Chemical Process Utilities
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Lecture No # 43
Cooling Tower
Theory and Some Basic Calculations

Welcome to the next lecture of chemical process utilities in this particular chapter we will discuss about the cooling tower. Now cooling tower are integral part of chemical unit operation and chemical system. And in this particular chapter we are going to discuss about the different aspects pertaining to the theory, as well as we perform some numerical calculations. Now, before we go into the detail of cooling tower previously we had discussion about the pipeline mechanical design under this, we discussed about the pipeline design equations.

Then we discussed about the expansion and flexibility aspect in different type of pipeline. We discussed about the restrained lines unrestrained lines. Apart from this, we discussed about the various wall assemblies and block wall sidewalls etc.

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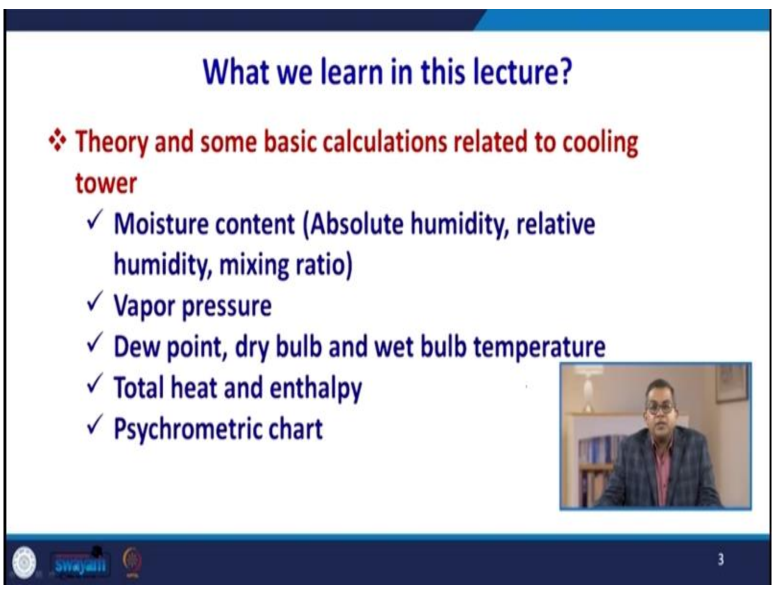

In this particular lecture we are going to discuss about the theory and the basic calculation aspects the pertaining to the cooling tower. In this particular lecture we will discuss about the moisture content this will discuss about the absolute humidity relative humidity, what is mixing ratio etc.

Then we will have a brief idea about the vapor pressure we will discuss about the dew point, dry bulb and wet bulb temperature.

All these are the integral part of the psychometric calculations. Then we will have a discussion about the total heat and enthalpy and at last we will discuss about the psychometric chart.

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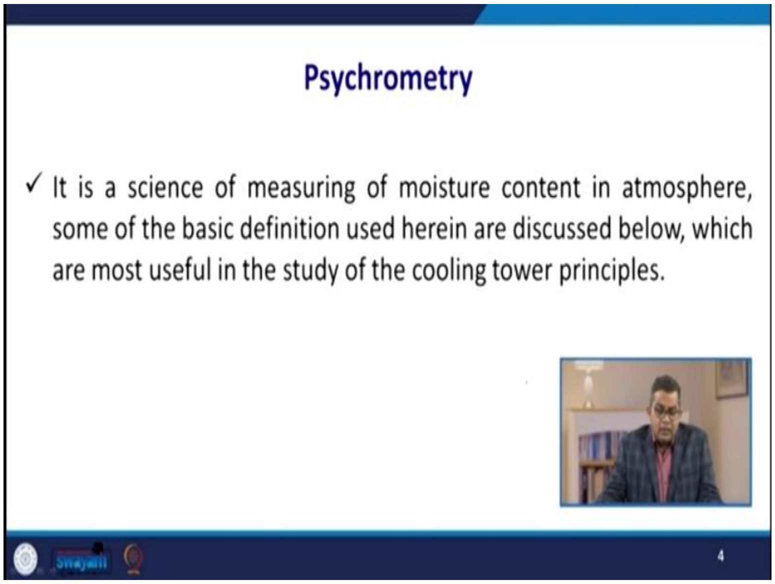

Now psychometric because we had given a term called dry bulb, wet bulb temperature etc and psychrometry is integral part of all these discussion. Now psychrometry, this is the science of measuring of moisture content in the atmosphere. Now, some of the basic definition used here in discussed and which are more powerful in the study of cooling tower principle.

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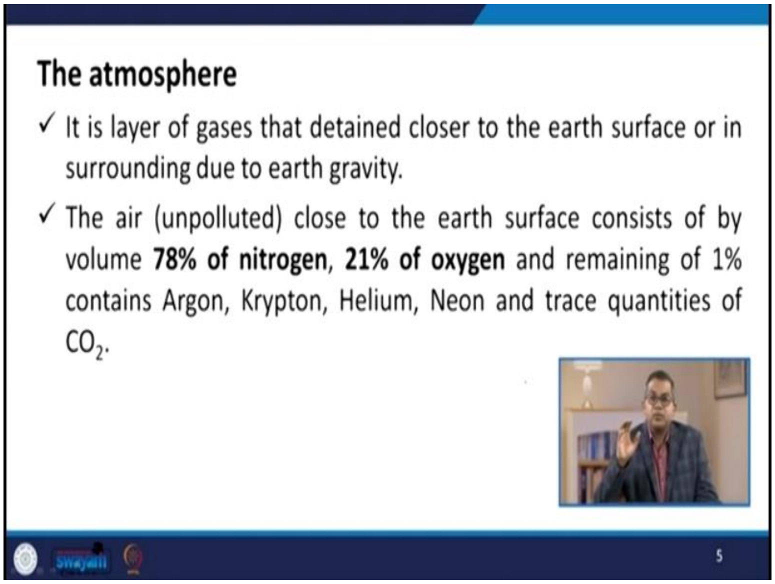

One is the atmosphere now it is the layer of gases that detained closer to the earth's surface or in surrounding due to earth gravity. Now, the unpolluted air that is very close to earth surface consists of by volume 78% of nitrogen 21% of oxygen and remaining 1% contains argon, krypton, xenon, helium, neon and trace quantities of carbon dioxide.

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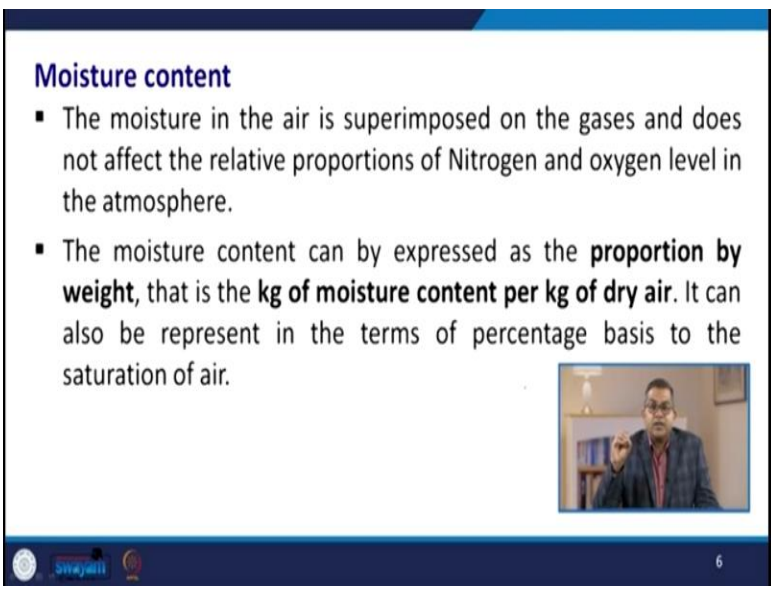

Moisture content the moisture in the air is superimposed on the gases and does not affect the relative proportion of nitrogen and oxygen level into the atmospheric air. The moisture content can be expressed as the proportion by weight and that is the kilogram moisture content per kilogram of dry air. It can also be represented in terms of a percentage basis of saturation air.

Now, this moisture content, play a very vital role because sometimes the relative humidity and a relative humidity is a very well-known term and, in this aspect, when we talk about the; dryness or atmospheric dryness etc. Then the content of moisture plays a very vital role. Sometimes during the rainy season, you may observe that the humidity is on at right at the top that maybe sometimes 90% or more than 90% moisture content in that atmospheric air

Now in that case you may experience that the drying of any operation under the edges of atmospheric condition, could not be possible just because of that difference, just because the moisture I mean air is rich with; the moisture. So the saturation of air is a point at which the given condition, no further moisture can be trapped in the air. And after that, the condensation will take place to start.

So in that case, which I was discussing about that particular example, the air is about to such saturate. In that case no further transfer of any kind of moisture be possible in to the air and that is the reason why you may experience that dryness or drying operation under the atmospheric condition is extremely difficult. The weight basis calculation is referred to absolute humidity and the percentage basis, are relative humidity.

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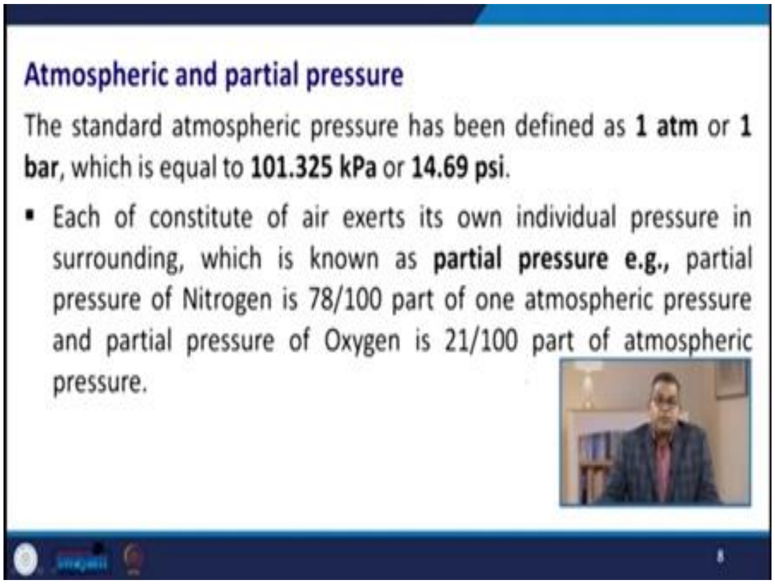

Now, let us talk about the atmospheric and partial pressure. Usually, when we talk about the different units are different standards or different benchmarks and pertaining to the pressure or atmospheric condition. Then we always look into the standard conditions and the standard atmospheric pressure is been defined as one atmosphere or one bar, which is equal to 101.325 kilo Pascal or 14.69 psi.

Now each of the constituent of air exerts its own individual pressure in surrounding which is known as partial pressure. In other words you can say the contributory pressure towards the atmosphere. Contributing pressure suppose, we are having the nitrogen in the atmosphere in that case. What is the contribution of the nitrogen gas to the atmosphere? That is referred as the partial pressure of nitrogen.

So partial pressure of nitrogen is amounted 78 by 100 part of one atmospheric pressure, and partial pressure of oxygen is 21 by 100 part of atmospheric pressure. Another important term in psychometric is a vapor pressure. The pressure exerted by water on its surface, is known as vapor pressure here, the pressure and temperature of water have a definite relationship.

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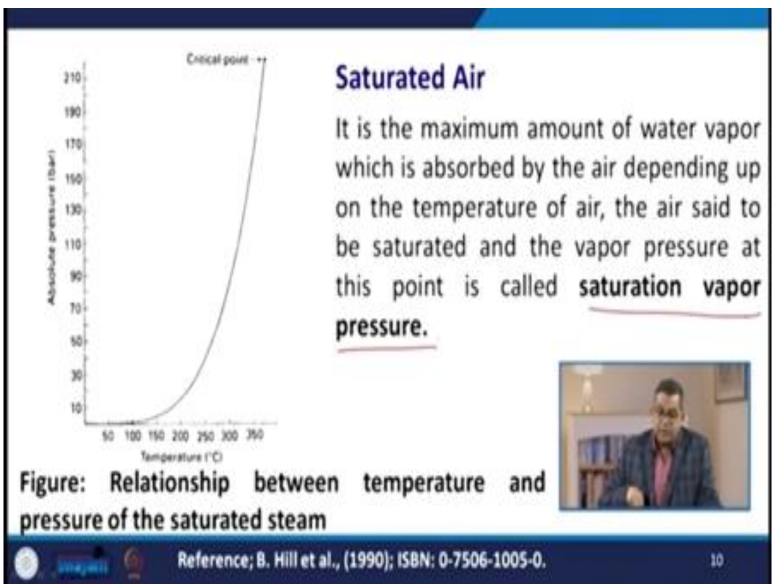

Now, when we talk about the various parameters, then one cannot overlook the importance of saturated here. We have already discussed a brief about the concept of saturated moisture or saturated air. It is the maximum amount of water vapor, which is absorbed by air, depending on the temperature of air the air is said to be saturated and the vapor pressure at this point is called the saturated saturation vapor pressure.

See, usually it is assumed that the normal air or normal atmospheric air is unsaturated in nature. So suppose, if you are having a cloth and if you put to the atmosphere or wetted cloth put to the atmosphere. Sometimes you may experience that it is dry. So where this moisture goes, it goes into the atmosphere because air is unsaturated. So it has it is having a tendency or it is having the capacity to take up the moisture from the object in question.

Now, if it is saturated then you may find it extremely difficult to get it dry. So that is the called a saturated air and the vapor pressure at this particular point is called the saturation pressure. In this particular figure you see that there is a relationship between the temperature and the pressure of saturated steam.

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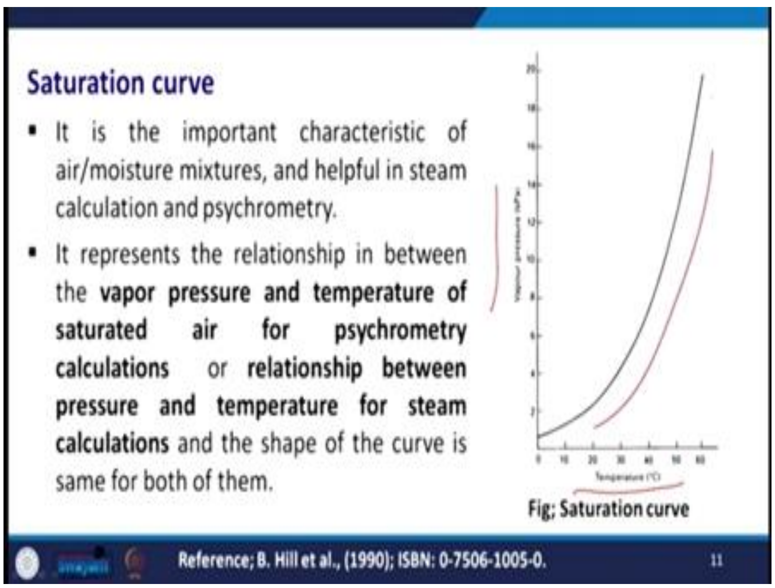

Now sometimes in different engineering perspective, you need to look bout the saturation curve. Now it is the important characteristic of air moisture mixture and it is helpful in steam calculation and psychrometric. It represents a relationship in between the vapor pressure and the temperature of saturated air for psychrometric calculation or relationship between the pressure and temperature for steam calculations.

And the Shape of curve is same for both of them. Now the point on the curve this various point on the curve indicates the maximum amount of water vapor that can be retained in the air at the point. That is the saturation vapor pressure at corresponding temperature. Another important term is called the absolute humidity. Now it is the amount of moisture in kilogram of water moisture per kilogram of dry air.

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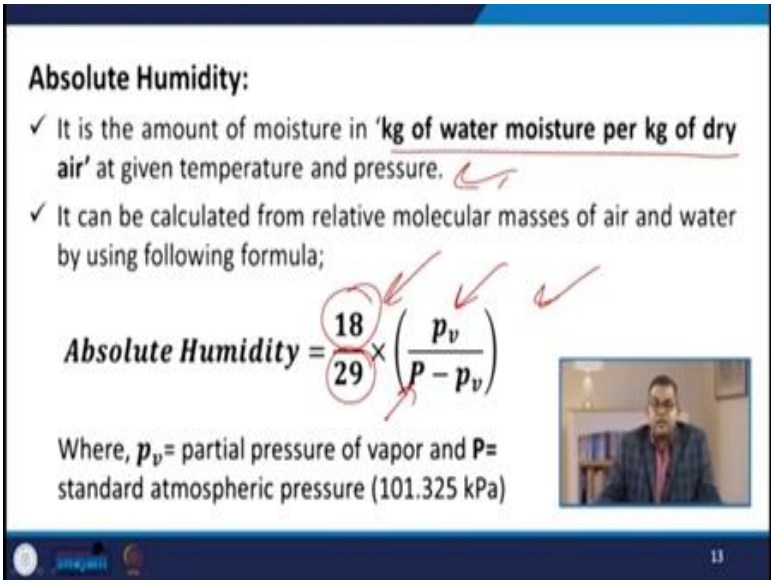

At a given temperature and pressure now, it can be calculated from relative moisture molecular masses of air water by this particular formula. So, absolute humidity can be represented as 18 by 29. 29 is the molecular mass of air and 18 is the molecular mass of water into p_v upon P – p_v where this p_v is the partial pressure of vapor and this P is the standard atmospheric pressure and sometimes as you recall in the previous slides, we discussed that it is 101.325 kilo Pascal.

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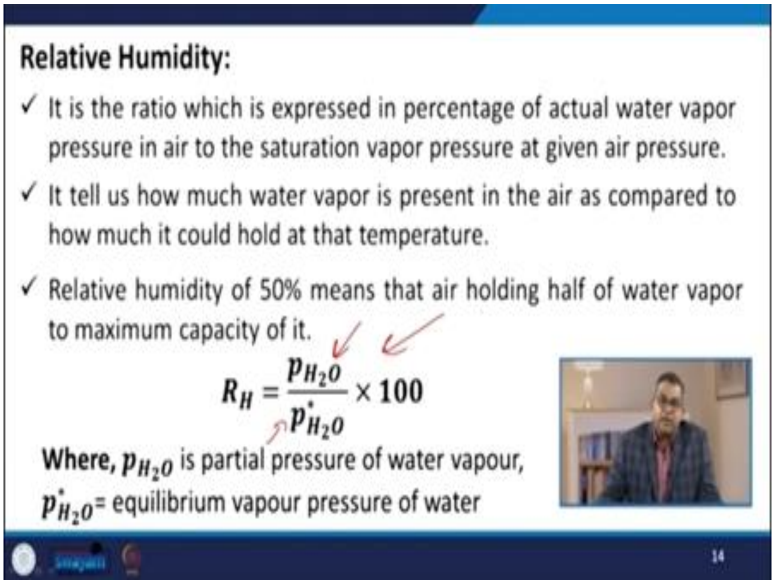
$$\boldsymbol{Absolute\ Humidity = \frac{18}{29} \times \left(\frac{p_v}{P - p_v}\right)}$$

Where, p_v= partial pressure of vapor and P= standard atmospheric pressure (101.325 kPa)



Relative humidity if you recall that the start of this lecture, I have used this particular term that is called the relative humidity. Now it is a ratio which is expressed in percentage of actual water vapor pressure in air to the saturation vapor pressure at the given air pressure. Now it tells us how much water vapor is present in the air as compared to how much it could hold at that particular temperature?

So this is very useful information pertaining to the drying. Now relative humidity of say 50% means that air holding half of the water vapor to the maximum capacity of it. So that means you are having the enough opportunity to intake the water by the given sample of the air. The mathematical representation of a relative humidity is represented as the partial pressure of water vapor that is represented as p_{H2O}.

Then the partial, then the equilibrium vapor pressure of water that is represented as the p star H_2O multiplied by 100. So it is the ratio of the partial pressure of water vapor to the equilibrium vapor pressure of water multiplied by 100. So it is usually represented it as in terms of a percentage.

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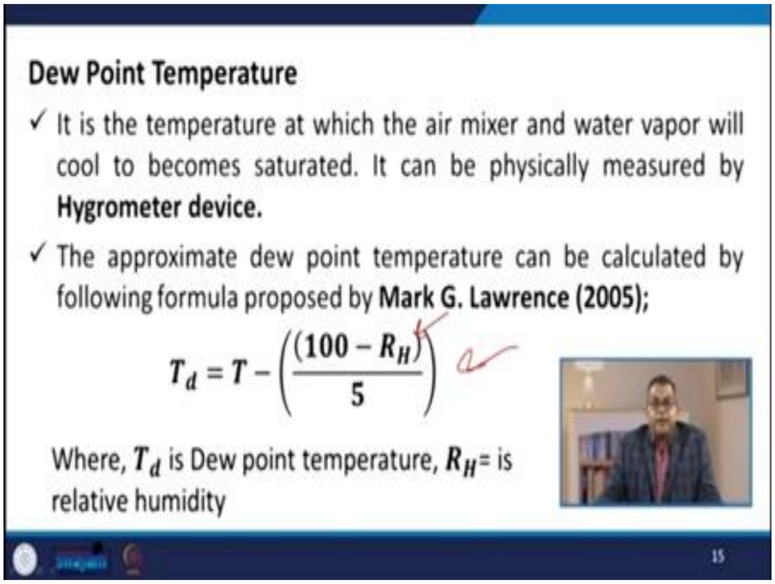
Relative Humidity (R_H);

$$R_H = \frac{p_{H_2O}}{p^*_{H_2O}} \times 100$$

Where, p_{H_2O} is partial pressure of water vapour, $p^*_{H_2O}$= equilibrium vapour pressure of water



Another important point which we need to address and that is the dew point temperature. It is a temperature at which the air mixture and water vapor will cool to become the saturated. It can be physically measured by hydrometer device. The approximate dew point temperature can be calculated by this particular mathematical relationship given by Lawrence and that is equal to T_d = T - 100 – R_H upon 5. Now T_d is the dew point temperature and R_H is the relative humidity.

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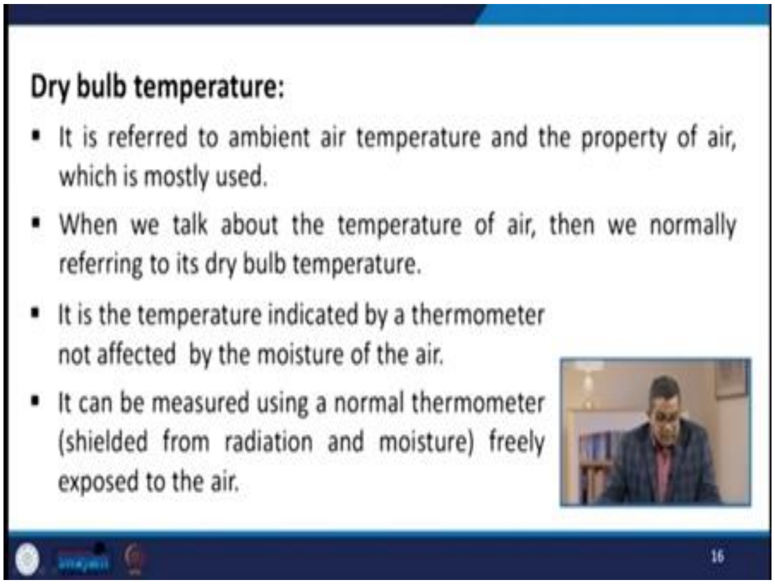
Dew Point (T_d);

$$T_d = T - \left(\frac{(100 - R_H)}{5}\right)$$

Where, T_d is Dew point temperature, R_H= is relative humidity



Another important thing is that is called the dry bulb temperature. It is referred to ambient air temperature and the property of air which is mostly used. Now when we talk about the temperature of air then, we normally refer to its dry bulb temperature. It is a temperature indicated by a thermometer not affected by the moisture of the air. Now it can be measured by using the normal thermometer that is shielded from the radiation and moisture.

Or it is inside housing that usually current of this radiation and moisture and it is freely exposed to the air.

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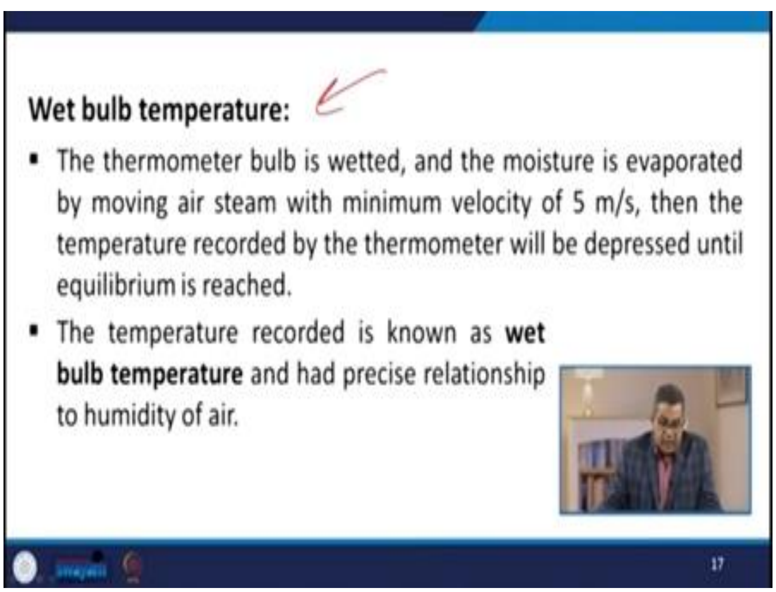

Another important thing that is called up wet bulb temperature. Thermometer bulb is wetted and the moisture is evaporated by moving air steam with the minimum velocity of say 5 meter per second. Then the temperature recorded by the thermometer will be depressed until equilibrium is reached. So, whatever temperature is recorded, that is known as a wet bulb temperature and had precise relationship to humidity of air.

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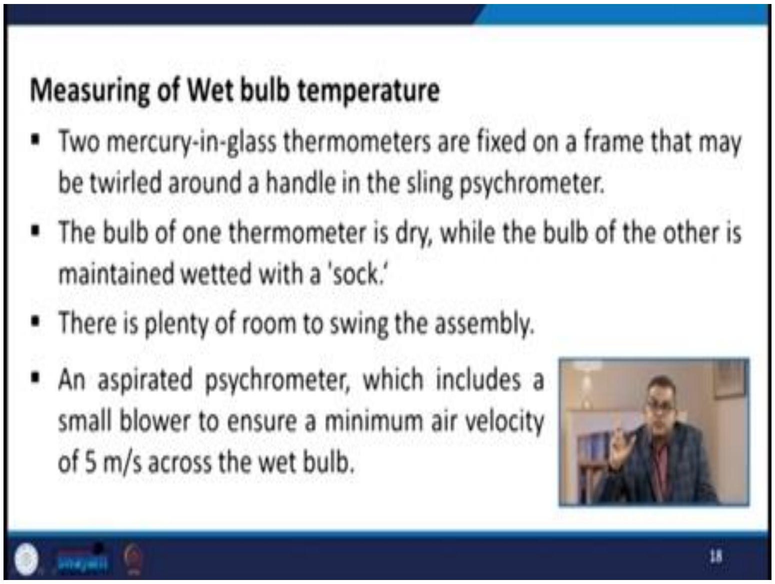

Now question arises that, how do we measure this wet bulb temperature. Now 2 mercury, in glass thermometers usually they are fixed on a frame and that may be twirled around a handle in a sling psychrometer. The bulb of 1 thermometer is dry while the bulb of other thermometer is maintained wetted with a saw.

Now there is a plenty of room by swing the assembly and aspirated psychrometer, which is in which includes a small blower to ensure a minimum air velocity of 5 meter per second as desired should be across the wet bulb.

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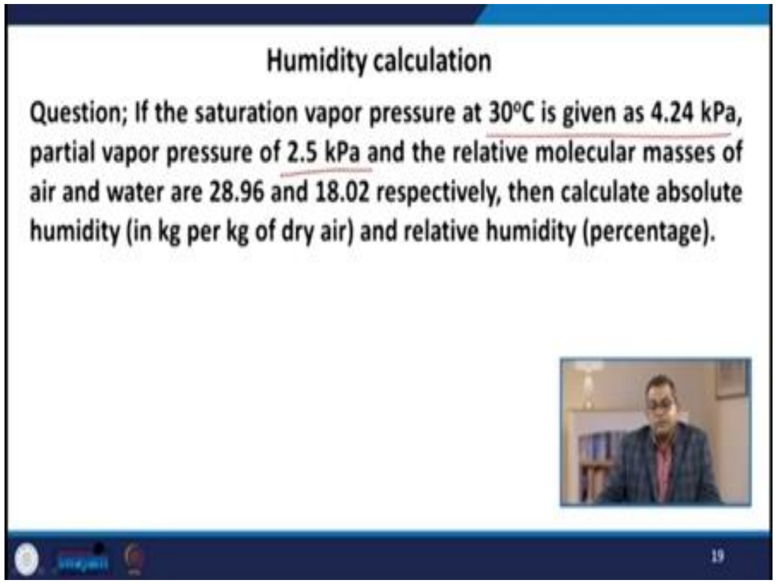

Now, since we have discussed various mathematical relations and various definitions. Now it is time to have 1 calculation or 1 numerical problem. Now, here I am putting 1 question to you that, if saturation vapor pressure at 30 degrees Celsius is given as 4.24 kilo Pascal, the partial vapor pressure of 2.5 kilo Pascal and the relative molecular masses of air and water are 28.96 and 18.02 respectively.

Then you need to calculate the absolute humidity that is in kilogram per kilogram of dry air, and the relative humidity and that we have already discussed that it is represented with respect to the percentage.

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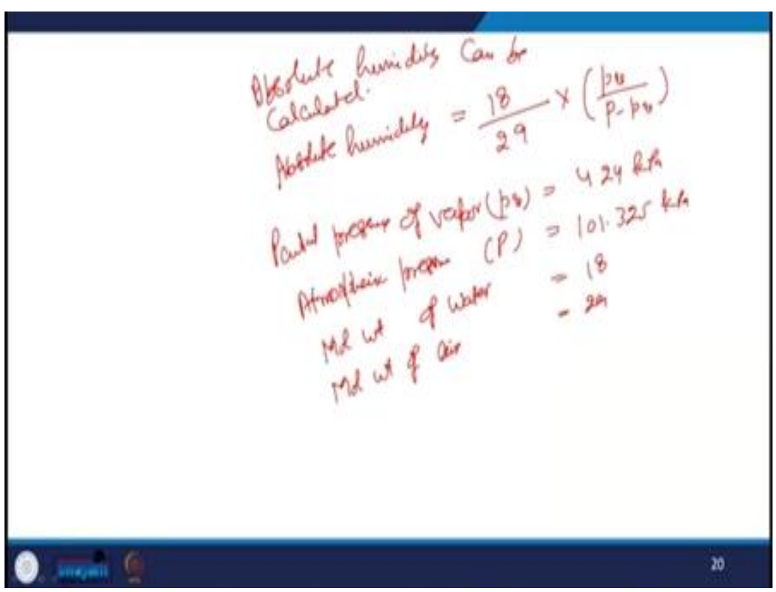

Now, you know that the absolute humidity can be calculated by this formula that is absolute humidity, which is already we have given this formula 18 by 29 into P_v upon $P - P_v$. Now here, if you see in this particular problem, the partial pressure of vapor that is P_v 4.24 kilo Pascal then atmospheric pressure P quite obvious it is 101.325 kilo Pascal. Molecular weight of water it is given 18 then molecular weight of air that is 29.

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Solution Q1:

Absolute humidity can be calculated as;

$$\boldsymbol{Absolute\ Humidity = \frac{18}{29} \times \left(\frac{p_v}{P - p_v}\right)}$$

The saturation vapor pressure at 30ºC = 4.24 kPa

Atmospheric pressure = 101.325 Kpa

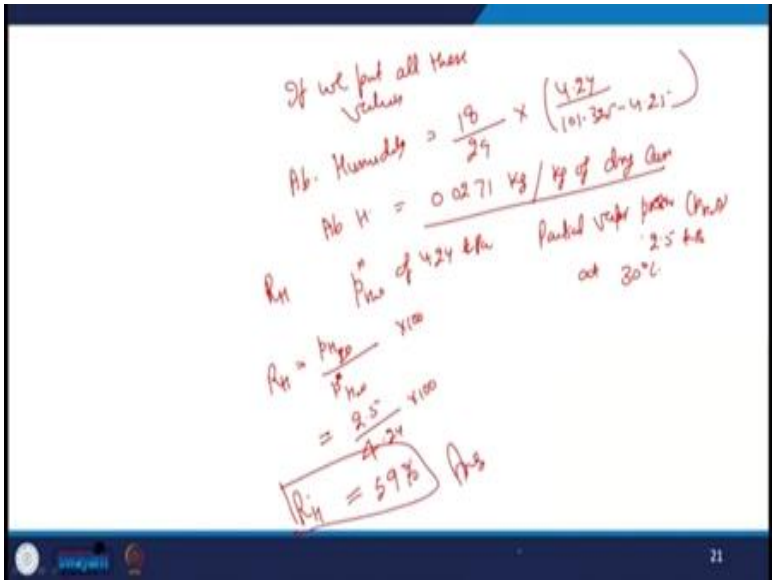
Molecular weight of water = 18

Molecular weight of air = 29

On putting all values in the above formula, we have

$$\boldsymbol{Absolute\ Humidity = \frac{18}{29} \times \left(\frac{4.24}{101.325 - 4.25}\right)}$$

Absolute humidity = 0.0271 kg/Kg of dry air



Now, if we put all these values, all these values then absolute humidity is equal to 18 by 29 into 4.24 upon 101.325 - 4.25. So, this is the absolute humidity calculation. Now, it comes out to be 0.0271 kilogram per kilogram of dry air. Now further calculation of relative humidity that is R_H. Now, if saturation vapor pressure that is p star, H_2O of 4.24 kilo Pascal and partial vapor pressure p H_2O is given as 2.5 kilo Pascal at 30 degree Celsius.

So R_H if you recall the formula that is the relative humidity. It is P_H_2O upon equilibrium pressure, partial pressure of water multiplied by 100. So we put forward that comes out to be 2.5 upon 4.24 into 100 and it comes out to be 59%. So relative, humidity will be 59% and that is the desired answer. Now another basic thing is related to that total heat or enthalpy, now any substance whose temperature above 0 contains heat energy

But for calculation involving we are having a fluid then, it should be standard practice to take 0 degree Celsius as a datum point for measurement. Now, there are 4 elements to the total enthalpy, or total heat content of an air water vapor mixture. One is the dry heat content of the air.

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Now, for relative humidity, we have;

saturation vapor pressure (P_{sat}) at 30ºC is given = 4.24 kPa

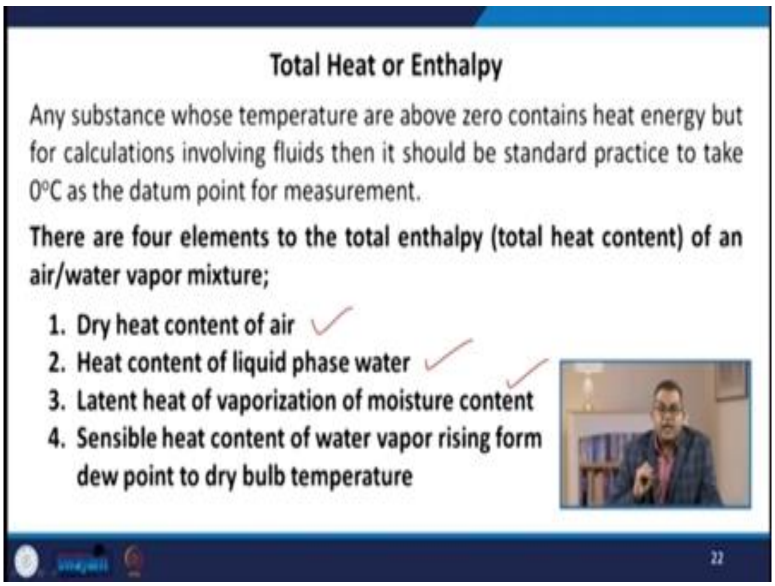
partial vapor pressure = 2.5 kPa

We know that the relative humidity can be written as;

$$R_H = \frac{p_{H_2O}}{p^*_{H_2O}} \times 100$$

$$R_H = \frac{2.5}{4.24} \times 100$$

$$R_H = 59\%$$



Now second is the heat content of liquid phase third is the latent heat of vaporization of moisture content and fourth one is the sensible heat content of water vapor rising from dew point to dry bulb temperature.

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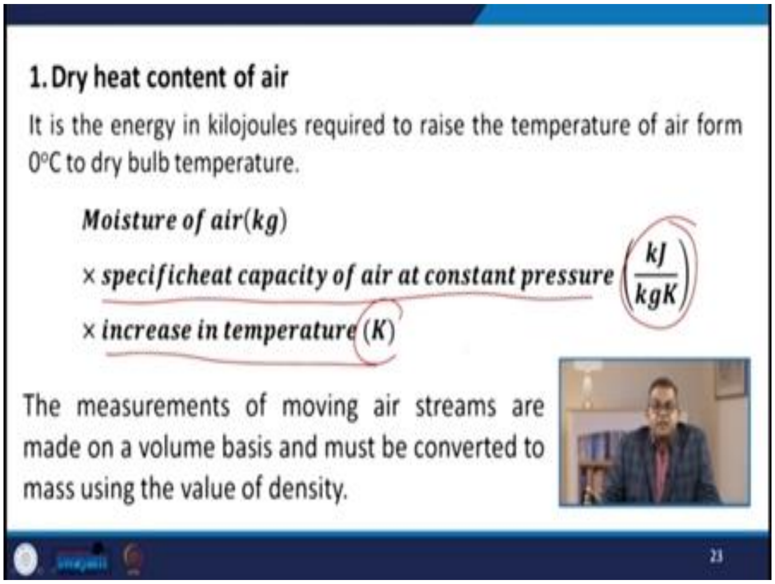

Now let us talk about the dry heat content of the air. It is the energy in kilo joules which is required to raise the temperature of air from 0 degree Celsius to dry bulb temperature recall that we have already discussed this dry bulb temperature. So the moisture of air in kilogram that is the specific heat capacity of the air at constant pressure. It is represented as a kilo joule per kilogram Kelvin into increase in the temperature referred in Kelvin.

Now, the measurements of moving air streams are made on a volume basis and must be converted to mass using the value of density.

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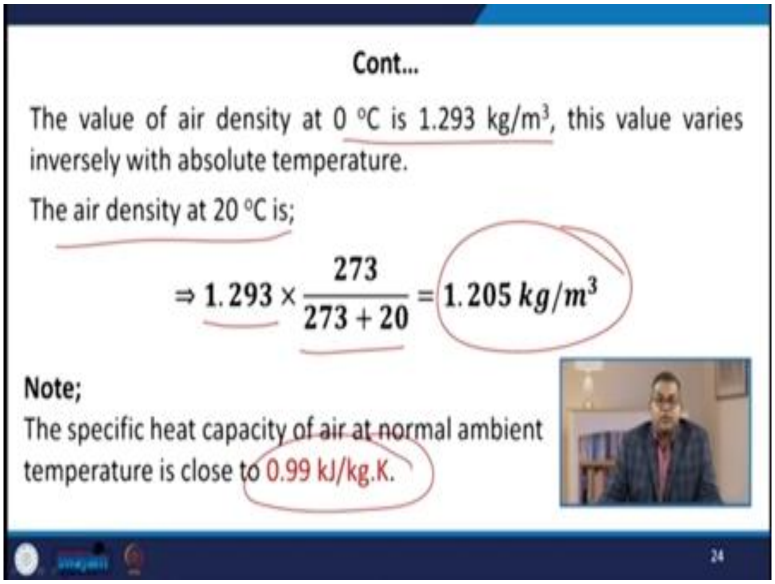
Dry heat content of air

$$\boldsymbol{Moisture\ of\ air(kg) \times specificheat\ capacity\ of\ air\ at\ constant\ pressure\ \left(\frac{kJ}{kgK}\right) \times increase\ in\ temperature\ (K)}$$



Now the value of air density at 0 degree Celsius is 1.293 kilogram per meter cube. And this value varies inversely with absolute temperature and air density at 20 degree Celsius is 1.293 into 273 upon 273 +20 degree Celsius temperature. So if you make it to the Kelvin it comes out to be 293 Kelvin and that is equal to 1.205 kilogram per meter cube. Now, the specific heat capacity of air at normal ambient temperature is close to 0.99 kilo joule per kilogram Kelvin.

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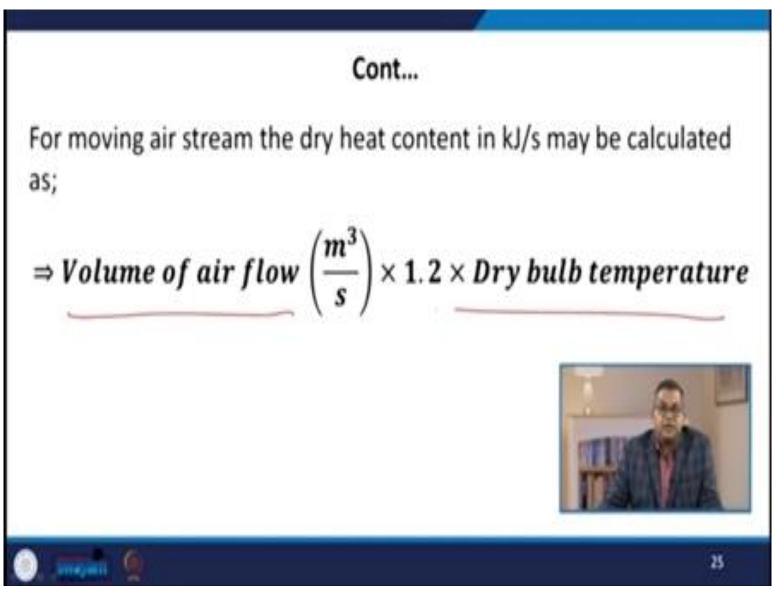

Now if we talk about the moving air stream by the dry heat content in kilo joule per second. It may be calculated as the volume of air flow, which is obviously in the meter cube per second into 1.2 into dry bulb temperature. So this is the mathematical formula through which you can calculate the moving air stream on the dry heat content.

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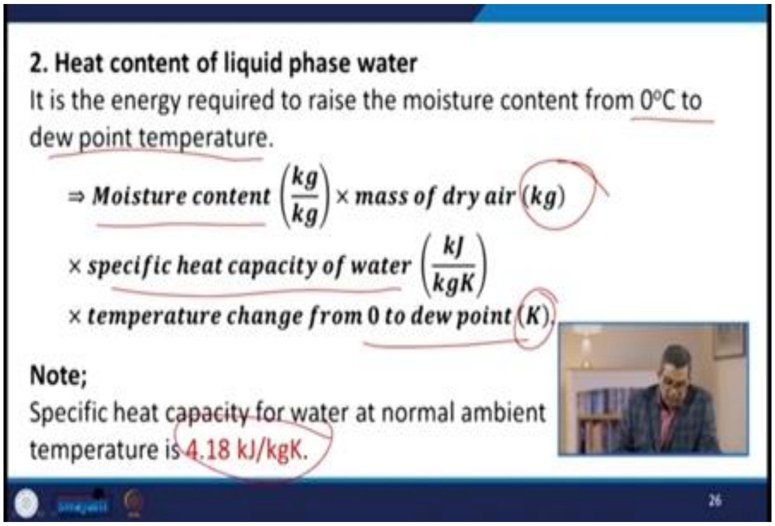
For moving air stream, the dry heat content in kJ/s may be calculated as;

$$\Rightarrow \boldsymbol{Volume\ of\ air\ flow} \left(\frac{\boldsymbol{m^3}}{\boldsymbol{s}}\right) \times \mathbf{1.2} \times \boldsymbol{Dry\ bulb\ temperature}$$



The second is the heat content of liquid phase water. Now, if the energy required to, raise the moisture content from 0 degree Celsius to dew point temperature. We have already discussed this dew point temperature that comes out to be moisture content, in kilogram over kilogram into mass of dry air that is in kilogram. Multiplied by the specific heat capacity of the water that is in kilo joule per kilogram Kelvin into temperature change from 0 to dew point and dew point temperature is represented Kelvin.

So the specific heat for water at normal ambient temperature is 4.18 kilo joule per kilogram Kelvin.

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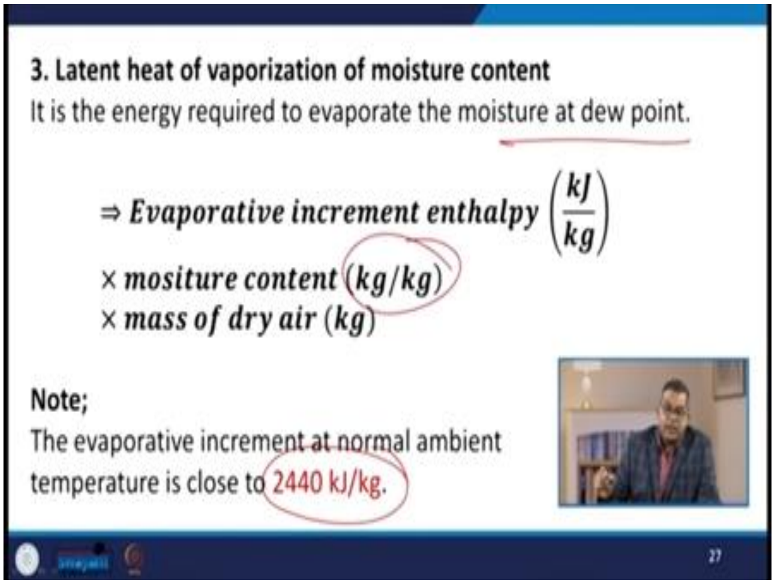
Heat content of liquid phase water

$$\Rightarrow \boldsymbol{Moisture\ content} \left(\frac{\boldsymbol{kg}}{\boldsymbol{kg}}\right) \times \boldsymbol{mass\ of\ dry\ air}\ (\boldsymbol{kg}) \times \boldsymbol{specific\ heat\ capacity\ of\ water} \left(\frac{\boldsymbol{kJ}}{\boldsymbol{kgK}}\right) \times \boldsymbol{temperature\ change\ from\ \mathbf{0}\ to\ dew\ point}\ (\boldsymbol{K}).$$



Now let us talk about the latent heat of vaporization of moisture content. Now it is the energy required to evaporate the moisture at dew point. So the evaporative increment enthalpy using having the unit kilo joule per kilogram into moisture content in kilogram over kilogram into mass of dry air that is in kilogram. So if we talk about this evaporating increment at normal ambient temperature which is close to 2440 kilo joule per kilogram.

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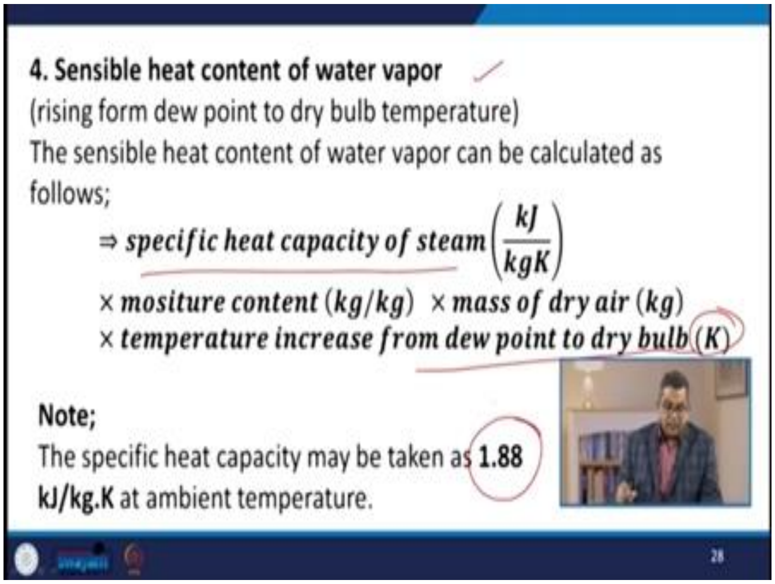
Latent heat of vaporization of moisture content

$$\Rightarrow \boldsymbol{Evaporative\ increment\ enthalpy}\left(\frac{\boldsymbol{kJ}}{\boldsymbol{kg}}\right) \times \boldsymbol{mositure\ content}\ (\boldsymbol{kg/kg})\ \times \boldsymbol{mass\ of\ dry\ air}\ (\boldsymbol{kg})$$



Then sensible heat content of; water vapor that, is arising from dew point to dry bulb temperature. The sensible heat content of water vapor it can be calculated as specific heat capacity of this team in kilo joule per kilogram Kelvin, into moisture content into mass of dry air in kilogram into temperature increase from dew point to dry bulb temperature. And that is in Kelvin, so specific heat capacity may be taken, as 1.88 kilo joule per kilogram Kelvin at ambient temperature.

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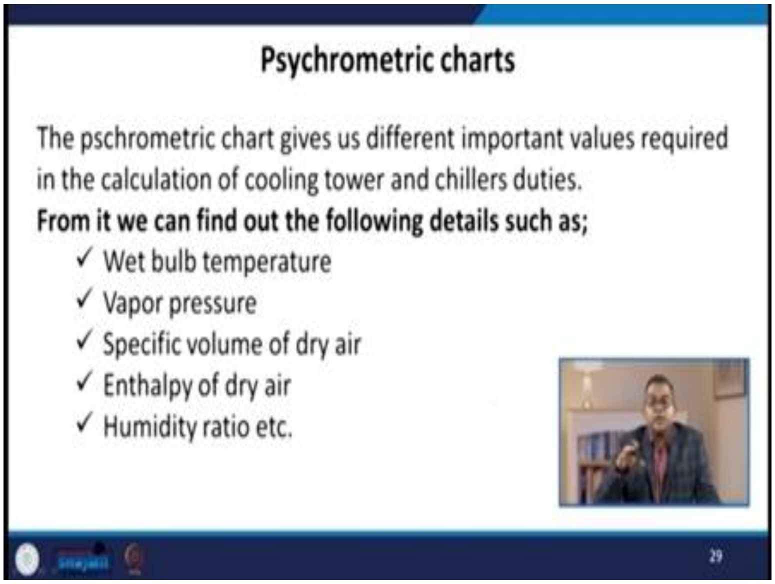
Sensible heat content of water vapor

$$\Rightarrow \boldsymbol{specific\ heat\ capacity\ of\ steam} \left(\frac{\boldsymbol{kJ}}{\boldsymbol{kgK}}\right) \times \boldsymbol{mositure\ content}\ (\boldsymbol{kg/kg})\ \times \boldsymbol{mass\ of\ dry\ air}\ (\boldsymbol{kg}) \times \boldsymbol{temperature\ increase\ from\ dew\ point\ to\ dry\ bulb}\ (\boldsymbol{K})$$

Note;The specific heat capacity may be taken as **1.88 kJ/kg.K** at ambient temperature.



Now psychrometric chart plays a very vital role in all kind of the calculation and it gives, a comprehensive information pertaining to whether we talk about the wet bulb temperature, vapor pressure, relative humidity, humidity ratio, etc. So it is a different this gives us various values and various important values required in the calculation of cooling tower and chillers. So we can find out like, in detail spectrum, if we talk that is a wet bulb temperature vapor pressure is specific volume of dry air.

We may get the enthalpy of dry air then humidity ratio etc. So enormous information you can have from this psychrometric chart.

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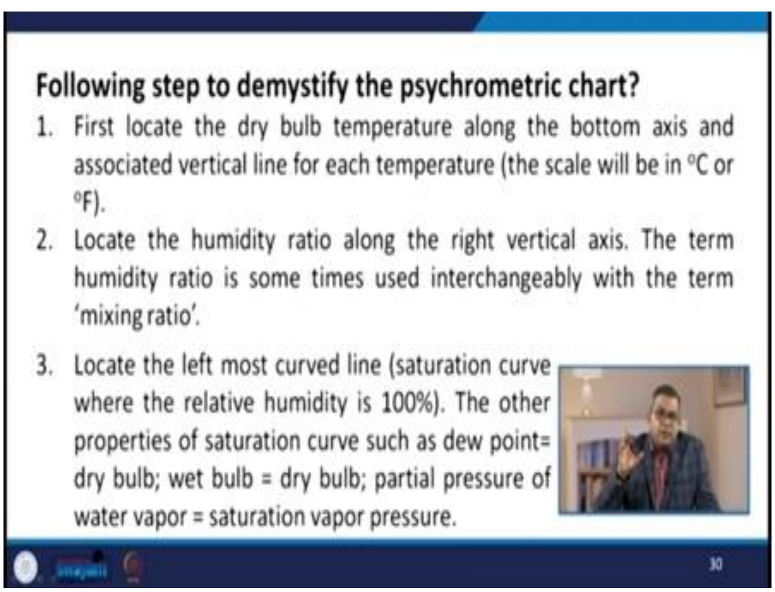

Now you need to take various steps for finding out the various values in the psychrometric chart. Now first thing is that to locate the dry bulb temperature along the bottom axis.

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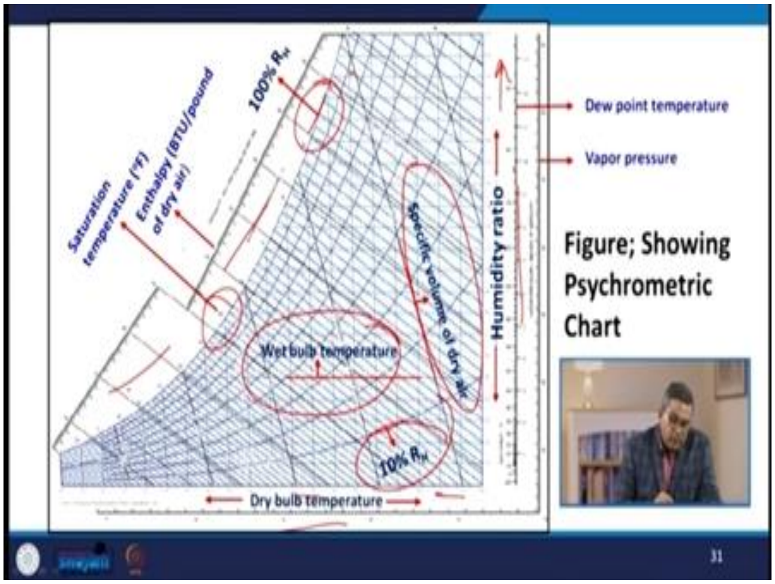

Here, we have represented this one this is with respect to the dry bulb temperature here you see and here, this is the humidity ratio. And apart from this, there are various curves like wet bulb temperature etc. So first you need to locate the dry bulb temperature along the bottom axis here. Then associated vertical lines for each temperature and scale will be either in degree Celsius or in Fahrenheit.

So you see that? This is attached with the temperature is skill then locate the humidity ratio along the right vertical axis. So here, you see that this is the humidity ratio to the right vertical axis. Now the term humidity ratio is sometimes used as interchangeably with the term of mixing ratio. So sometimes it is referred as the mixing ratio. Now locate the left most curve line that is a saturation curve. Here you see this is the saturation curve.

There are the relative humidity is 100%. So you can locate that where is the relative humidity, is 100%. Here you find that the relative humidity is 100% the other property of saturation curve like dew point equal to dry bulb wet bulb equal to dry bulb or partial pressure of the of water vapor or saturation vapor pressure etc you can have this one.

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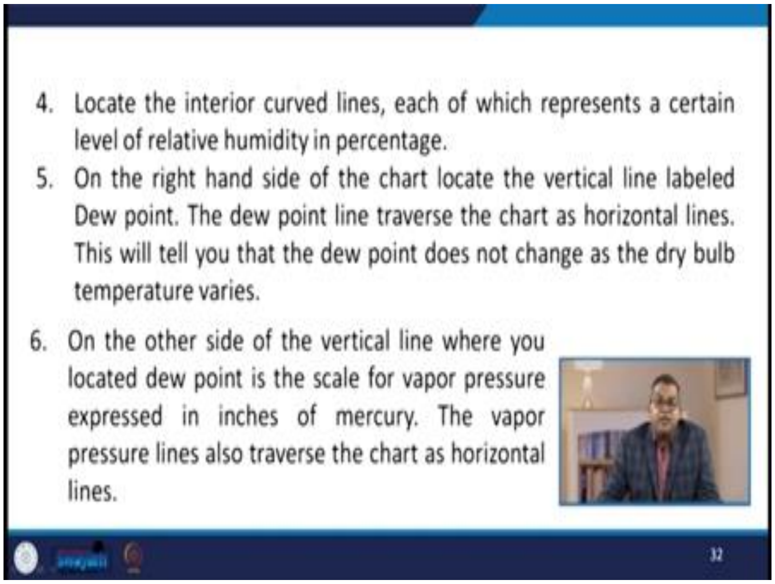

Now locate the interior curve lines here you need to locate the interior curve lines of which represent a certain level of relative humidity in percentage. Now on the right hand side of the chart, locate the vertical lines labeled as a dew point. The dew point of the line traverse the chart as horizontal line and this will let you know the dew point does not change as the dry bulb temperature varies.

On the other hand side of the vertical line here where you may find the dew point is the scale for vapor pressure expressed in inches of mercury. The vapor pressure lines also traverse the chart as horizontal line. So here you see that the wet bulb temperature and specific volume of dry air and this is the saturation temperature and you may find the enthalpy. Now here to be more precise you can see that this is the dew point temperature and vapor pressure and other designated values.

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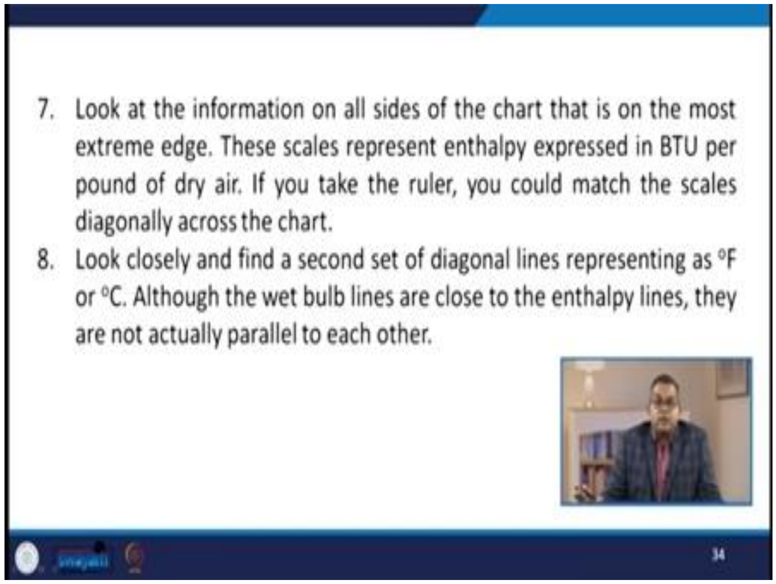

Now look at the information on all side of the chart that is on the most extreme edge. Now, these scales represent the value or enthalpy expressed in BTU British thermal unit per pound of dry air. Now if, you take the ruler you could match the scales diagonally across the chart and you need to look closely and find a second set of diagonal lines here you see the different lines.

Representing the as Fahrenheit or Celsius although the wet bulb lines are close to the enthalpy lines they are not actually parallel to each other.

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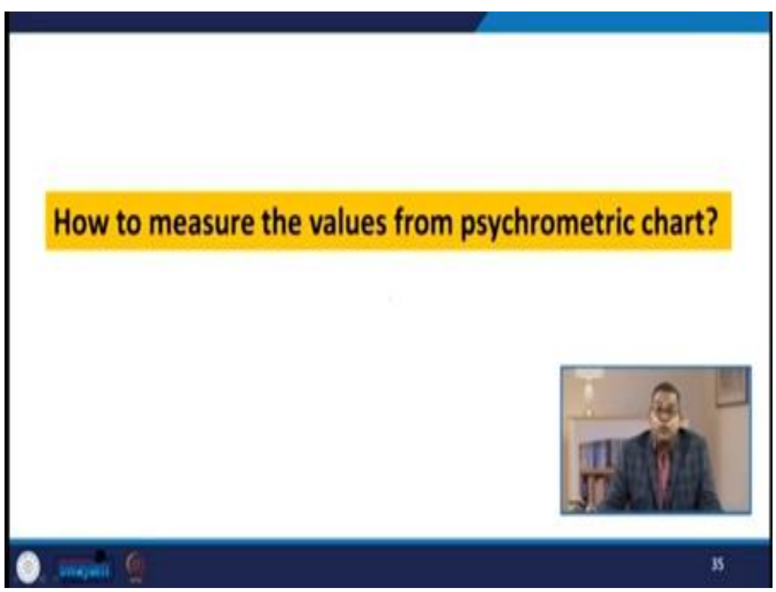

Now question arises how to measure the values from psychrometric chart.

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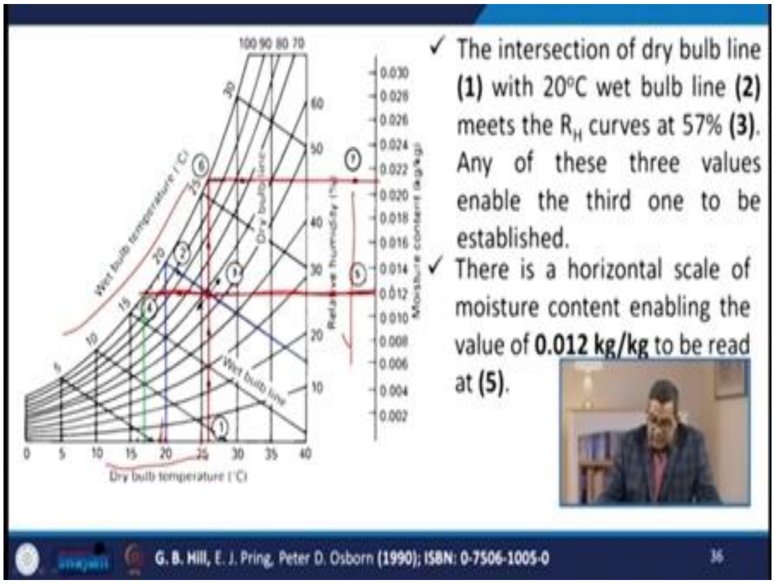

And that is the most practical approach. Now here you need to find out first the intersection of dry bulb line. Now here you see that this is the dry bulb line. This is the dry bulb temperature here the wet bulb temperature curve and this relative humidity. So this intersection of dry bulb line with say 20 degree Celsius here you see this is a 20 degree Celsius meets the relative humidity curve.

Usually it is at 50 means the relative humidity curve at 57% now any of these three values enable the third one to be established. Now there is a horizontal scale of moisture content enabling the value of say this is the horizontal scale of moisture content. This enabled the value of 0.012 kilogram per kilo gram.

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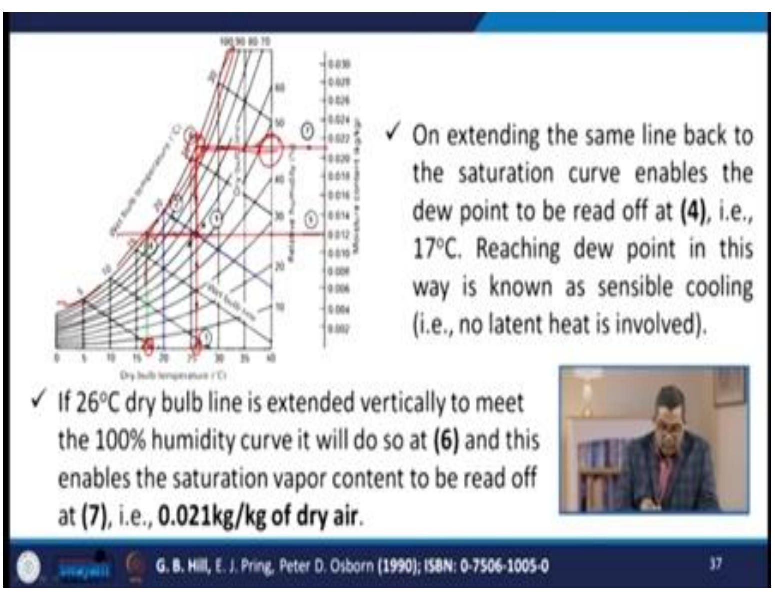

Now if we extend the same line back to the saturation curve here this enables and this gives you the information pertaining to the dew point now in this way. And that is nearly you see that it is nearly 17 degree Celsius. Now reaching the dew point in this way is known as sensible cooling there is no latent heat is involved. Now if you say 26 degree Celsius dry bulb line is extended.

Now here you see that this is the 26 degree Celsius dry bulb line is extended vertically to meet this 100% humidity curve. Then it meets at point number 6 and this enables the saturation vapor content to be read at the at this juncture and which is comes out to be 0.021 kilogram per kilogram of dry air.

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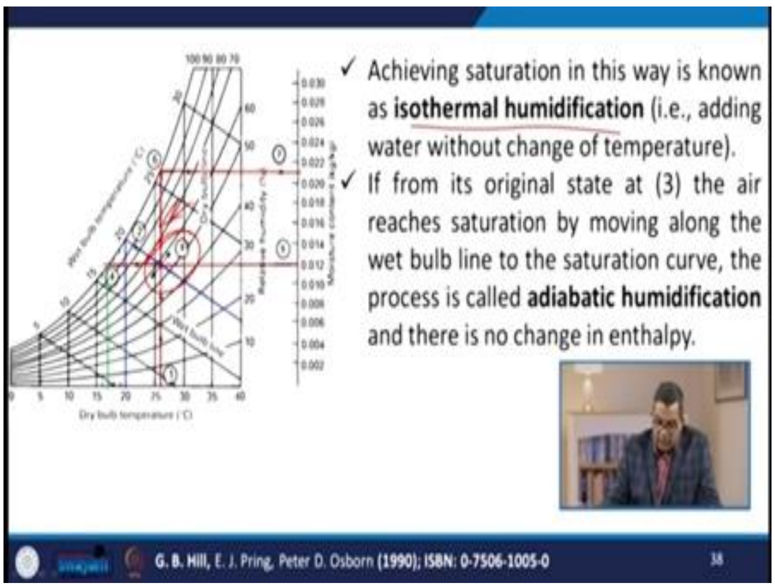

Now achieving the saturation in this way is known as isothermal humidification. That is the addition adding water without the change of temperature. Now, if from its original state now this is the original state the air reaches the saturation by moving along, side the wet bulb temperature to the saturation curve. That process is called the adiabatic humidification and there is no change in enthalpy.

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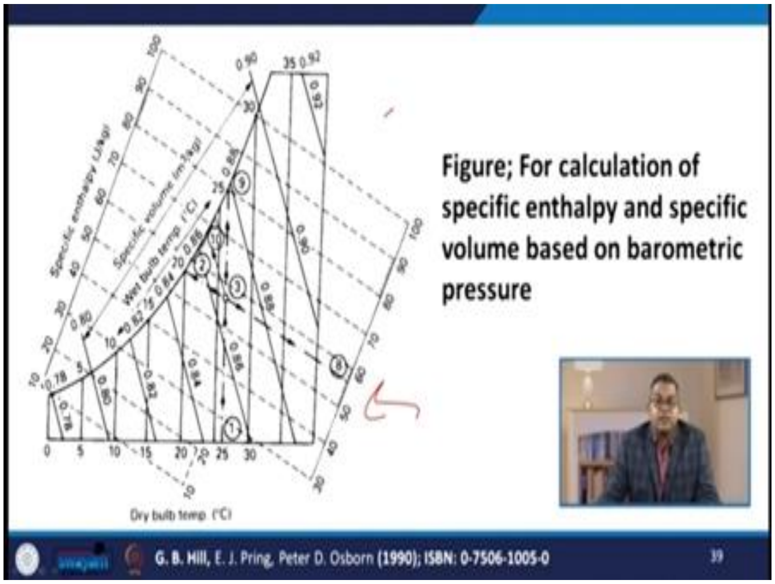

Now here you see that there is this for calculation of this specific enthalpy and specific volume based on the barometric pressure. So it is a complex structure with respect to the dry bulb temperature and specific enthalpy is given.

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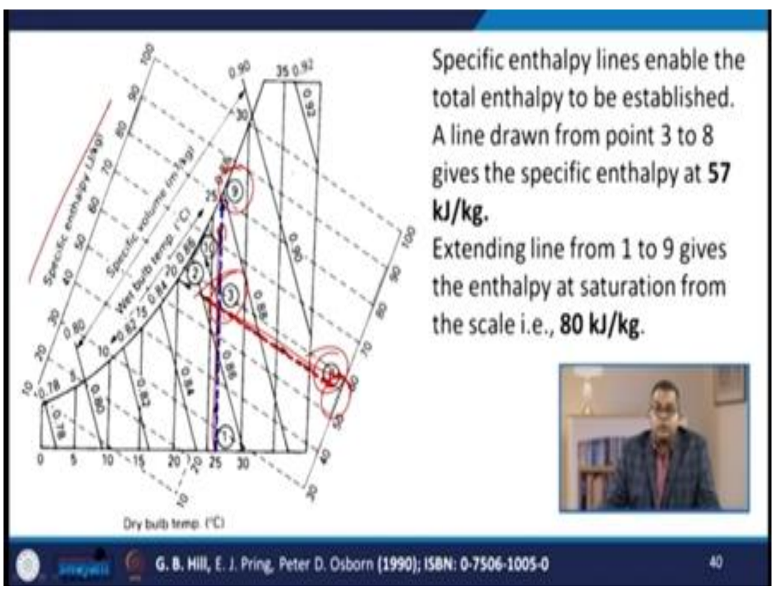

Now specific enthalpy lines these enable the total enthalpy to be established. Now if we draw a line from point number 3 to 8 like this gives the specific enthalpy that is 57 kilogram per kilo joule. Now if we extend this line further to the point number 9 here. It gives the enthalpy at saturation from the scale and this comes out to be nearly 80 kilo joule per kilogram.

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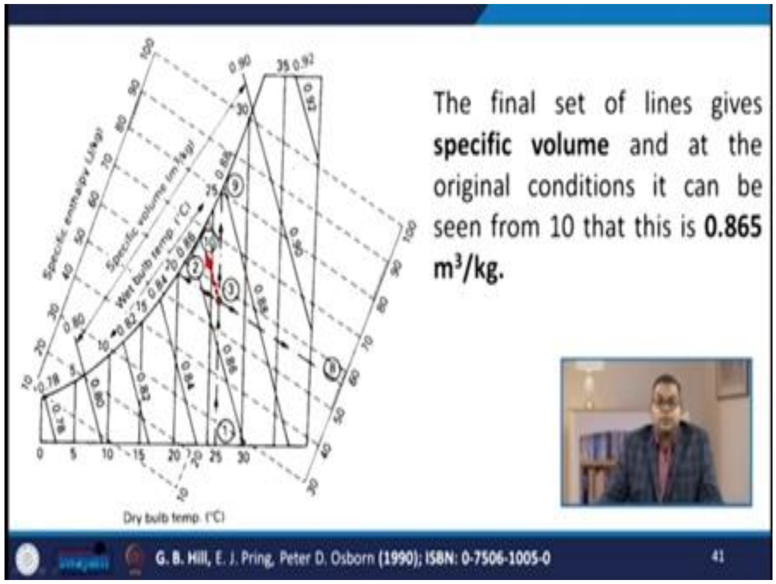

The final set of lines, this gives the specific volume and the original condition can be assessed and that is 0.865 meter cube per kilogram.

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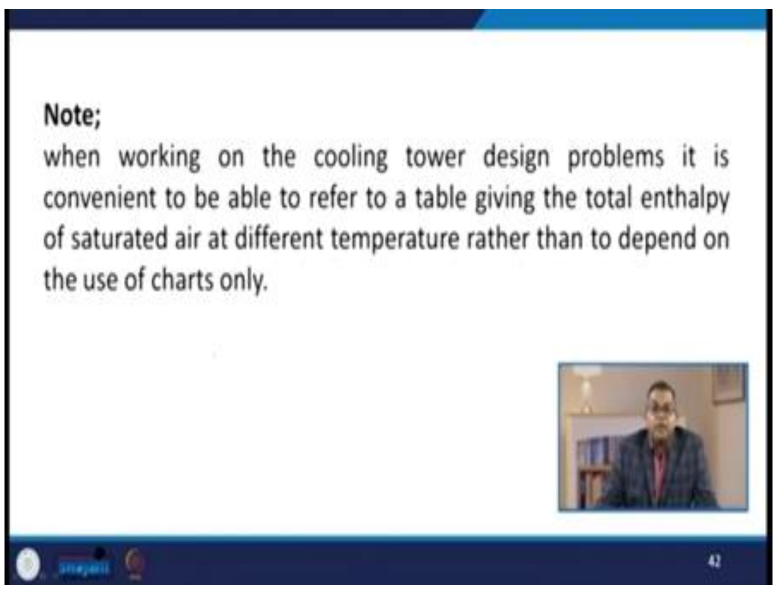

Now when, working on the cooling tower design problem it is convenient to able to refer to a table giving the total enthalpy of saturated line air at different temperature rather than to depend on the use of charts only. Now when; we talk about the wet bulb temperature and the system equilibrium. Suppose that the unsaturated air is brought into contact with the liquid water under adiabatic condition there is no heat transfer take place between the systems.

As the air is not saturated water will evaporate into it and because air is unsaturated and increase in the humidity of the air. The latent heat of evaporation of water cannot be supplied to surrounding as the process is adiabatic. So must be supplied by the cooling of either water or air or both of them. Now, if you consider that a stream of unsaturated air at constant initial temperature and humidity is passed over a wetted surface.

The initiative temperature of wetted surface is approximately the same as air. Then evaporation of water from the wetted surface, lower the temperature to it.

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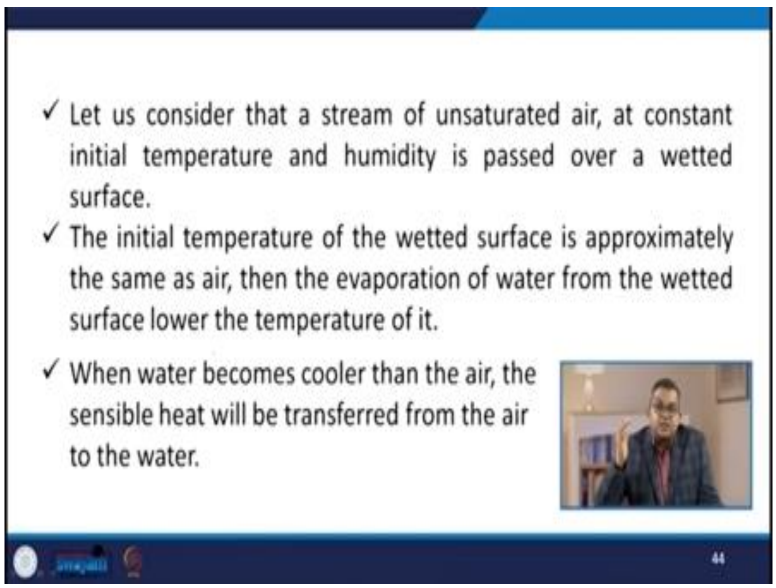

Now when, water become cooler then air the sensible heat will be transferred from air to water.

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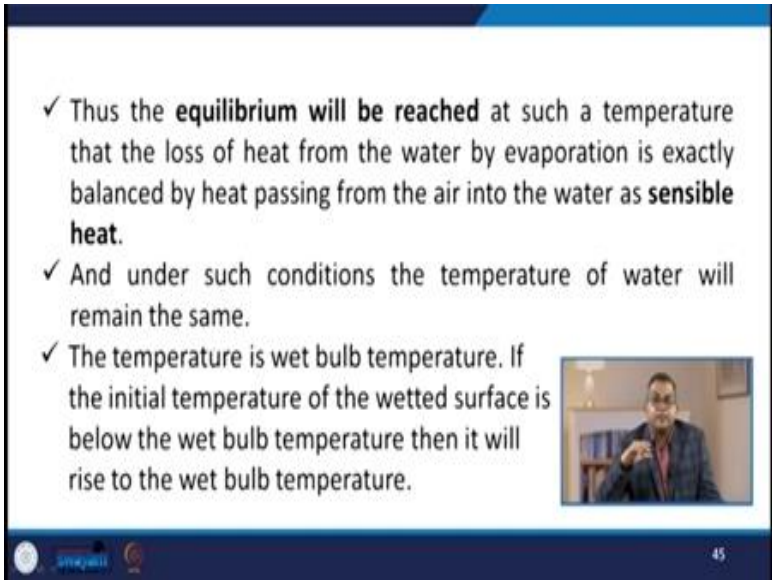

Thus, the equilibrium will be reached at such temperature and that the loss of heat from water by evaporation is exactly balanced by the heat passing from air into the water as sensible heat. Now under such conditions the temperature of water will remain the same. The temperature is the wet bulb temperature, and if the initial temperature of the wetted surface is below the wet bulb temperature. Then it will rise to the wet bulb temperature.

So in this particular lecture, we discussed about the different definitions which are essential for the designing of cooling tower and which is again, the integral part, of our process utilities for your convenience.

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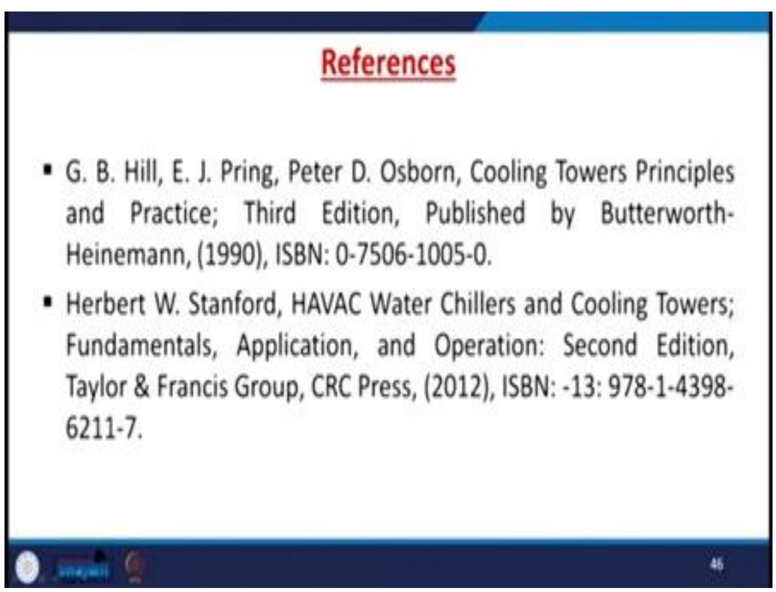

We have enlisted, couple of references. You can see those references if you need to have a further knowledge. Thank you very much.