature T 2, say let us say temperature T c. So, some amount of heat transfer is taking place, and it is always said that if T h or rather T c is lesser than T h, then the direction of heat transfer will always be from 1 to 2 two two one heat transfer is not possible, unless we add some additional effects in the form of a heat pump or refrigerator.

So, the second law of thermodynamics gives you the direction of heat transfer. The first law of thermodynamics define sorry the zeroth law of thermodynamics defines the concept of temperature. Second law of thermodynamics is saying that there will be heat interaction between system and surroundings as long as they are in a different temperature, but it does not say anything about the direction of temperature which is given by the second law of thermodynamics, which says that the heat transfer will always be from the high temperature to the low temperature, just like shown in this particular case.

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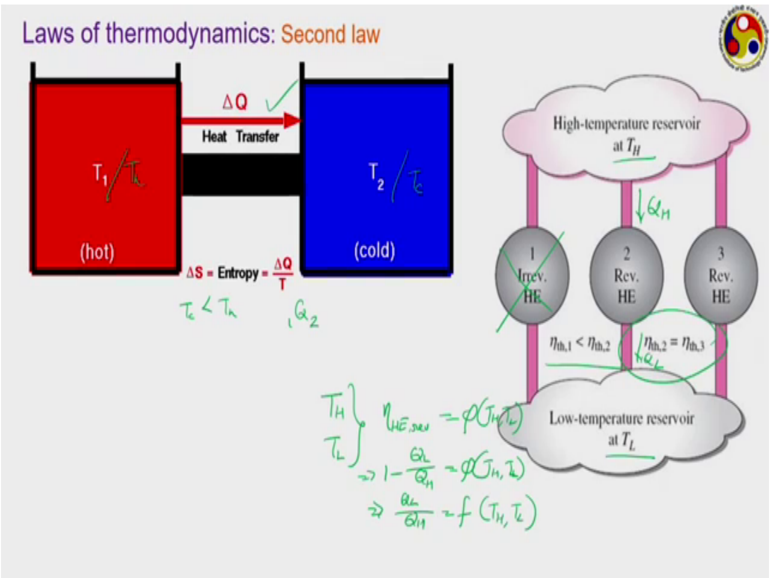

We do not need to talk about the concept of entropy here, but something else that we can add here that in the form of the corollaries of the second law. There are several corollaries possible from the second law, but we are interested in only two of them, which are more popularly known as the Carnot's principle. There are two Carnot principle. The in both the cases, we are concerned about one high temperature reservoir, another low temperature reservoir.

So, here the high temperature reservoir is given a temperature T H, the low temperature one is given a temperature T L. And for the moment just forget about this third heat engine, here we are involved with only two heat engine, one is engine number 1, which is an irreversible engine. And other is engine number 2, which is a reversibility. Both are working between the same temperature reservoirs. Then the Carnot principle says that, the efficiency of the reversible one will always be higher than the irreversible one or to put in more formal term.

The efficiency of a reversible heat engine will always be greater than the efficiency of an irreversible heat engine, while working between the same two temperature reservoir, so same two thermal reservoirs. So, there is a first Carnot principle, but here we are concerned about the second Carnot principle. Let us remove this one from our system, we have now two and three, both are reversible heat engines, and both are working within the same two reservoirs.

Then the second Carnot principles says that, the both of them will be having the same efficiency that is in more formal term the efficiency of any Carnot engine working between two given thermal reservoirs, any reversible heat engine or Carnot engine working between two given thermal reservoirs will always be the same.

Now, what does that suggest, here we are saying that once we are given with these two temperatures T H and T L, the temperatures of the two reservoirs. Then whatever may be the nature of your heat engine, corresponding efficiency of any reversible heat engine will always be some constant value, you cannot change by changing the nature of the reversible, cycle it will always be the same.

As long as the temperatures T H and T c are given, what does that suggest, then this efficiency has to be a function of only these two temperatures and nothing else. So, this efficiency is definitely a function of T h and T L or as per our the notation of an efficiency, we know it can be written as 1 minus Q L upon Q H, where Q L is amount of heat rejected to the reservoir temperature T L. And Q H is the amount of heat added that is this is Q H, and this is Q L.

So, this has to be a function of T H and T L that means, Q L upon Q H has to be some function of this two temperatures T H and T L, so that is something that we have to make use of to define something called the thermodynamic temperature scale or that single point temperature scale, which you roughly mentioned in the previous slides.

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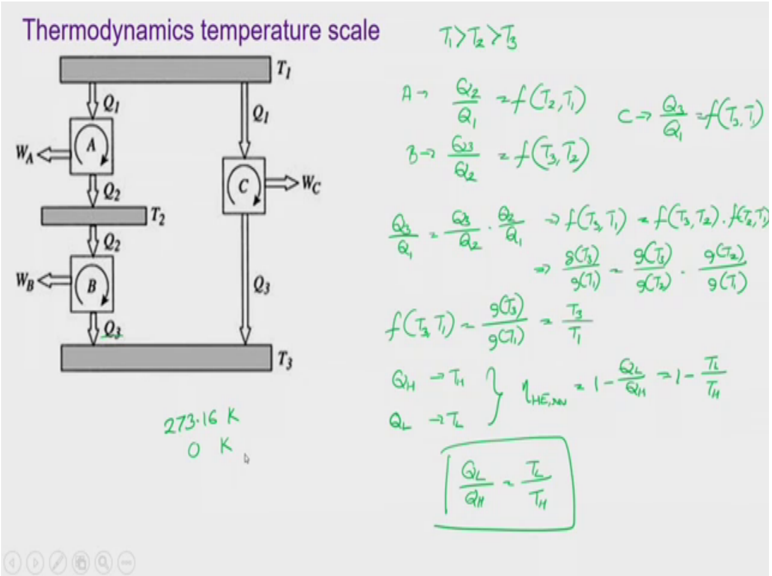

To derive the current expression for this function f, like here we know that the efficiency or corresponding ratio of heat interaction is a function of only the two temperatures. Now, we have to identify the nature of this function f. So, here we consider this particular situation, here we have three reservoirs one at temperature T 1 at T 2 and T 3, here this T 1 is greater than T 2 greater than T 3.

So, there are three engines also A, B, and C. A is working between T 1 and T 2 taking Q 1 amount of heat, rejecting Q 2 amount of heat to T 2, and for the producing W a amount of work. Now, B is working between T 2 and T 3, taking the same Q 2 amount of heat which was reacted by engine A, and finally giving Q 3 amount of heat to reservoir at T 3 and giving W b amount of work. And look at C, it is working directly between T 1 and T 3, taking Q 1 amount of heat, and rejecting Q 3 amount of heat to produce work W C.

Now, how we can say that this both of them will be equal to Q 3, because this two engines together can be replaced by a in common engine in that which is working within the reservoirs T 1 and T 3 or in other way, we can come we can visualize engine A and B to be working together with each other or coupled with each other.

In that case this combined cycle or combined engine, definitely will be taking the when it is taking Q 1 amount of heat, then definitely will be rejecting Q 3 amount of heat, because all reversible engines will be having the same efficiency. And here A, B, and C all three are assumed to be reversible engines. So, both are rejecting, both B and C are rejecting, Q 3 amount of heat to the reversible temperature T 3.

Now, as per the derivation that we have done in the previous slide, we know that for the engine number A, we have Q 2 upon Q 3 or sorry Q 2 upon Q 1 that is heat rejection by heat addition has to be a function of the corresponding temperature T 2 and T 1, the temperature between which this engine is working. For engine B, similarly heat rejected is Q 3, heat added is Q 2 that has to be a function of T 3 and T 2. And for the engine C, which is working between T 1 and T 3, then heat rejection which is Q 3 reversible by heat addition Q 1 has to be a function of what, has to be a function of T 3 and T 1 is not it.

So, if we combine them Q 3 upon Q 1 is equal to Q 3 upon Q 2 into Q 2 upon Q 1 that is functions of T 3, T 1 is equal to functions of Q 3 upon Q 2 is a function of T 3, T 2 into function of T 2, T 1. Now, look at this expression quite carefully. This expression says that the left hand side is a function of only T 1 and T 3. However, the right hand side we have a product of two functions; one is the product of T 3 and T 2, other is a function of T 2 and T 1.

But, the left hand side is not a function of T 2, then when that is possible that is possible only if this function f is a form something like g of T 3 by g of T 1 is equal to g of T 3 by g of T 2 into g of T 2 by g of T 1, only the f is a function of a function or a formula like this that is the numerator is the sole function of T 3 and denominator is the sole function of T 1 or in more formal term the numerator is a sole function of the lower temperature, and denominator is a sole function of the upper temperature or higher temperature, then only this is possible. So, we know that now, if T 3, T 1 is equal to g of T 3 by g of T 1.

Now, next question is what is the form of g? Now, there are several functions which can satisfy this, and our choice of function is completely arbitrary. So, we shall be going by what was suggested by lord Kelvin, he suggested a very simple form where is suggested to take this ratio as just T 3 upon T 1, which is the simplest possible definition. And that is found to be work perfectly for all applications of this principle, and therefore is always taken.

So, what we are getting then, we are having now the efficiency for a heat engine which is taking Q H amount of heat from a reservoir at temperature T H, and rejecting Q L amount of heat to a reservoir temperature T L form them efficiency of this reversible heat engine is given as 1 minus Q L upon Q H, and therefore it is 1 minus T L upon T H, which is known as the Carnot efficiency.

But, for our purpose of this temperature measurement, we are not interested about this we are more interested about this particular situation Q L upon Q H is equal to T L upon T H. It is not at all saying that the Q L is equal to T L, whether it is saying that the ratio of this to heat interactions will be equal to the ratio of the corresponding reservoir temperatures. And that provides something known as the thermodynamic temperature scale look at this, here we are saying that the temperatures of the two reservoirs are are the ratio of the temperature of the two reservoirs is just equal to the ratio of the corresponding heat transfer.

Now, think about the Celsius and Fahrenheit scales. They are we specified those 0 or 32 values based upon one physical phenomenon, which is the melting of ice under atmospheric condition. Now, in the pressure changes corresponding melting temperature will also change, and then we can idea we cannot identify that new melting temperature is 0, because the condition has changed that means, the definition or that of the references in those scales are dependent upon the properties of some fluid, which is not the case here.

Here it is it does not matter, whether there is some kind of phase change phenomenon going on inside T 1 or inside T 3 or something else. We are just directly getting that the ratio of these two heat interactions is equal to the ratio of the corresponding temperatures. And that is why, it is called the thermodynamic temperature scale, it is independent of the behavior of any material, and is an absolute relation.

However, we still need one final parameter to define the scales, because it is only giving us a ratio of T L and T H that is why, we generally take the triple point of water in Kelvin scale that triple point of water is given a value of 273.16 Kelvin. And of course, the absolute 0 is given a value of 0 Kelvin.

And then accordingly, we can we can put 273.16 number of each subdivisions between these two temperatures to get the Kelvin scale working i or you can say this absolute 0 actually are a true proper point which is independent of any fluid properties, and therefore that should not be mixed with the ice point or steam point. But, this is also a perfect parameter which does not depend, which is definitely the triple point of water, but it is again independent of temperatures and pressures; so, again absolute constant for this.

So, the different temperature scales which are defined based upon this particular principle, they are called thermodynamic temperature scales or sometimes called the single point temperature scale, because we just need one reference point like this particular one here for Kelvin or Rankine scales.

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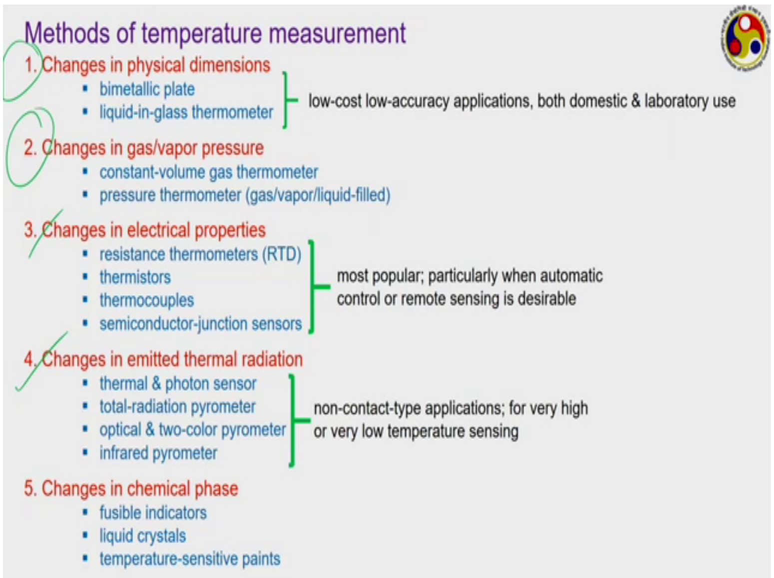

So, with this knowledge, let us move on to check out what are the different ways, we can measure temperature. The first method the more popular one or very popular one for domestic applications, that is the change in physical dimension something like the bimetallic plates or liquid in glass thermometer. Then change in gas or vapor pressure, constant gas constant volume gas thermometer, and pressure thermometer, which can be gas filled liquid filled or vapor filled.

Then we can talk about the changes in electrical properties, there are several very popular options like the resistance temperatures or resistance temperature detector RTD in short. Thermistors, thermocouples probably the most common technique used or common method for technical use, semiconductor-junction with sensors.

Then change in immediate thermal radiation, thermal and photon sensor, total-radiation pyrometer, optical and two-color pyrometer, and infrared sensors or infrared pyrometer. Changes in chemical phase, it is a much newer use, and not that much in industrial scale, but more at research scale like fusible indicators, liquid crystals, temperature-sensitive paints etcetera, all can be considered.

Out of all these five kinds of categories, the first one that is changes in physical dimensions, these are low-cost, low-accuracy applications. So, for domestic or for crude laboratory applications, we can always go for this. However, more popular one is the change in electrical properties like RTD, thermocouples etcetera very popular in industries, and also in scientific research. Particularly, when you are looking for automatic controller remote sensing, then we have to go buy something like this or more advanced option. And the changes in emitted thermal radiation that is a non-contact-type applications for very high or very low temperature sensing, we generally make use of them.

So, today let us check out, the first and second kinds. In the next lecture, we shall be talking about this third kind, shall talking about this third kind in the third lectures sorry second lecture. And in the third lecture, we shall be talking more about this particular one. But, today our focus is on this type A and B, which are more smaller discussions, and probably you already know about most of them.

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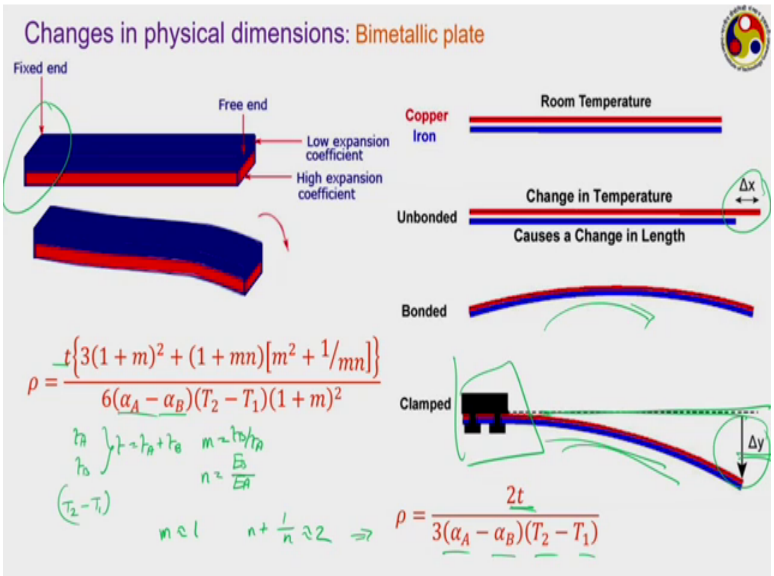

So, the first device that comes into mind is the bimetallic plate, which falls under this first category that is changes in physical dimension. Here the idea is very simple, you have two plates, two metallic plates having different coefficient of expansion, and we couple them just like the just like shown here. They are fixed with the along the along the longer surface, but one of the end is also fixed of the one of the end of this combined bar is also fixed, and the other end is free.

Now, when the temperature changes their coefficient of expansion is are different, accordingly their modified lengths also will be different, but there is their strictly or their joined together strictly. Then it will be not possible for them to expand separately, so only way out is to get bend. Just shown here under room temperatures with examples of copper and iron, they are joined together, they are having exactly same dimensions.

Now, if they are not at all connected with each other, then copper is expected to have a larger thermal expansion with elevated temperature like this much higher increase in the copper length is expected. But, when they are bonded with each other, then of course copper cannot bend or cant increase length without affecting the length of the iron part. And therefore, what it does is it form a bend like this, just look at this one here definitely the red one is having as it is on the outer side, it is having a longer length compared to the blue one, which is on the inner side.

And we can also have a clamp type of situation to measure the amount of deflection that has taken place like it is fixed at one end, and the other end is free. So, it is bending and we are measuring the amount of deflection that has taken place, and that can really be referred to the modified temperature, because under standard temperature, calibration temperature, it was just perfectly horizontal like this. So, this angle is a measure of the deflection and subsequently a measure of the temperature.

Quite often the radius of curvature of after the bend, I mean I am talking about this particular curvature that is given by a relation like this. Here this t refers to or let us say t A is the thickness of bar A, t B is the thickness of bar B, t is the total thickness that is t A plus t B, and m is the ratio of the 2 that is t B upon t A. And n is the ratio of the corresponding young's modulus E B upon E A. And T 2 minus T 1 is the temperature range over for which we are doing this particular calculation. And alpha A and alpha B are the corresponding thermal expansion coefficients of material A and B respectively.

Now, there are several situations, when the thickness of t A and t B are generally taken to be same. So, in that case m becomes equal to 1. And it is also common design feature to have n plus 1 by n is equal to 2. When that happens, then this relation for rho takes a much simpler form, then we have rho equal to 2 t upon 3 into alpha A minus alpha B into T 2 minus T 1. So, this t generally is known, because there is a design parameter alpha A and alpha B are material properties. So, they are also known beforehand. So, we can measure the change in temperature T 2 and T 1 or I should say T 2 minus T 1, so that is how vibrating plates works that is a simple configuration, but there can be several possible designs of biometric plate.

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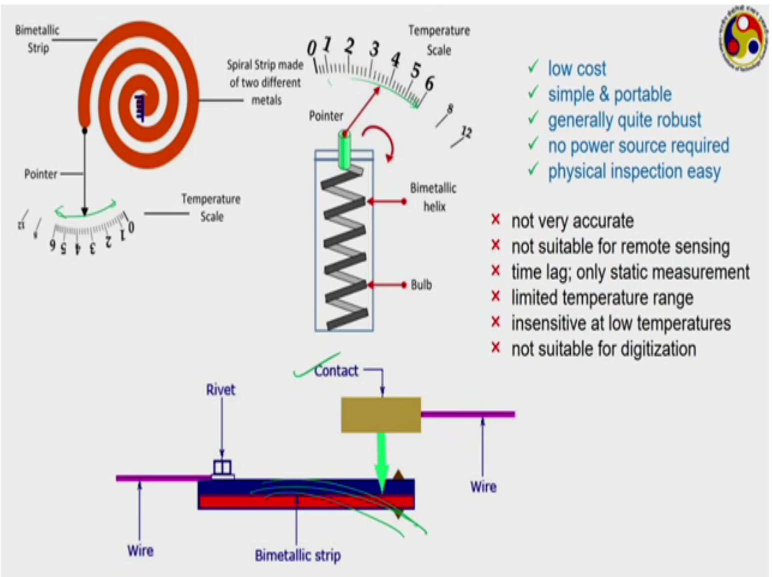

Like we can have a spiral type of design, where the center of the spiral is fixed and the phi end can expand, and can accordingly move over this particular scale. Another possible design can be a helix, where we have a bimetallic helix again because of the expansion, the because of the thermal expansion, the pointer can move over this particular side scale.

There are several advantages of such bimetallic thing like we can have a very low cost, simple and portable, we can always take them anywhere for measurement purposes generally are quite robust, and no power suits required which is a big advantage. And physical inspection is quite easy, because you are talking about a small device which simple machinery, but the problem is they are not the most accurate one, they are not suitable for remote sensing also. You need to take the scale or thermometer in contact with the surface, where you want a temperature measurement cannot give you measurement from some distance.

Time lag is there, because the pointer need some time to settle down at a particular location like the expansion or the bending, whenever itself may take some time. So, it is suitable more for static measurement. Limited temperature range, because temperature range is limited by the properties of these two metals; finally, insensitive to insensitive at low temperatures, and not suitable for digitization. So, while they can still be used for temperature measurement; but they are more popularly used for several other normal applications such as switches, something known as a thermostat.

In case of thermostat, we have a bimetallic strip, and we have this particular contact we have this particular contact, initially it is in contact with the metal strip. But, if the as a temperature keeps on increasing, the strip will get bend in this direction. Accordingly, disconnecting the contact beyond a certain point, and thereby stopping the flow of current through this. The application of such kind of bimetallic strip, you can find in domestic refrigerators, when they keep on following some kind of on up schedule. And also sometimes in old grandfather clocks, whereas the temperature fluctuates with the time of day or with the season, they can provide accurate measurement of the time without changing the or without changing the effective length of the arms.

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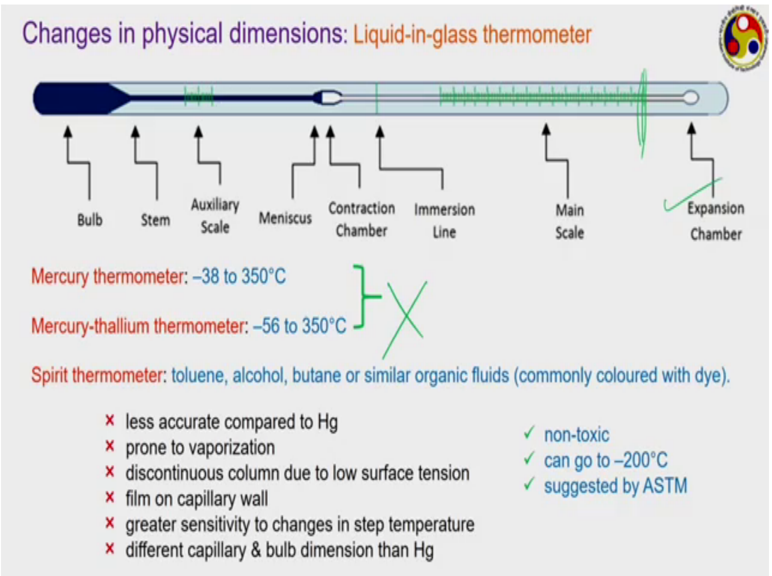

The other option very popular one or the most popular one that you know is the conventional thermometer. Something probably before this lecture, you knew as the term thermometer by the term thermo meter, but this is more specific name of this one is the liquid in glass thermometer, where we have a capillary filled cavity or I should say we have a capillary tube through which we have some kind of liquid temperature sensing liquid that can move up and down of the capillary tube.

The picture that I am showing that is having a horizontal orientation, but practical cases generally it is put in a vertical orientation, where we can see several components some of them are compulsory, where some of them are also optional. The first one is a bulb. This is the bulb which act as the storage of the fluid that we are using.

So, we generally have a very thin glass wall which should be thin enough, so that the fluid inside can sense the temperature of the surface in contact of which you are bringing this one. But, at the same time it should also be hard enough to sustains minor vibrations or minor shocks, the valve bus volume of the bulb needs to be carefully designed, so that it can how is just enough amount of fluid to enough to provide reading over the entire volume of the or provide the entire scale of this without overflowing the scale or without leading to any kind of overflow.

And the thermal expansion coefficient of the bulb, and the corresponding glass tube should also be compatible with that of the liquid. Then we have the after bulb, we have the steam the steam generally made of annealed glass depends on, and the property of the glass depends very much on the temperature range for which you are using like the scale that you are using for measurement of sub 0 temperature may not be suitable, when you are measuring temperature range of 200 or 300 degree Celsius.

The and also it is important to minimize the effect of thermal expansion, because you have to understand that as the temperature of the fluid changes, and its volume expands, similarly the volume of the glass also wants to glass also is expanding. And we somehow have to go for some kind of compromise or the coefficient of expansion for the glass needs to be arranged such that it is effect is minimal on the final reading. And that is what it is important to choose the material for the stream depending upon the temperature range of operation.

And also the portion, the void portion like here the dark portion refers to the liquid whichever you are operating with, and this empty void portion of the stream which is not contained in liquid at this particular moment, they should be pressurized by certain kind of medium, so so that it can avoid the column separation of the mercury column, and also avoid the vaporization of the fluid inside, when the temperature increases.

Then we can have an auxilary scale, this auxilary scale actually is an optional item. And this auxilary scale refers to a scale, which is well below the main scale this is the main scale. This particular one is a main scale, which is the zone of interest or temperature range of interest. The auxiliary scale is generally refers to a temperature will below the main scale temperature quite often used for calibration purpose, like it may refer to the 0 degree Celsius in case of Celsius scale which we may not be using on a normal operation purpose, but occasionally just to check whether the thermometer is working correctly or not. We may I would like to check this one with this auxiliary scale.

The meniscus refers to the separation part of or the liquid filled part and the void part of this, then we have this contraction chamber. This contraction chamber is again an optional item optional in a sense that, it is providing a slightly expanded volume within the capillary tube, so that we can manage the total volume of liquid that is going into the main capillary or towards the main scale.

Thereby somehow controlling the total height of the liquid column; this immersion line certain thermometers may also have the immersion line which is this one this, refers to the height up to which the thermometer must be immersed to get a proper measurement. So, if we are using this particular thermometer, then starting from this bulb up to this line, we want it to be immersed into the zone of application, and the rest part will be open to the atmosphere.

And finally, we have this expansion chamber which is a compulsory part, which is present in any thermometer. If there is a sudden rise in the volume of fluid, suppose we have used it for a temperature which is higher than this maximum range. Then thermometer will be expanding beyond the main scale and to arise that expansion, we provide this expansion chamber. So, there are several possible liquids that can be used, but most popular one definitely you know is a mercury thermometer which can operate over a range of minus 38 to about 350 degree Celsius, because mercury starts to feeds around minus 38 degree Celsius, and its boiling temperature is around thirty 350 degree Celsius.

So, when the boiling temperature is more or less ok; but the freezing temperature is quite high compared to several applications. We can lower this freezing temperature A bit, if we use a mercury thallium mixture, then it goes to minus 56 degree Celsius which can be sufficient for if you are looking for so with a temperature measurement in the (Refer Time: 56:08) of condition or in the toughest of conditions, but if you are looking for certain kind of cryogenic applications etcetera, this is still quite high.

Now, mercury thermometer is everywhere or I should say the liquid in glass thermometer, and mercury a thermometer synonymous because of such widespread application it has. But, the problem with mercury has several advantages of course, but the problem is mercury is it is toxic. And that is why several international organizations have nowadays recommended not to use mercury thermometer actually ASTM has given a recommendation or a restriction that it is not going to calibrate any mercury thermometer from now onwards. So, it may happen that mercury thermometer may become a staff for the museum in future, but may not be very near future just because of its wide availability and applicability and use of use.

Now, the option for replacing mercury, mercury-thallium composition or combination also has the same disadvantages. Now, the option for replacing them is can be a spirit thermometer, there can be several organic fluids or they toluene, alcohol, butane, they can also be options. One problem with them that they are opic in nature, so it may be difficult to observe their rise that is why, they are often colored with certain kind of dye red or blue color dye or very commonly used.

Spirit thermometer has several disadvantages. Before we talk about its advantages, we should mention the disadvantages. Like it is definitely less accurate compared to mercury, prone to vaporization, because they have lower boiling temperature, they can have their surface tension is low and there, so you may have discontinuous liquid column, thereby giving a wrong reading. They can form film on the capillary while coming down, and also there is sensitivity, they have a greater sensitivity to changes in step temperatures or I should say this should not be strip temperature, it should be steam temperature.

So, they have a greater sensitivity to changes in steam temperature, because the coefficient of expansion of most of the spirits like alcohol, and most of the common classes that is used there is not that big difference. And that is why, they are quite sensitive to the changes in the steam temperature, but they have certain advantages another advantage is the disadvantage I should say.

The dimensions of the thermo meter will be different compared to the dimensions of the mercury. So, we properly need to do the calibration, and also the calculation of the dimensions. But, the biggest advantage for them is non-toxic that is why that is what this coal over the mercury thermometer. They are lower temperature can be much much lower can go up to minus 200 degree Celsius, thereby making them eligible for several cryogenic applications. There is again another point of this core over mercury. And they have been suggested by ASTM; because ASTM has is not recommending or calibrating mercury or mercury based materials for thermo meter applications.

Another advantage that can be mentioned in this or I should say another advantage of this mercury thermometer that their cost can be slightly lower compared to the spirit based thermometer cost can be slightly lower compared to the mercury thermometer. Another possible alternative can be something conventionally known as the low hazard precision thermometers or low hazard precision LiG thermometer. LiG just refers to liquid in glass. Low hazard precision LiG thermometers, which can be a replacement of mercury based thermometers, they generally use some non-toxic biodegradable materials, but those materials are proprietary items of the manufacturers not clearly specifying the properties of this, but they may have a maybe a future option.

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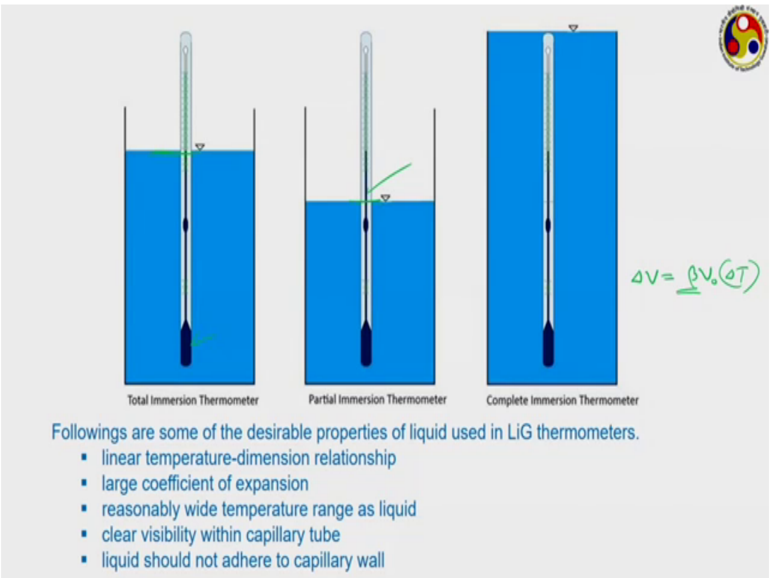

Now, another point that we have to be careful, while using this liquid in glass thermometer is the level of immersion, how much should we immerse this? There are three kinds of situations, we can have total immersion thermometer, where the bulb and the entire liquid column or that should be immersed. So, the only the meniscus, it should be exists lightly above the container or zone, where we are measuring the temperature, but entire of the bulb, and the liquid column should be exposed to the temperature which we want to measure.

This is probably the most common or I should say the most advantageous kind of thermo meter, most accurate option that we can have, but one problem is that how can we know how much should we immerse that will only come from the after getting the temperature measurement, and maybe going to a few trial and error. They are commonly used in constant temperature baths, where you want to maintain a constant temperature in some kind of liquid pool or container, this can be a good option.

Then partial immersion thermometer, where we have a line specified just like shown in the previous slide immersion line. This in every situation it is to be immerse up to see up to this height at least, there are several scenario, where the length of the thermometer may be more compared to the depth of the container, where we are looking for temperature measurements. So, it is not possible to go for total immersion, rather we go for the partial immersion. But, you have to ensure that the thermometer is immersed up to this immersion line.

And finally, we have the total immersion thermometer. In case of total immersion, the entire body of the thermometer is immersed; it is not a very common application. Thermometric fluids should have the following properties for making them eligible in LiG thermometers like linear temperature dimension relationship, so that we can have a perfectly linear scale. Like if we you probably know that the temperature expansion for any fluid delta l, the if instead of writing delta l if I write suppose delta V the change in volume of any fluid, generally can be given as beta V naught delta T, where delta T refers to the corresponding change in temperature, V naught is the initial volume correspond to some reference temperature, and beta is the thermal expansion coefficient.

Now, this thermal expansion coefficient may not be a constant is a constant a perfect constant, you are going to get a perfectly linear scale, but itself can vary with temperature, and similarly the glass cover also can vary with temperature. So, the thermometer scale should properly take care of this. Large coefficient of expansion, this is where the spirit thermometer a better, because their coefficient of expansions are much larger compared to mercury. And therefore, they can give much larger sensitivity.

Reasonably wide temperature range as liquid, this is none of the options that is mercury or spirits are good in this is because mercury has a reasonably high upper limit of around 350 degree Celsius, but the lower limit is quite high. Whereas, the alcohol based thermometers can go up to minus 200 degree Celsius, but they starts vaporizing in beyond 150 to 200 degree Celsius, and therefore they are not usable at higher temperatures.

Clear visibility within the capillary mercury scores over spirit, because mercury is opic and clearly visible within the capillary. However, alcohol is transparent and can be used only after, it is colored with certain kind of dye. And the liquid should not adhere to the capillary wall, which is again mercury better is mercury is a better mercury is better compared to spirits.

So, you can see that there are several points at least in terms of this one and this one, mercury is definitely better this one, mercury is better for higher temperature side. Alcohol is better in terms of this particular one. And that is why mercury thermometer is from more popular compared to the alcohol thermometers, but because of this toxic nature, you may see them completely out of market in the next 30, 40 years. These are thermal expansion based device; we shall quickly be talking about two more devices or another category, where we are talking using the changes in gas and vapor pressures.

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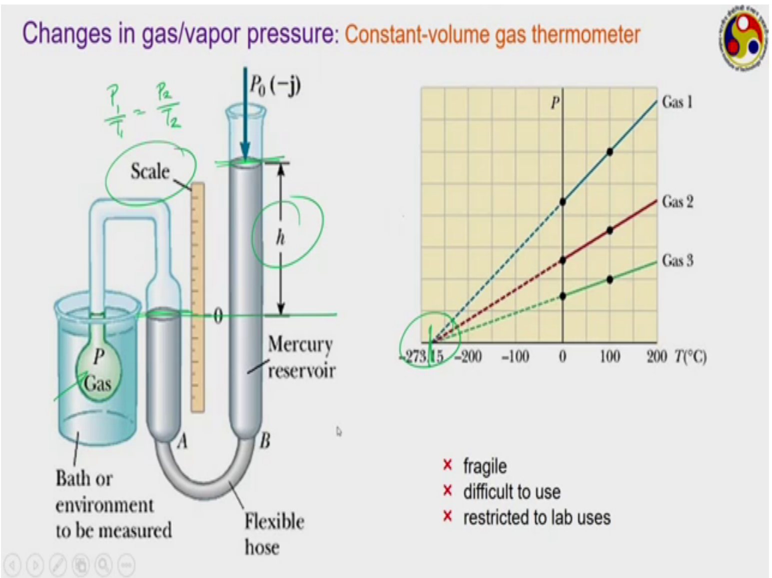

And the one that comes here is a constant-volume gas thermometer. This is something that uses the expansion of gas with temperature. Here we have a fixed mass of gas maintained in a particular container. Now, this once we come emerge this container into the environment or expose to the you want to measure the temperature, we make we keep the volume constant as the volume remains constant, then it is pressure has to increase because from if this gas follows the ideal gas equation of state.

We know that we have P 1 upon T 1 is equal to P 2 upon T 2, during a constant volume process. So, temperature will keep on increasing linearly with the pressure or conversely I should say as the temperature increases, pressure will keep on increasing linearly with this temperature. We generally have a mercury based manometer to keep provide us a reading of this increased pressure. This side is open to the atmosphere, and this side is subjected to the pressure inside this container. So, the difference in this mercury column is going to give you the value of the pressure inside, and instead of pressure you can mark this particular scale in terms of greatly in terms of temperature.

This constant volume gas thermometers are actually the ones that gave us the idea of the absolute zero. Because, if we do experiments with different gases, you can find for all the gases the x line extrapolating the negative temperature direction converge to a particular point, where the volume becomes 0 theoretically at least. Practically all the gaseous continents will below this temperature, however theoretically this is the temperature at which the volume of all gases will become zero, and that is the one we marked as the absolute temperature.

Now, constant volume gas thermometer, generally you is used as a reference for calibration purpose, but may not be for industrial use. Because, it is generally fragile again, you need to keep this one in contact with the body, where we want to get the measurement. It is quite difficult to use for practical purposes, and there so it is restricted only for laboratory purposes.

By the by I have not mentioned a space separate advantage or disadvantage for the liquid in glass thermometer, because those are quite similar to the bimetallic strips. So, you can just think about the same points that is they need to be brought in contact with the their advantage can be their small, cheap, portable, and quite well used, but disadvantage can be they can be frazzled. And they can they need to be taken in contact with the body, so not possible for remote measurement.

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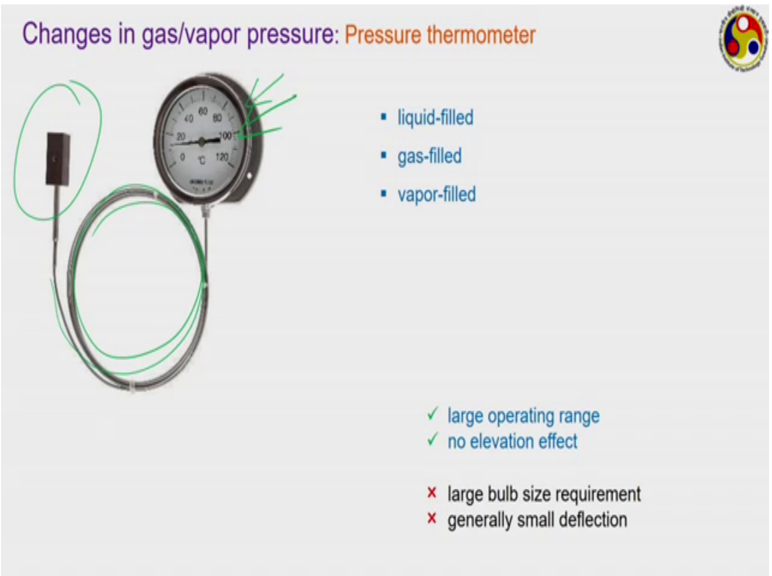

Now, constant volume gas thermometer has an improvement in the form of pressure thermometer, where instead of a con fixed container or a rigid container, we are having a chamber in within which we can have certain fluid. And as a temperature changes its pressure again changed its pressure, and that is sensed by this particular pressure measurement gauge.

Here the container is connected with a long tube, the length of this tube can be very very long even in the range of 100 meters. Thereby providing option of remote measurement that is this particular part can be kept at one location, and that team pressure measure learnings or the temperature sensor can be kept at a comic at a distance far away from this facilitating the remote measurement. We can have a liquid filled option, where the in medium is maintained specifically at liquid phase throughout.

Now, liquids are more incompressible in nature. So, as the temperature changes, the sensing will come more in terms of a change in volume of liquid. We can have gas field, where it is maintained completely under gaseous situation. And we can also a vapor field, where we maintain a liquid vapor mixture. Thereby the as the temperature changes, corresponding saturation pressure also changes, and that is sensed to get the measure of the temperature.

They have generally a very large operating range much larger compared to the earlier ones that we have discussed. But, for the gas field once particularly, we can have very wide range limited only by the condensation of gases at the lower side, and possible dissociation of the gases at very high temperatures. And there is no elevation effects as well that is they are independent of the effect of gravity generally.

But, the disadvantage can be large bulb size requirement, and generally they lead to very small deflection unless, there is significant change in temperature. So, this gas or a vapor pressure base thermometers are generally used more standards or calibration purposes. In the next class, we shall be discussing about the electrical property based temperature measurements which are generally more you technical, you more used for technical purposes.

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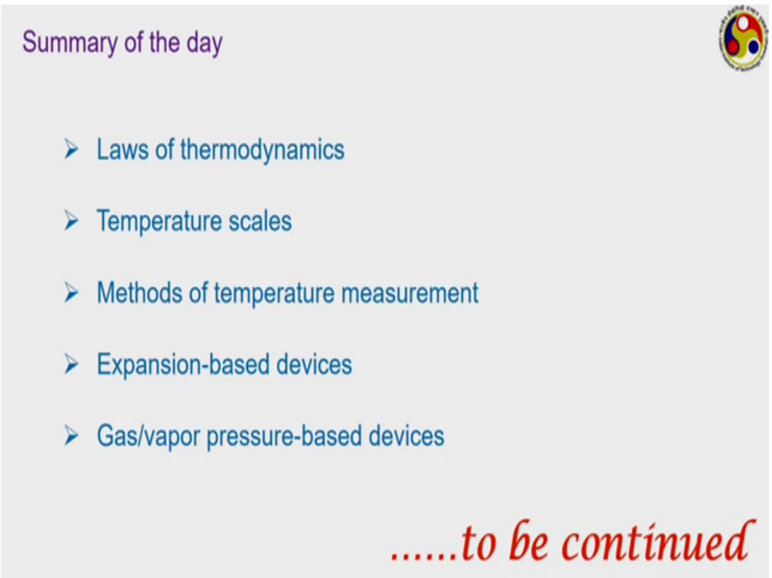

So, if we want to summarize, what we have done today. We discussed about the laws of thermodynamics, define the temperature from the context of the zeroth law. And the thermodynamic temperature scale from the context of the second law, we have discussed about the two point and single point temperature scales. Then different methods of temperature measurements were summarized, then you talked about the expansion based devices.

Two devices basically, one is the bimetallic strip, and other is the liquid in glass thermometer. Then we have talked about the gas vapor pressure base thermometers. So, we mentioned about the constant volume gas thermometer and the pressure thermometer, so that is it for the day. Next class, we shall be back with the measuring tools like RTD and thermocouples.

So, till then, thanks a lot.