Cryogenic Hydrogen Technology
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Week - 08
Lecture 36
Temperature Measurement

Welcome to this lecture on Cryogenic Hydrogen Technology. And in this lecture, we will try to understand some of the temperature measurements. So far, we have talked about the hydrogen production, then we have talked about its storage and in that connection, we have said that we are storing it in both gaseous condition, we are also storing it in the liquid you know condition. So, when it is in the liquid condition it is in cryogenic temperature domain, but in gaseous condition obviously, it is at room temperature and around. So, both I mean temperature measurement at both room temperature and cryogenic temperature is supposed to be or it is expected that it will be necessary, but in this lecture, we will try to particularly look at the cryogenic temperature measurement basically, because most of the time we are familiar with the room temperature applications. So, if there is any specialty connected to the cryogenic temperature measurement we will look at in this lecture.

So, the topic for this lecture is cryogenic temperature measurement in general, but as such we will try to look at the pertinent the things pertinent to cryogenic temperature and hydrogen temperature measurement. So, these are the things that we will try to look at these are there are primary thermometers and secondary thermometers. So, this primary thermometer is basically the one which does not need any calibration. So, the measurement takes place from the first principle and like you know the vapor pressure thermometer or this constant volume thermometer, these are the typical examples of you know primary thermometers.

So, out of that two we will be talking about the vapor pressure thermometer and the secondary thermometers all of the thermometers which will need calibration before we use it called the secondary thermometers. So, in that secondary thermometer primarily we will look at the resistive type thermometers that may have a positive coefficient or it may also have a negative coefficient. So, these secondary thermometers will also include like I mean thermocouples and then we have the diodes capacitance. So, many other types will you know come in, but many of them may not be suitable for cryogenic application or I mean ah particularly at hydrogen ah temperature. So, we need to be careful about selecting ah temperature I mean same temperature sensor depending on the temperature application.

So, we will come to that part later on. So, now let us look into the vapor pressure thermometer. So, this vapor pressure thermometer imagine that we have some liquid with us and this liquid ah temperature is ah something around ah you know between 15 K to say around 30 or 32 K within this range we are having some liquid and we want to measure the temperature of this and we are employing a vapor pressure thermometer. So, when we said that this is the primary thermometer ah this type of thermometers may not be practically ah used or it is not I mean in used in practice, but you will find that often it is necessary if we want to calibrate our system ah with the help of this kind of ah primary thermometers. So, we will have a you know gas bulb where ah or we have a temp pressure measurement system this is a ah pressure sensor and we have a small bulb where we have ah the liquid hydrogen.

$$\ln(\mathrm{P}) = \left(\frac{A}{T}\right) + B$$

$$\ln\left(\frac{P}{P_o}\right) = C_1 - \frac{C_2}{T} - C_3 \ln\left(\frac{T}{T_O}\right) - C_4 T + C_5 T^2$$

So, when we deep in this ah liquid container now depending on its temperature around the surrounding this is the thin world ah tube which is containing liquid hydrogen and this temperature of it is you know if we have some liquid on the vapor on top of ah this liquid ah basically this liquid will be in equilibrium with the surrounding one and the vapor pressure on top of it ah will depend on the temperature at which this liquid is ah kept. So, ah we will have some temperature indication sorry pressure indication and from that pressure indication we would be able to find out this temperature of this ah surrounding or particularly this liquid and the surrounding are in equilibrium. Now ah this pressure is uniquely related to the ah ah temper ah vapor pressure is uniquely related to this temperature of this liquid and this is ah mainly ah related by the Clausius Clapeyron equation. So, if we look at that equation it is dP by dT by delta S by delta V that is the change in the entropy and the change in the volume ah and this can be related to the enthalpy sorry the ah vaporization enthalpy and ah this is ah that latent heat and the temperature and the delta V. So, if we integrate this equation keeping that L constant that latent heat constant ah we will find that this will take a shape like ah ln P equals to A by T plus B and ah then the more generalized I mean form ah that is an empirical form is like this where we will have ln P by P0 and it is related to some constants ah C 1 to C 5 and this constants are known for hydrogen.

So, for this C3 part as you can see which involves ah the ln T by T0 ah is equals to 0. So, this part would not be there here this P0 is basically the pressure that is ambient 101.325 kPa and T0 is the temperature at atmospheric pressure. So, that is the normal boiling point we will take it as 20.27 Kelvin.

So, this is how ah you know this temperature and pressure are related. So, if we have some pressure indication that is we are getting ah some P we should be able to find out the temperature using this relation. So, now ah let us try to have a numerical problem based on this particular ah equation. So, imagine that we have found a liquid hydrogen vapor pressure thermometer where the pressure indication is given as 20 kPa. So, if we have 20 kPa ah vapor indication what could be the possible temperature.

ah Now, here ah at this point we can see that this is the equation that has to be used all these constants have already been ah told and P0 is also given. So, we know P by P 0, but this is this part is also you know 0 because we have seen that ah C3 is equals to 0. So, we have ah this relation. So, we can try to calculate it using ah I mean it would be an iterative solution. So, what we can do is that ah we can ah take the Newton's method like we can write this function ah f of T is equals to C1 minus C2 by T ah minus C4 by T because ah this C3 is no longer there it would be 0.

So, then you have ah I think this is C5 ah T square this is a plus sign. So, this is like this minus we have ln ah P by P0. So, this is the ah expression for the function ah which involves t and ah the derivative of it we can take it as ah say C2 by ah T square then minus C4 then we have ah 2 C5 into T this is this would be the ah first derivative. So, first of all you know we have to ah find out an expression for this temperature ah from this expression and ah I mean initially we should try to make a guess and from that ah temperature you know approximation ah we can try to find out the next best solution. So, that is ah T2 that should be ah the first approximation and then we should have f T1 by f prime of T1.

So, if we know the temperature T1 if we can make some initial guess then we can try to calculate this function f T and also we can try to calculate the f prime T that is the derivative of this function and then we can ah you know try to get a better estimate for the second and that will be an iterative process. So, this is the Newton's method ah for calculating the temperature in in an iterative process. So, let us look ah into the calculation and we have ah this calculation let us go to the axial sheet because ah this is a iterative solution. So, you should be ah able to you know calculate it with the help of. So, here we have given 20 ah then we have this ah first guess ah then we can write it as like ah ah T would be ah 101.325 minus ah 3.90 that is C1 and ah I mean ln of this is A4 is basically that 20 ah Kelvin ah that is this value. So, from ah the first approximation we can see that we have ah this value of the first guess is 18.21 Kelvin ah. Now, we can in the next process we can try to calculate this f T and f T expression we have already talked about. So, this is how we calculate the f T which depends on you can see the ah pressure ln P by P0 that is ln P by P0 and the first approximation that is ah 18.21. So, based on that we have this f T equals to 3.90796 and then f prime T also we have calculated from that expression based on 18.21 we have these two values f T and f T prime f prime T. So, the second ah best estimates the first estimate was 18.21. Now, we are ah based on these two values we are trying to find out the next best one and here you see this is B4 that is the first ah temperature and minus f T by f prime T. So, f T is in C4 and f prime T is D4. So, we get a second estimate that is 15.61. Now, with this value we will subsequently calculate f T and f prime t and that would give you ah 18 point the third estimate is 15.836. So, now, this will be taken to you know calculate the next best one. So, we find it is 18.843. So, that is a quite you know close ah I mean the up to the first decimal point we are finding its agreeing. If we go for the fifth you know iteration then we find that it is you know up to the third decimal point which is matching and we can conclude that the temperature will be 15.84 ah Kelvin. So, ah instead of say 15 sorry ah 20 kPa if it is say 14 kPa ah you can find out that the temperature would be 15.09 or if we say that it is 30 kPa it would be like ah 18 point 16.78. So, that means, ah you can see that this temperature measurement is sensitive to of course, the pressure and we can also try to find out what is the sensitivity and for that what we have to calculate is ah let us go back. So, we have talked about this problem and for this we have also calculated the temperature corresponding to this ah 20 kPa, but if we want to find out what is that ah sensitivity then we can calculate it with the help of ah the sensitivity would be dP dT ok.

$$S_0 = \frac{dP}{dT} = P(\frac{C_2}{T^2} - \frac{C_3}{T} - C_4 + 2C_5T)$$

So, for a small change in temperature how much is the change in pressure. So, this would become you know P ah then you have C2 by T square minus ah it is C3 by T minus it would be C4 plus 2 C5 into T and what we find is that from the previous calculation what we could see that there is if there is a very small change ah instead of you know ah 14 sorry 20 if it is a 15 or 14 ah it there is a change in the temperature or it is a big change in the temperature. So, it is very sensitive to the pressure change. So, ah for a small change in the temperature we can see that there is a large change in the ah pressure. So, that is what is the sensitivity.

So, it it is ah ah it is very sensitive, but the problem with this particular ah vapor pressure thermometer is that it is limited to the I mean it works between the two-temperature limit that is one point is a triple point of liquid hydrogen the other part is the ah critical point of because between these two limits it is existing in the liquid form. So, whenever we are trying to relate it to the vapor pressure. So, it has to have the in the liquid form and it has to be in the liquid form and that remains in the liquid form between these two limits and ah so, we can measure only between the triple point and the critical point. So, it is a limited by that otherwise ah it is a ah good ah or sensitive thermometer. So, which can be used you know for ah calibrating the system particularly at low temperature.

So, now let us go to the secondary ah thermometers ah which we ah practically use for different applications and ah like ah there are several thermometers ah as we have already told that ah there are positive temperature coefficient thermometers like ah platinum and rhodium iron. Then we have also the negative temperature coefficient ah thermometers like Cernox and then we have the diodes then we have thermocouple, but this thermocouple particularly that example that we have ah shown I mean thermocouples like ah chromel, alumel or say the copper constant and particularly the copper constant and we can employ it between ah 70 Kelvin to nearly ah I mean room temperature and above. But ah the thermocouples for cryogenic ah chromel below 70 Kelvin ah we have the chromel and gold iron. So, this is the gold ah Au and ah there is a small amount of ah you know iron with ah 0.03 percentage of iron mixed with this gold and that is used as another element other than the other part is ah chromel.

So, there has to be two elements ah and one is this chromel the other one is gold and iron with a small amount of iron. So, this thermocouple can go to a very low temperature I mean below ah the normal boiling point of hydrogen. So, this positive temperature coefficient particularly this m ah ah what is called this platinum resistance thermometer is ah ah I mean well known for cryogenic application, but ah it cannot be used for ah liquid hydrogen temperature because it will be not sensitive at that point. So, mostly we employ this platinum resistance thermometer up to a temperature of ah I mean 70 or to some extent you know I mean for certain application we can even go to 30 Kelvin ah ah. But regarding this choice of this thermometers there are ah you you should buy it from ah the recognized vendors and there are several cryogenic organizations who can sell this kind of ah temperature senses.

But ah this platinum resistance thermometer as I have said that it is not sensitive down to the normal boiling point of hydrogen, but this rhodium iron which is again another positive temperature coefficient ah RTD, but that can be used ah ah safely to low temperature and it is sensitive to I mean ah even below 20 Kelvin. On the negative ah temperatures coefficient, we have the cernox which can go ah from positive ah I mean room temperature down to ah 20 Kelvin or even lower. So, we can safely use that, but regarding the use of ah this ah what is called ah this resistive type thermometers say be it positive or ah negative ah there is a particular ah circuit that we should use for measurement of the temperature. Similarly, what we will have is the ah what we know is that the resistance ah in general we have seen that this is R0 into 1 plus alpha T and this alpha T alpha is the ah temperature coefficient it may be positive it may be ah negative depending on the positive coefficient and negative coefficient ah RTDs. So, what we have is ah you know this resistance is varying with temperature and this is the resistance at a particular known temperature often we ah ah you know ah find this or you know R0 we ah put it as ah 0 degree centigrade ah or 273 Kelvin and ah then we can you know find out the RT ah resistance at a particular temperature that we are trying to ah measure and if we know the coefficient alpha we would be able to calculate this temperature T.

So, that is how ah we try to do, but how do we measure the temperature? So, for that what we need is ah basically ah constant current ah source and say imagine this is the ah resistance or RT and we want to this is in in in a current ah cold environment. So, we are sending a small amount of current I which is flowing through this circuit ah with a constant you know current source we have ah and this is a constant current it is flowing and we are measuring the voltage across this. So, this ah current is known and this ah voltage is also known. So, V equals to I into RT and this voltage by measurement of this voltage and current is known.

So, RT can be calculated. So, this is ah V by. So, we have measured the RT ah from the knowledge of V and I and ah once we know this RT we can ah put it in this equation to find out the temperature. So, this is how we ah measure the temperature at ah I mean room temperature or at low temperature, but there is a problem that when we try to calculate this RT ah along with that what we will have is ah the resistance of this wire and this connecting wire. Ah It is particularly because when this is in cryogenic environment ah you know to avoid external heat leak what we do is that we try to make these wires as thin as possible. So, that from outside there is no additional heat going in though we have to use of ah you know ah current and that will definitely ah you know make some I square R loss that will be added to the system as heat input, but to you know reduce this ah I square R loss we put this current as small as possible, but along with that to avoid additional heat input to the system we generally make this wires very thin.

So, the moment we make these wires thin definitely it will increase the resistance of this resistance of these wires will come in picture. So, basically when we are measuring the RT it automatically includes the resistance of this wire which will not be you know taken into account ah ah I mean which is not included within this sensor. So, ah that means, we are doing some error in the measurement and this is of course, called the two wire measurement technique ah two wire measurement, but to avoid this ah I mean error associated with the lead resistance what we can do is ah we can try to put this resistance ah and this say lead resistance for example, would be there of course, and ah we put ah two more wires ah very close by where we will you know these are the lead resistance or R RL RL and RL this is RT. And we measure the voltage in between and put the current ah you know sorry this is where we put the current here and ah so, now we have four wires out of that you know two are for sending the current and two are for measuring the voltage. So, this is how ah it is ah I mean try we try to put it in the cryogenic environment and this RL which is now you know included ah I mean this lead resistances ah they will be as if you know combined with the what is called the input impedance or the output impedance of the ah sensors or the voltmeter and the ah voltmeter or the current source.

For the current source we have high ah in output impedance and for the voltmeter we have the high input impedance ah. So, it it will be included I mean all this lead resistances. So, here ah as we have understood that there are four wires 1 2 ah 3 4 and out of that two are used for measuring the voltage and two are for passing the current through the circuit. So, we call it as four wire technique ah four wire technique is ah mostly used in ah cryogenic environment to avoid this ah the lead resistance ah I mean as a errors associated with the lead resistances. So, that is how we do it in the ah positive and negative temperature coefficient ah resistive sensors ah.

Particularly when we have the negative temperature coefficient RTDs that means, as we lower the temperature ah for the positive temperature coefficient we know that when the temperature is increasing the ah resistance in increasing, but when it is ah the temperature is lowered the resistance keep on decreasing. So, that means, when at low temperature we have small resistance or smaller resistance and I square R is ah going to be ah you know lesser ah when as we lower the temperature. But for the negative temperature coefficient RTDs we will find that as we lower the temperature the resistance is going to increase. So, with the lowering of temperature since this is ah the resistance is increasing. So, we will find that there would be a larger I square R.

So, we have to be very careful about selecting the current. If we are using some kind of milli ampere current ah in this ah positive resistive ah resistance RTDs ah we should be ah depending on the resistance at low temperature we may have to use ah micrometer or even less ah current constant current for measuring this ah what is called the ah resistance and from there as we said that we will be able to find out the temperature. Regarding the thermocouple ah we ah are probably familiar with ah the circuit ah we have a temperature junction then we have the 2 wires here in this case say if it is chromel the other one is gold say A and B would be there along with that we will have you know the copper wires which will be taken to the ah you know I mean voltmeter. So, this voltage will be measured and from this voltage you know we would be able to measure this temperature. But in between what we know is that there has to be a reference junction and this reference junction is often 0 degree centigrade, but ah in practice what we do is that ah there is a I mean it it is not always convenient to keep a 0 degree centigrade reference point instead we ah keep it at a room temperature or at a fixed temperature and we measure that temperature or often these days you know there would be a cold junction compensation as it called CJC cold junction compensation.

So, that is to be ah done or most of the time when you are buying the thermocouples there would be the cold junction compensation and from there we will be you know ah basically ah measuring this voltage and that voltage can be related to the temperature. So, this emf or the voltage that we are measuring ah and the temperature those are uniquely ah I mean connected to the temperature type of thermocouple those are in use. So, if it is a gold iron or the chromel and gold iron thermocouple the emf versus the temperature would be different than the copper constant thermocouple. So, you are supposed to ah choose ah depending on the temperature that you are going to measure and you have to say ah I mean ah select the appropriate ah temperature calibration I am sorry ah the chart for measuring the or finding out the temperature. So, that is about ah the temperature measurement in a nutshell and we can conclude ah this is the these are the references you can ah check for finding out the different temperature measurements in details.

And in conclusion we can say that this is the vapor pressure thermometer is limited you know is applicable within a limited temperature zone, but the secondary thermocouples or second sorry thermometers ah it’s use depends on the temperature and available instruments. And not only that there is another factor that if ah this temperature sensors are used for magnetic application you need to be ah I mean added ah precautions has to be taken. So, you have to be sure that they are not these thermocouples are same the temperature sensors are not being affected by the magnetic field because the magnetic field can also alter ah some of this temperature ah I mean measurement techniques. So, that is how ah we can calculate the temperature or measure the temperature by different techniques. Thank you for your attention.