Applied Thermodynamics
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Module - 05
Refrigeration and Air-Conditioning System
Lecture - 40
Fundamentals of Psychrometrics

Dear learners, greetings from IIT Guwahati we are in the Applied Thermodynamics course module 5 Refrigeration and Air–Conditioning.

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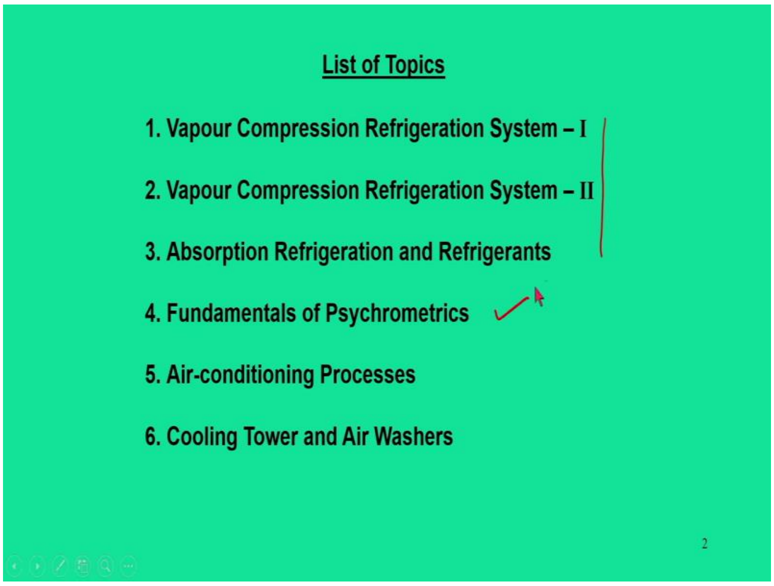

List of Topics

1. Vapour Compression Refrigeration System – I
2. Vapour Compression Refrigeration System – II
3. Absorption Refrigeration and Refrigerants
4. Fundamentals of Psychrometrics ✓
5. Air-conditioning Processes
6. Cooling Tower and Air Washers

Till last class we covered three lectures which are based on vapour compression refrigeration system and vapour absorption refrigeration systems. In addition to that we discussed about refrigerants and their nomenclature as well as designations. Now, we will move on to air conditioning processes, its thermodynamic aspects.

So, under this heading we have three lectures, lecture number 4 fundamentals of psychrometrics, then 5 air conditioning processes, 6 cooling tower and air washers. Now, we are in the lecture number 4 that is Fundamentals of Psychrometrics.

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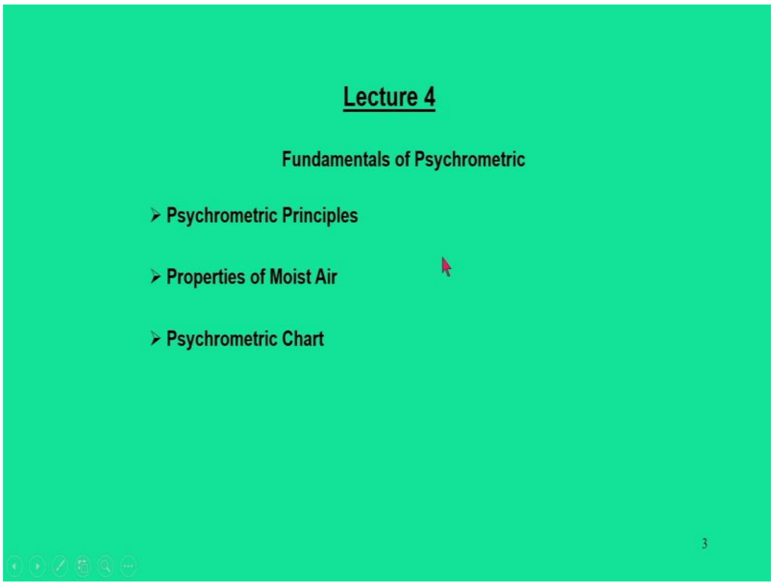

Lecture 4

Fundamentals of Psychrometric

- Psychrometric Principles
- Properties of Moist Air
- Psychrometric Chart

Under this lecture we will be addressing the following topics what are the psychrometric principles, why you are going to study psychrometrics and different properties of moist air. So, till this point of time when you talk about air we only talk about dry air, but whenever you are dealing with psychrometric then you must deal with moist air. And we have to evaluate its properties to address all the thermodynamic fundamentals.

Then we will move on to psychrometric charts. So, on this psychrometric chart we are going to say that how you are going to calculate or evaluate the properties of moist air on a single psychrometric chart. So, this is all the topics that you are going to address in this lecture.

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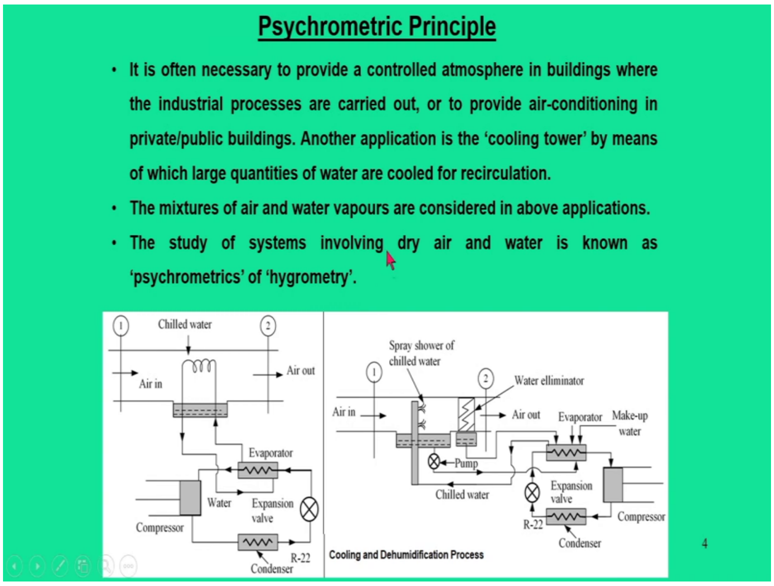

Psychrometric Principle

- It is often necessary to provide a controlled atmosphere in buildings where the industrial processes are carried out, or to provide air-conditioning in private/public buildings. Another application is the 'cooling tower' by means of which large quantities of water are cooled for recirculation.
- The mixtures of air and water vapours are considered in above applications.
- The study of systems involving dry air and water is known as 'psychrometrics' of 'hygrometry'.

Cooling and Dehumidification Process

So, let us start the first one that is psychrometric principles. The very basic fundamental aspect is that, why we should know the psychrometrics? What is the requirement? Now, when you dealt with refrigerations, our main attention was focused on coolness in terms of temperature below 0°C or in that range.

Maybe we also require comfort cooling as well as some situation, we require the temperature to be -10, -20°C. So, that depends on the cooling requirement. However in some situations in addition to the temperatures, we also have to look into the water vapours present in the air. So, while looking into water vapour present in the air we have to quantify its value for which some of the properties we are going to determine.

So, when you talk about air conditioning processes, it is essentially simultaneous control of temperatures which is relatively low. At the same time we have to look into the water vapour quantifications present in the air, so as to have comfort cooling.

So, these two simultaneous control is possible only when we know the moist air and its properties. So, those studies that involves the dry air as well as water vapours present is known as the psychrometrics or many a times we call as hygrometry. This particular figure shows a kind of applications where air is intentionally made moist.

So, one way when you increase the water vapours in the dry air, such a process we can call it as a humidifications and in some cases we can also think of removing air from the water vapour. So, you can say it is a dehumidification process. So, in one sense, here air is allowed to pass through a chilled water circulating coil. So, as a result the air gets humidified as well as temperature also comes down.

So, it is a cooling and humidification, another way is that when you are using water eliminators. So, you have to remove the water vapours present in the air. So, that way when we are taking it out we can say dehumidification of air. So, there are many processes heating humidifications, cooling dehumidifications; many combinations are possible depending on the requirement. And such a study requires the knowledge of humidity as well as the temperatures.

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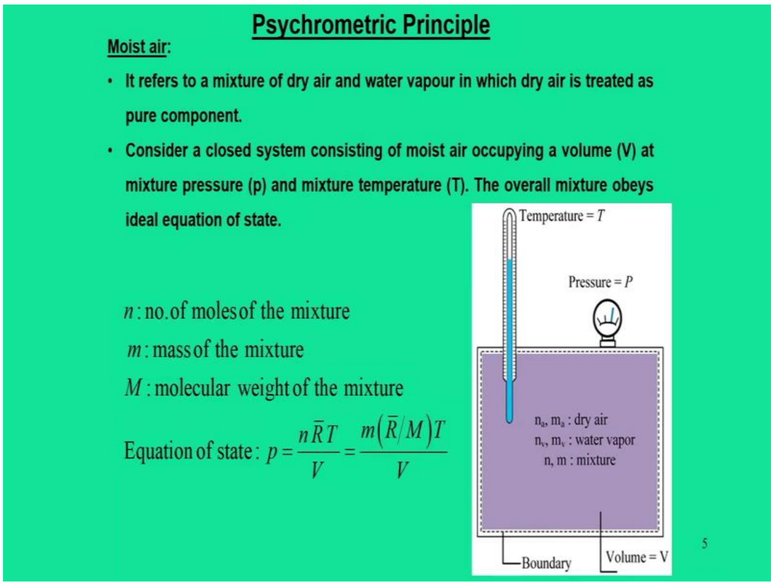

Psychrometric Principle

Moist air:

- It refers to a mixture of dry air and water vapour in which dry air is treated as pure component.
- Consider a closed system consisting of moist air occupying a volume (V) at mixture pressure (p) and mixture temperature (T). The overall mixture obeys ideal equation of state.

n : no. of moles of the mixture

m : mass of the mixture

M : molecular weight of the mixture

Equation of state: $p = \frac{n\bar{R}T}{V} = \frac{m\left(\bar{R}/M\right)T}{V}$

And for that thing we have to define what is a moist air. So, basically moist air in a Layman sense we understand when there is some water vapours present in the air, we say air is moist. So, for example, thermodynamically if you take a control volume and in that volume we have a mixture that contains dry air and water vapour.

And these mixtures are stored in this container and from which we can measure its temperature T and pressure p. So, what we say? Irrespective of air or water vapour, the mixture temperature is at T, the total pressure that is measured is p.

But; however, within this moist air depending on the quantity of water vapours, the total pressure remains same, but the component of pressures in the form of dry air or water vapour may be different. And of course, even though they are at same mixture temperatures. So, that is the reason we have to quantify how much water vapour is present, what is the water vapour pressure inside this moist air; to study you have to know this moist air.

So, one way to look at this problem is in a sense that the when you talk about water vapours, and water is treated as a pure substance. So, whenever we are in the saturated vapour region and beyond that saturated vapour region when you deal with a mixture, then we can use our steam table data to quantify the correct state or the magnitude of water vapour corresponding to that temperatures.

And of course, since it is a vapour, we can also use this ideal equation of state for water vapours in which we can say that M is the molecular weight of the mixture. When we say molecular weight of the mixture we have to say dry air as well as the water vapours. So, we can use that equation of state to quantify or find out the mixture pressure.

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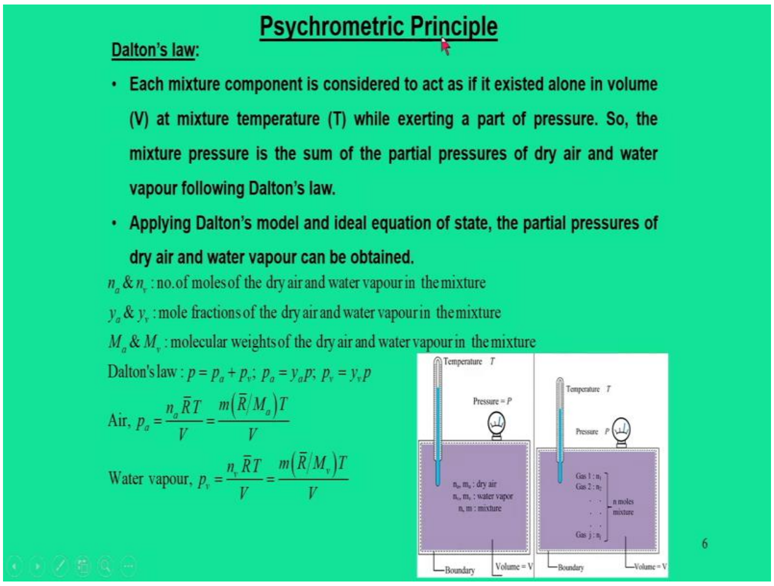

Psychrometric Principle

Dalton's law:

- **Each mixture component is considered to act as if it existed alone in volume (V) at mixture temperature (T) while exerting a part of pressure. So, the mixture pressure is the sum of the partial pressures of dry air and water vapour following Dalton's law.**
- **Applying Dalton's model and ideal equation of state, the partial pressures of dry air and water vapour can be obtained.**

n_a & n_v : no.of moles of the dry air and water vapour in the mixture

y_a & y_v : mole fractions of the dry air and water vapour in the mixture

M_a & M_v : molecular weights of the dry air and water vapour in the mixture

Dalton's law : $p = p_a + p_v;\ p_a = y_a p;\ p_v = y_v p$

Air, $p_a = \dfrac{n_a \bar{R} T}{V} = \dfrac{m\left(\bar{R}/M_a\right)T}{V}$

Water vapour, $p_v = \dfrac{n_v \bar{R} T}{V} = \dfrac{m\left(\bar{R}/M_v\right)T}{V}$

Another important aspect in the psychrometric principle is Dalton's law. In general the Dalton's law says that in a gas mixture if there are n number of gases and they are kept in a container for which the total pressure is p and the temperature is T; that means, all the mixture is at a temperature T.

And each gas has certain number of moles and, so gas 1 has n_1 number of moles, gas 2 has n_2 number of moles. So, each gas will have its components or contribution in terms of the total pressureand we call this as a partial pressures and for gas 1, gas 2 and so on. So, likewise we have the total pressure is equal to sum of the partial pressures of each gas.

So, likewise we can say p is equal to $p_1 + p_2 + p_j + p_n$. So, that is the basic principle what we call as a Dalton‘s law. And this Dalton’s law we can apply to our systems and in our systems there are only two constituents one is dry air, other is the water vapours.

So, we can say the total pressure may be equal to the partial pressure of air + partial pressure of vapours. And this partial pressure of air we can express in the form of mole fraction $p_a = y_a p$; that means, y_a is the number of moles of mixture for the air and y_v is the number of moles for vapour.

So, that way we can quantify this p_a and p_v. And ultimately when you put this ideal gas equation of state for air and water we can write this equations $p_a = \frac{n_a \bar{R} T}{V} = \frac{m\left(\bar{R}/M_a\right)T}{V}$, V is your total volume, T is the mixture temperature.

Similarly, we also can find out the partial pressure of water vapour knowing the molecular mass of vapour. And of course, this p_a and p_v are evaluated at same mixture temperature T. So, this is how the Dalton’s law is going to be applied and for our study dealing with the psychrometrics.

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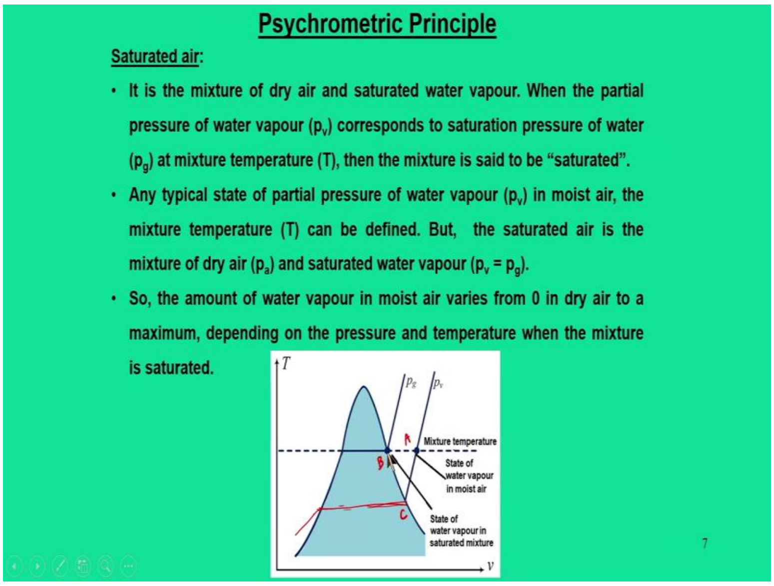

Psychrometric Principle

Saturated air:

- It is the mixture of dry air and saturated water vapour. When the partial pressure of water vapour (p_v) corresponds to saturation pressure of water (p_g) at mixture temperature (T), then the mixture is said to be "saturated".
- Any typical state of partial pressure of water vapour (p_v) in moist air, the mixture temperature (T) can be defined. But, the saturated air is the mixture of dry air (p_a) and saturated water vapour ($p_v = p_g$).
- So, the amount of water vapour in moist air varies from 0 in dry air to a maximum, depending on the pressure and temperature when the mixture is saturated.

Then moving into next principle what we call as saturated air. Now, when you talk about moist air, that means, water vapour is present in it. So, for such a systems; that means, if you take water as a pure substance and recall our temperature volume diagram, in that temperature volume diagram we can draw this constant pressure lines in this manner.

So, one such line is p_v that is partial pressure of vapour. So; that means, if you have a state of moist air at this point A, then at this point A we can draw a vertical on the temperature axis, we can find the mixture temperature.

Now, that mixture temperature, the air exist and that state we say its a state of water vapour present in the moist air. There are two ways in which we can bring this point to a saturation curve. So, one way is that we can cool this or compress this to reach the saturation curve at same vapour pressure other is we can go along the same mixture temperature and it cuts the saturation vapour pressure.

So, the one point is B, another point we can record as C. So, from A to C we can reach if you can cool this and side by side you can compress this then we can reach the saturation curve C and that point we say it is saturated. But this saturated is at same vapour pressure. Other way it can reach is the saturated air state at point B, but when you are going at same mixture temperatures.

So, the saturated air is nothing but the mixture of a dry air and saturated water vapour. So, when the partial pressure of water vapour corresponds to saturation temperature p_g at mixture temperature T, then air is saturated.

So, basically when we have to reach the saturated air then we must recall two things we have to go along the same mixture temperature, wherever it cuts the saturation curve. And in this case it is point B, that case we call this as saturated air.

So, any typical state of partial pressure of water vapour p_v in the moist air, the mixture temperature can be defined. But the saturated air of the mixture p_a and saturated vapour p_v now becomes p_g. So, originally when here we say the water vapour present in this mixture has partial pressure p_v, but when you are reaching the saturated state, we say now p_v becomes p_g because pressure is increased. And of course, the amount of water vapour present in the air can vary from 0 to 1. When it is 0 it is dry air and when it is a maximum it is saturated air, so depending on the pressure and temperature when the mixture is saturated.

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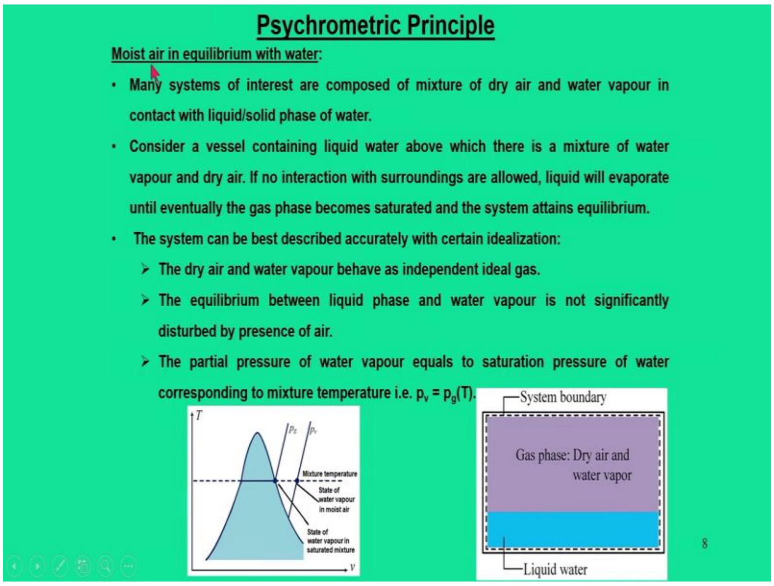

Psychrometric Principle

Moist air in equilibrium with water:

- Many systems of interest are composed of mixture of dry air and water vapour in contact with liquid/solid phase of water.
- Consider a vessel containing liquid water above which there is a mixture of water vapour and dry air. If no interaction with surroundings are allowed, liquid will evaporate until eventually the gas phase becomes saturated and the system attains equilibrium.
- The system can be best described accurately with certain idealization:
    - The dry air and water vapour behave as independent ideal gas.
    - The equilibrium between liquid phase and water vapour is not significantly disturbed by presence of air.
    - The partial pressure of water vapour equals to saturation pressure of water corresponding to mixture temperature i.e. $p_v = p_g(T)$.

Another important aspect is that when you deal with moist air in equilibrium with water. So, many a times in our study of air conditioning processes, we used to be dealing with a water and air simultaneously. Sometimes the water may be in the saturated state, maybe in a steam or a liquid.

So, depending on this case, the moist air can be equilibrium with water. There are many systems of interest in which we require the mixture is in contact with liquid phase or solid phase of water, in some cases it is contact with ice also. So, we can take a situation that when you can have a system which has a vessel containing a liquid water and above which there is a mixture of water vapour and dry air.

So, if there is no interaction with surroundings allowed, these liquids will evaporate and eventually the gas phase becomes saturated and system attends equilibrium. So, this particular experiment can be done in a closed container if we can put some liquid water with half filled. And if you keep it holding and after some time we can have two distinct phases, one is complete liquid water phase, other can be in a gas phase.

And in the gas phase, in the remaining part of this volume becomes a composition of gas which means it is a mixture of dry air and water vapour. So, we can say the mixture is in equilibrium. So, such a system can be best described accurately with certain idealization that is dry air and water vapour, they behave as two independent ideal gas.

So, one thing we can say is that for this liquid water, separate treatment can be done as far as the stream table is concerned and they are saturated liquid state. And other things we can do it that this gas phase, we can separate one part as dry air, other part can be of water vapours.

So, the equilibrium between liquid phase and water vapour is not significantly distributed by the presence of air. The partial pressure of water vapour is equal to saturation pressure of water corresponding to the mixture temperatures. So, we can make some assumption, so that we can model this moist air when it is equilibrium with water.

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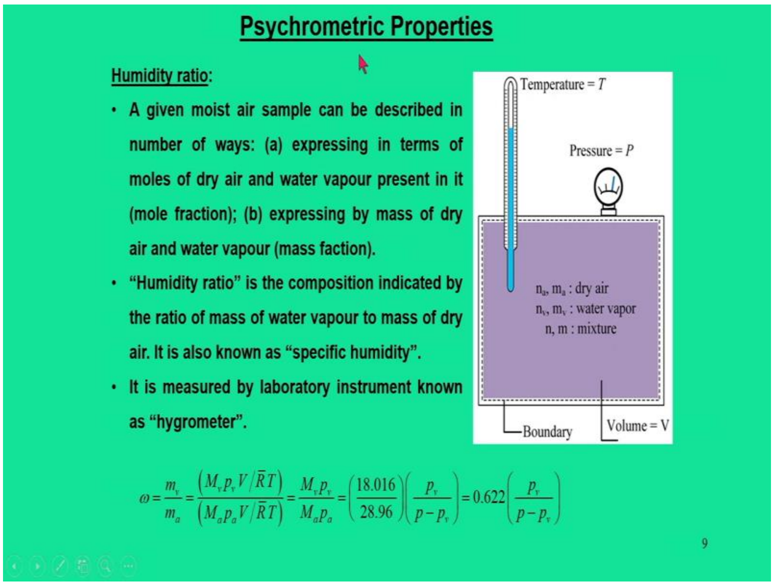

Psychrometric Properties

Humidity ratio:

- A given moist air sample can be described in number of ways: (a) expressing in terms of moles of dry air and water vapour present in it (mole fraction); (b) expressing by mass of dry air and water vapour (mass faction).
- "Humidity ratio" is the composition indicated by the ratio of mass of water vapour to mass of dry air. It is also known as "specific humidity".
- It is measured by laboratory instrument known as "hygrometer".

$$\omega=\frac{m_v}{m_a}=\frac{\left(M_v p_v V/\bar{R}T\right)}{\left(M_a p_a V/\bar{R}T\right)}=\frac{M_v p_v}{M_a p_a}=\left(\frac{18.016}{28.96}\right)\left(\frac{p_v}{p-p_v}\right)=0.622\left(\frac{p_v}{p-p_v}\right)$$

Next thing we will move into psychrometric properties, the first properties that we are going to discuss is the humidity ratio. So, if you recall our analysis that we have a moist air having certain compositions n_a and m_a is the number of moles and mass of that dry air, n_b and m_b as number of moles of water vapour and mass of water vapours, n and m are the moles of mixture and mass of the mixture, they are kept in a container.

Now, how you are going to quantify? The first way of quantifications is to define its properties. There are two ways in which this moist air sample can be described, first one by expressing in terms of moles of dry air and water vapour present in it, so we call this as a mole fraction. Other way is that we can express them in terms of their mass, so we call as a mass fractions.

There are two ways mole fraction or mass fractions. Now, when we say humidity ratio as one of the properties, it is the composition indicated by the ratio of mass of water vapour to the mass of dry air. So, that means, $\omega=\frac{m_v}{m_a}$.

Now, here this mass we can express from the ideal gas equation of state for water vapours. So, in terms of molecular weight, partial pressure of vapours and of course, we have universal gas constant. And all these things are addressed because the total volume is fixed and mixture temperature is fixed. And similarly we also can find out the mass of air.

After simplifications we are in the position that this equation gets simplified we got a ratio of molecular masses for water vapour and air. So, we put their absolute values of molecular masses then we have p_v and p_a. So, if you say total pressure p and p_a is your air pressure. So, using the Dalton's law we can write $p_a = p - p_v$.

And ultimately the omega, which is humidity ratio is expressed by a simple expressions that is $\omega = 0.622\left(\frac{p_v}{p - p_v}\right)$. So, here the 0.622 terms arises because we have taken the molecular mass of water vapour and air ratio. So, this is one way that we represent humidity ratio.

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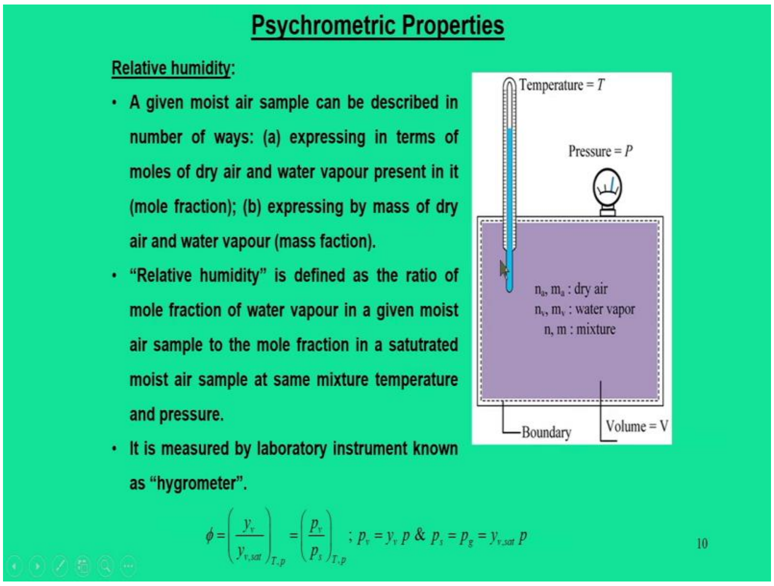

Psychrometric Properties

Relative humidity:

- A given moist air sample can be described in number of ways: (a) expressing in terms of moles of dry air and water vapour present in it (mole fraction); (b) expressing by mass of dry air and water vapour (mass faction).
- "Relative humidity" is defined as the ratio of mole fraction of water vapour in a given moist air sample to the mole fraction in a satutrated moist air sample at same mixture temperature and pressure.
- It is measured by laboratory instrument known as "hygrometer".

$$\phi = \left(\frac{y_v}{y_{v,sat}}\right)_{T,p} = \left(\frac{p_v}{p_s}\right)_{T,p} \; ; p_v = y_v\, p \;\&\; p_s = p_g = y_{v,sat}\, p$$

The other way of expressing this property is in terms of relative humidity. So, in that case what you have to use? You have to take the ratio of mole fraction of water vapour in a given moist air sample to the mole fraction of saturated moist air sample in the same mixture pressure and temperatures. So, relative humidity is defined in that manner. So, if you say $\phi = \left(\frac{y_v}{y_{v,sat}}\right)_{T,p}$.

So, $\phi = \left(\dfrac{p_v}{p_s}\right)_{T,p}$ and here the mole fraction we can write in terms of $p_v = y_v\, p$ & $p_s = p_g = y_{v,sat}\, p$ where, p stands for the total pressure. So, interestingly when you talk relative humidity it is unitless. Whereas, when we talk about humidity ratio it has some unit and these unit we are expressed in kg of water vapour per kg of dry air.

So, that is how it is defined. So, in a sense that although both numerator and denominator are kg, but since you need to separate it out for dry air and the moist air in the humidity ratio, then we have assigned a unit. But on the other hand, relative humidity does not have any unit.

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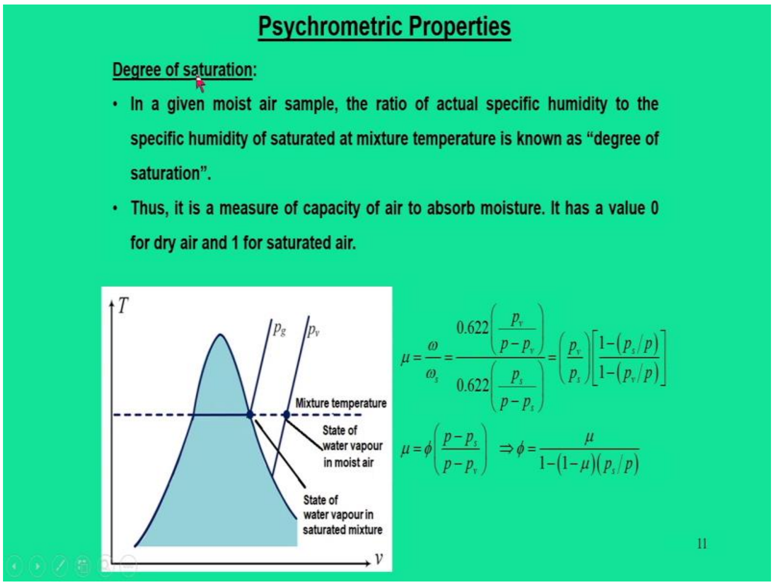

Psychrometric Properties

Degree of saturation:

- In a given moist air sample, the ratio of actual specific humidity to the specific humidity of saturated at mixture temperature is known as “degree of saturation”.
- Thus, it is a measure of capacity of air to absorb moisture. It has a value 0 for dry air and 1 for saturated air.

$$\mu = \frac{\omega}{\omega_s} = \frac{0.622\left(\dfrac{p_v}{p-p_v}\right)}{0.622\left(\dfrac{p_s}{p-p_s}\right)} = \left(\frac{p_v}{p_s}\right)\left[\frac{1-(p_s/p)}{1-(p_v/p)}\right]$$

$$\mu = \phi\left(\frac{p-p_s}{p-p_v}\right) \Rightarrow \phi = \frac{\mu}{1-(1-\mu)(p_s/p)}$$

The another term that is of interest is degree of saturations. So, this is nothing different, but you can mix these two terms relative humidity and humidity ratio. And to define this particular term, so two properties when we linked together, we call this as a degree of saturation that is µ. The ratio of actual specific humidity to the specific humidity of saturated at mixture temperature is known as degree of saturation.

So, $\mu = \frac{\omega}{\omega_s}$, which is the actual specific humidity and specific humidity if the mixture would have been saturated. $\mu = \frac{0.622\left(\frac{p_v}{p-p_v}\right)}{0.622\left(\frac{p_s}{p-p_s}\right)}$ So, when you talk about ω, we say it is a vapour pressure; when you talk about ω_s, this vapour pressure now becomes saturated pressure.

So, after simplifying this we can get a expression $\mu = \left(\frac{p_v}{p_s}\right)\left[\frac{1-(p_s/p)}{1-(p_v/p)}\right]$. So, ultimately we have an expression μ and ϕ that link together in the form of partial pressures of water vapour of actual state, saturated air and the total pressure p. And after doing some kind of simplifications we are able to represent ϕ as a function of μ and p s as well as p. So, this is just a corollary of the other two information.

$$\mu = \phi\left(\frac{p-p_s}{p-p_v}\right) \quad \Rightarrow \phi = \frac{\mu}{1-(1-\mu)(p_s/p)}$$

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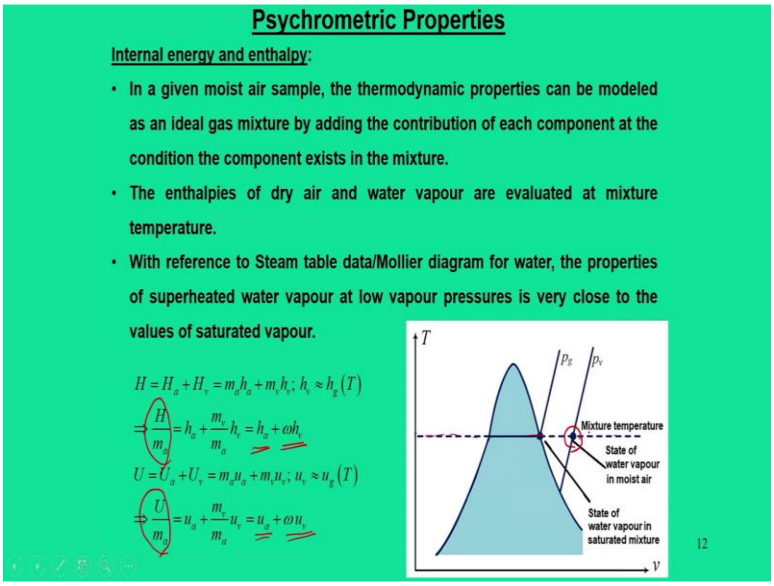

Psychrometric Properties

Internal energy and enthalpy:

- In a given moist air sample, the thermodynamic properties can be modeled as an ideal gas mixture by adding the contribution of each component at the condition the component exists in the mixture.
- The enthalpies of dry air and water vapour are evaluated at mixture temperature.
- With reference to Steam table data/Mollier diagram for water, the properties of superheated water vapour at low vapour pressures is very close to the values of saturated vapour.

$$H = H_a + H_v = m_a h_a + m_v h_v;\ h_v \approx h_g(T)$$

$$\Rightarrow \frac{H}{m_a} = h_a + \frac{m_v}{m_a} h_v = h_a + \omega h_v$$

$$U = U_a + U_v = m_a u_a + m_v u_v;\ u_v \approx u_g(T)$$

$$\Rightarrow \frac{U}{m_a} = u_a + \frac{m_v}{m_a} u_v = u_a + \omega u_v$$

Next property that we are going to talk about is the internal energy and enthalpy. So, thermodynamically when you deal with different temperatures, the other properties are internal energy and enthalpy. And of course, when we have flowing stream, we define in the form of enthalpy, when you have a stagnant stream or control volume system or a closed system, then you use internal energy.

So, we are looking at a state in a T v diagram, at that point if you want to quantify what is the enthalpy and internal energy. Then there are two ways the total enthalpy can divided as enthalpy of dry air plus enthalpy of water vapours.

So, this dry air part can be dealt separately $m_a h_a$ and this is nothing but $c_p T_a$ because it is a dry air component. And $m_v h_v$ is nothing but the vapour pressure component. So, once you know the mixture temperature and if it is a saturated it is close to value of $h_v \approx h_g(T)$ and this enthalpy value is close to the saturated vapour state. So, from this we can simplify in terms of per unit mass of dry air.

So, if you take $\frac{H}{m_a}$, this is nothing but specific enthalpy of the mixture. It has two components $h_a + \omega h_v$, one is enthalpy of dry air and other is enthalpies of moist air. Similarly, we also can have internal energy per unit mass of dry air as two components internal energy for dry air and internal energy for water vapours, which is nothing but $\frac{U}{m_a} = u_a + \frac{m_v}{m_a} u_v = u_a + \omega u_v$.

And many a times we say when you say u_v is nothing but it is a saturated vapour state. So, it is a gas phase and that is evaluated at mixture temperature. And this mixture temperature is nothing but this particular temperature at which it can be located in the T v diagram.

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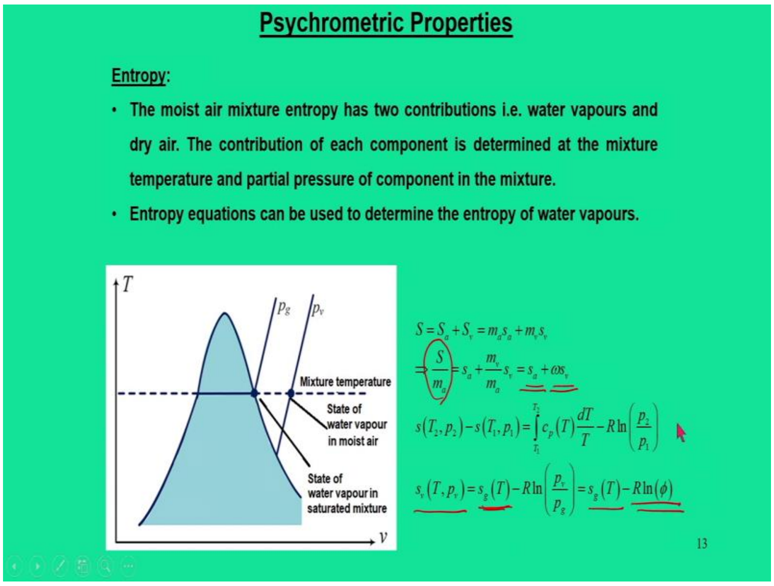

Psychrometric Properties

Entropy:

- The moist air mixture entropy has two contributions i.e. water vapours and dry air. The contribution of each component is determined at the mixture temperature and partial pressure of component in the mixture.
- Entropy equations can be used to determine the entropy of water vapours.

$$S = S_a + S_v = m_a s_a + m_v s_v$$

$$\Rightarrow \frac{S}{m_a} = s_a + \frac{m_v}{m_a} s_v = \underline{\underline{s_a}} + \underline{\underline{\omega s_v}}$$

$$s(T_2, p_2) - s(T_1, p_1) = \int_{T_1}^{T_2} c_p(T)\frac{dT}{T} - R\ln\left(\frac{p_2}{p_1}\right)$$

$$\underline{s_v(T, p_v)} = \underline{s_g(T)} - R\ln\left(\frac{p_v}{p_g}\right) = \underline{s_g(T)} - \underline{\underline{R\ln(\phi)}}$$

And similar sense we also have entropy. So, entropy has two components as well here water vapours and dry air and each components can be dealt separately. So, in same sense, the entropy of the mixture that is per unit mass of dry air is $\frac{S}{m_a} = s_a + \omega s_v$. So, here the important aspect is that how to find out s_v entropy of water vapours.

Of course, for dry air component, we can find out in similar way as you do in the thermodynamic aspects. Now, when you talk about water vapours, so you have to recall our entropy equations which is evaluated between two states. So, here the two states are one is the actual state other is the saturated vapour at mixture temperature T and partial pressure p_v.

So, that is your actual state, but the corresponding reference point to take this difference is if the air is saturated, it would have $s_v(T, p_v) = s_g(T) - R\ln\left(\frac{p_v}{p_g}\right)$. So, p_v is your vapour pressure and p_g is your pressure when the air is saturated or gas phase pressure. So, now it becomes $s_g(T) - R\ln(\phi)$.

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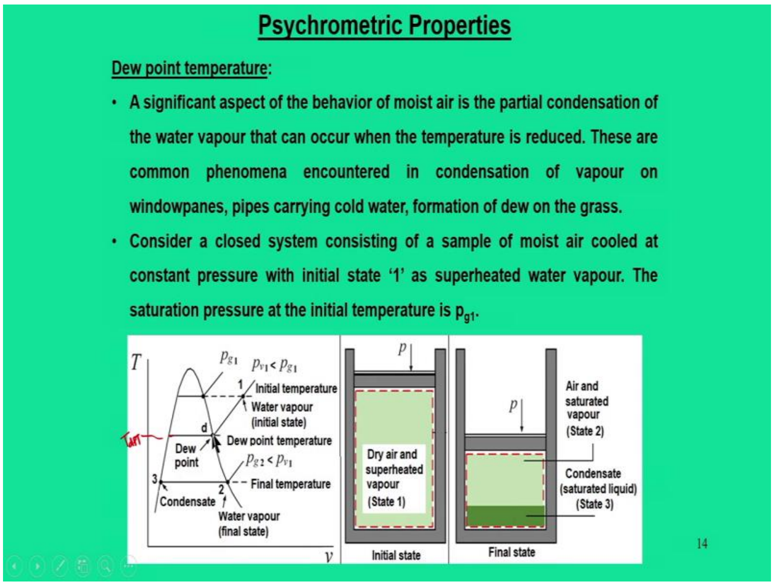

Psychrometric Properties

Dew point temperature:

- A significant aspect of the behavior of moist air is the partial condensation of the water vapour that can occur when the temperature is reduced. These are common phenomena encountered in condensation of vapour on windowpanes, pipes carrying cold water, formation of dew on the grass.
- Consider a closed system consisting of a sample of moist air cooled at constant pressure with initial state '1' as superheated water vapour. The saturation pressure at the initial temperature is p_{g1}.

The next important property is dew point temperature, it is in fact a very important properties. Because we all come across dew in our day to day life or condensed water vapours they are part of day to day life. And mostly they happen in the winter and these water vapours comes as a droplets on the grass during the winter or sometimes the window panes when you deal with air conditioning systems.

Now, what is this dew and why it happens? To understand this particular behaviour, we can define this in the thermodynamic sense. First thing is that we take a container which consists of a dry air and superheated vapour state. That means, superheated vapour is there; that means, thermodynamically we can fix state 1 in a temperature volume diagram.

So, this state 1 is nothing but a volume which contains mixture of dry air and superheated vapour. Now, what you do? We want to cool this, now if you want to cool this, there are two ways of cooling, one of the method is that in a constant pressure based cooling.

So, when I say cooling so that means, from point 1 if I start cooling, specific volume drops, so mixture gets compressed. And if you keep doing and we will reach at a state that at one particular point, this will reach the saturation curve on this saturation point that is point 'd' and we reach the saturation curve.

And below this, temperature cannot be reduced further. Because you already cross the saturation point on this curve and at same pressure, cooling is not possible. as if you do this, it is going to change the phase. So, you have to go along the saturation curve. So, that means, at that time your pressure must decrease further.

Now, when the pressure decreases, also temperature drops, but volume increases. So, initially you start with a initial temperature T_1 and finally, we reach at a final temperature T_2, this is how we talk in terms of temperature.

But if you look at actual composition wise, the composition will have two stages; in one stage we will have state 2. And this state 2 is nothing but dry air and saturated air vapour mixture. Other way will be that we will have some condensed saturated liquid at the bottom.

So, this point is denoted in the T-v curve as point 3. So, basically 2 to 3 process is a constant temperature process and during this process, cooling happens, but here there is a phase change. So, it means that the water vapour change its phase, now they become liquid. So from, where this liquid starts?

So, liquid normally starts from the point when we reach the saturation curve. The first time when you reach the saturated curve at the point ‘d’. So, point ‘d’ is known as the dew point and that temperature if you draw the vertical then that temperature we can say it is T_{dpt}. So, the dew point temperature happens from its initial state if you do the cooling process at same vapour pressure, it reaches the saturation curve and we reach this dew point temperature.

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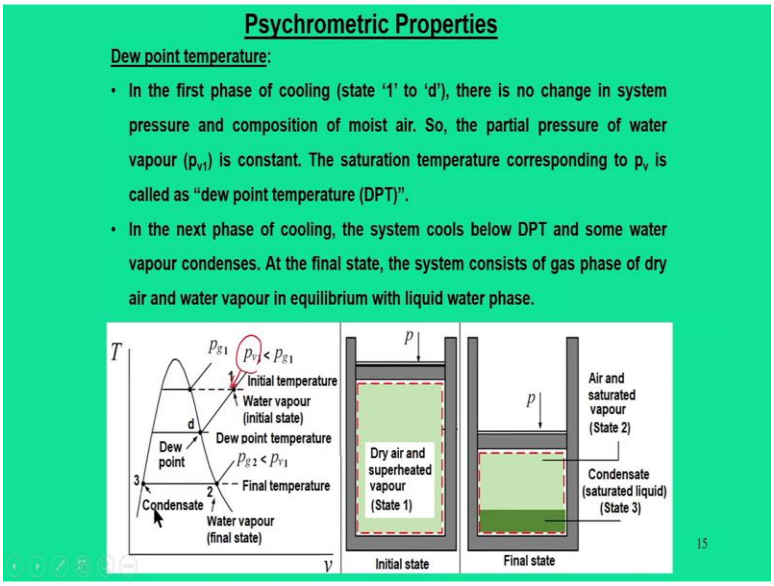

Psychrometric Properties

Dew point temperature:

- In the first phase of cooling (state ‘1’ to ‘d’), there is no change in system pressure and composition of moist air. So, the partial pressure of water vapour (p_{v1}) is constant. The saturation temperature corresponding to p_v is called as “dew point temperature (DPT)”.
- In the next phase of cooling, the system cools below DPT and some water vapour condenses. At the final state, the system consists of gas phase of dry air and water vapour in equilibrium with liquid water phase.

So, this is how it is explained here and typically you have three pressures as of now. So, correspondingly, initially we have pressure p_{v1}, this pressure corresponds to state 1. And at same at same initial temperature if you draw the vertical line, we reach this saturation curve at this point and that point your p_{g1}.

Obviously, if you look at this curve p_{v1} is less than p_{g1}. And subsequently, when you reach at point 2 it will have another pressure and that is this p_{g2} and this p_{g2} also less than p_{v1}. So, in this process we are landed with three pressures, one is actual vapour pressure which is present in this mixture.

Other way is that at the initial temperature and final temperature, the saturated values of gas phase pressure. So, it is p_{g1} for the initial state, p_{g2} for the final state. And in terms of mixture wise, we have two components one is air and saturated vapour at state 2 which is saturated and gas phase state and other way is the condensate which is the saturated liquid state.

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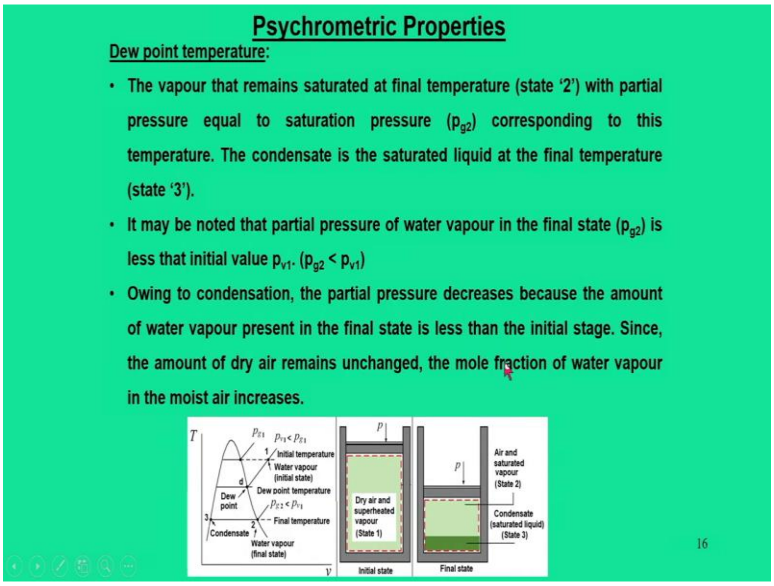

Psychrometric Properties

Dew point temperature:

- The vapour that remains saturated at final temperature (state '2') with partial pressure equal to saturation pressure (p_{g2}) corresponding to this temperature. The condensate is the saturated liquid at the final temperature (state '3').
- It may be noted that partial pressure of water vapour in the final state (p_{g2}) is less that initial value p_{v1}. ($p_{g2} < p_{v1}$)
- Owing to condensation, the partial pressure decreases because the amount of water vapour present in the final state is less than the initial stage. Since, the amount of dry air remains unchanged, the mole fraction of water vapour in the moist air increases.

So, finally, the very basic bottom line is that during the condensation the partial pressure decreases because the amount of vapour pressure present in the final state is less than the initial state. Since, the amount of dry air remains unchanged the mole fraction of water vapour in the moist air increases. So, this is the summary when you talk about dew point temperature.

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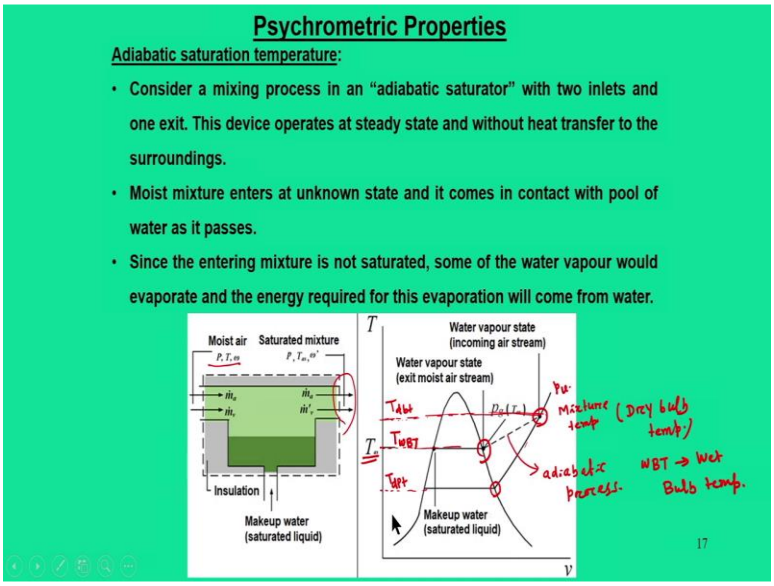

Psychrometric Properties

Adiabatic saturation temperature:

- Consider a mixing process in an "adiabatic saturator" with two inlets and one exit. This device operates at steady state and without heat transfer to the surroundings.
- Moist mixture enters at unknown state and it comes in contact with pool of water as it passes.
- Since the entering mixture is not saturated, some of the water vapour would evaporate and the energy required for this evaporation will come from water.

Another approach in our psychrometric properties is adiabatic saturation temperatures. So, from this last segment of discussion, we said that if you have initial state. And for that initial state if you draw a vertical, so it cuts this temperature T and this temperature we call this as a mixture temperature. And normally, this mixture temperature we call this as a dry bulb temperature, so, we say T_{dbt}.

Now, in our last segment we discussed about the dew point temperature. So, in the same pressure p_v, if you cool this gas we will reach at this point and if you draw a vertical on this temperature axis, we reach dew point temperature T_{dpt}. So, basically define two temperature one is dry bulb temperature other is the dew point temperature. The another way that we can define this temperature is that we can use adiabatic saturation.

So, what does this physically mean that suppose we have a moist air which is at certain condition pressure p, T and ω and on this moist air, we add a water. Now, this moist air whatever state it may be, we keep adding water so that the final state is the saturated mixture. And thermodynamically what we say is that entire system is enclosed or given a perfect insulation, so that no heat transfer is possible from this moist air to this surroundings.

So, it is a complete adiabatic process. Now, when you say complete adiabatic process then how you are going to locate that state in this temperature volume curve? So, this particular way, we go along a dotted line and this dotted line represents that it is a adiabatic process.

Now, when you keep adding moisture into this air. So, we reach another point nothing but water vapour state in the exit and that means, exit moist air stream is completely saturated.

So, that point of time, we drop this vertical, we call this as a adiabatic saturation temperature. And in the psychrometric term, this adiabatic saturation temperature, we call this as a wet bulb temperatures. So, it is T_{wbt}. So, very basic fundamental understanding is that for a given state of mixture, there are three temperatures one is when it is at mixture temperature that is T dry bulb temperature other is we can have a wet bulb temperature.

To reach the wet bulb temperature we have to go through an adiabatic saturation process. And third is we have dew point temperatures and to reach this dew point temperatures, we have to cool this gas till we reach the saturation point, but at constant p_v at same pressure.

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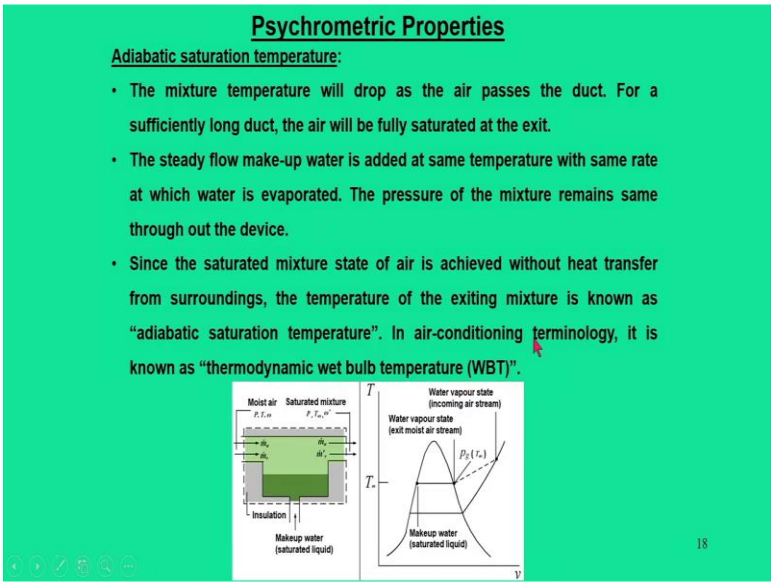

Psychrometric Properties

Adiabatic saturation temperature:

- The mixture temperature will drop as the air passes the duct. For a sufficiently long duct, the air will be fully saturated at the exit.
- The steady flow make-up water is added at same temperature with same rate at which water is evaporated. The pressure of the mixture remains same through out the device.
- Since the saturated mixture state of air is achieved without heat transfer from surroundings, the temperature of the exiting mixture is known as "adiabatic saturation temperature". In air-conditioning terminology, it is known as "thermodynamic wet bulb temperature (WBT)".

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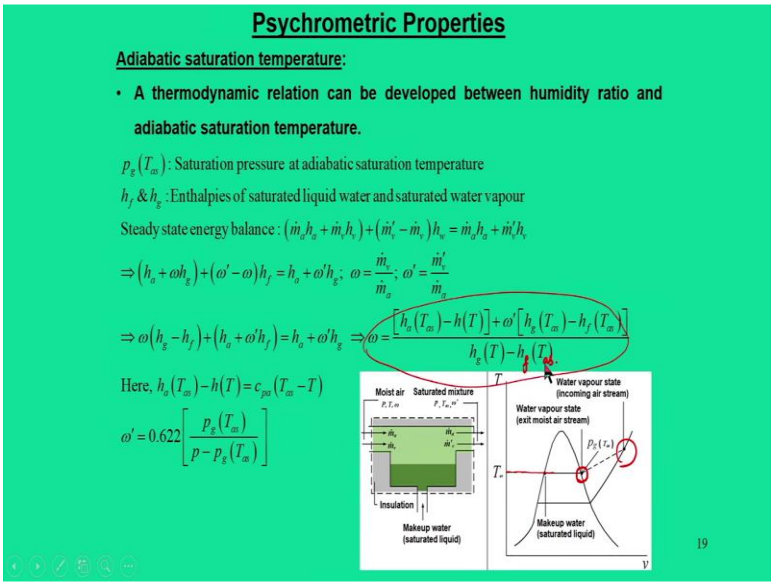

Psychrometric Properties

Adiabatic saturation temperature:

- A thermodynamic relation can be developed between humidity ratio and adiabatic saturation temperature.

$p_g(T_{as})$: Saturation pressure at adiabatic saturation temperature

h_f & h_g : Enthalpies of saturated liquid water and saturated water vapour

Steady state energy balance: $(\dot{m}_a h_a + \dot{m}_v h_v) + (\dot{m}'_v - \dot{m}_v) h_w = \dot{m}_a h_a + \dot{m}'_v h_v$

$$\Rightarrow (h_a + \omega h_g) + (\omega' - \omega) h_f = h_a + \omega' h_g;\ \omega = \frac{\dot{m}_v}{\dot{m}_a};\ \omega' = \frac{\dot{m}'_v}{\dot{m}_a}$$

$$\Rightarrow \omega(h_g - h_f) + (h_a + \omega' h_f) = h_a + \omega' h_g \Rightarrow \omega = \frac{[h_a(T_{as}) - h(T)] + \omega'[h_g(T_{as}) - h_f(T_{as})]}{h_g(T) - h_f(T_{as})}$$

Here, $h_a(T_{as}) - h(T) = c_{pa}(T_{as} - T)$

$$\omega' = 0.622\left[\frac{p_g(T_{as})}{p - p_g(T_{as})}\right]$$

All these things are explained here, there are some thermodynamic relations that can be developed between the humidity ratio and adiabatic saturation temperatures. So, p_g is the gas pressure T_{as} is your adiabatic saturation temperature. So, this point is

$p_g\left(T_{as}\right)$ and when you reach this point, we say we have reached the adiabatic saturation temperatures in this temperature axis.

And h_f & h_g is enthalpy of saturated liquid and saturated vapour. So, a steady flow energy equations can be applied $\left(\dot{m}_a h_a + \dot{m}_v h_v\right) + \left(\dot{m}_v' - \dot{m}_v\right) h_w = \dot{m}_a h_a + \dot{m}_v' h_v$ where $\dot{m}_a h_a + \dot{m}_v h_v$ is your inlet state. And other inlet is the makeup water that gets added this makeup water which is getting added that means, final mass minus initial mass of water vapour and that is equal to final energy.

And remember when you talk about this makeup water, so it is water at liquid state so that is what it is written as h_w. And from this we can find out the humidity ratio at the inlet state that is when the moist air enters into the systems. $\omega = \frac{\dot{m}_v}{\dot{m}_a};\ \omega' = \frac{\dot{m}_v'}{\dot{m}_a}$

And we also can find out the specific humidity or humidity ratio when the air stream comes out. This equation can be simplified in this manner and finally, we land off in this particular expressions. So, this particular expression has information about enthalpy and this enthalpy needs to be calculated which is there in their bracket.

$$\omega = \frac{\left[h_a\left(T_{as}\right) - h\left(T\right)\right] + \omega'\left[h_g\left(T_{as}\right) - h_f\left(T_{as}\right)\right]}{h_g\left(T\right) - h_f\left(T_{as}\right)}$$

So, here the h_a is to be calculated at this adiabatic saturation temperature. This arbitrary is at mixture temperature T. And similarly, h_g stands for the gas phase. So, h_f is your liquid state and this temperature value is to maintain at adiabatic saturation temperatures.

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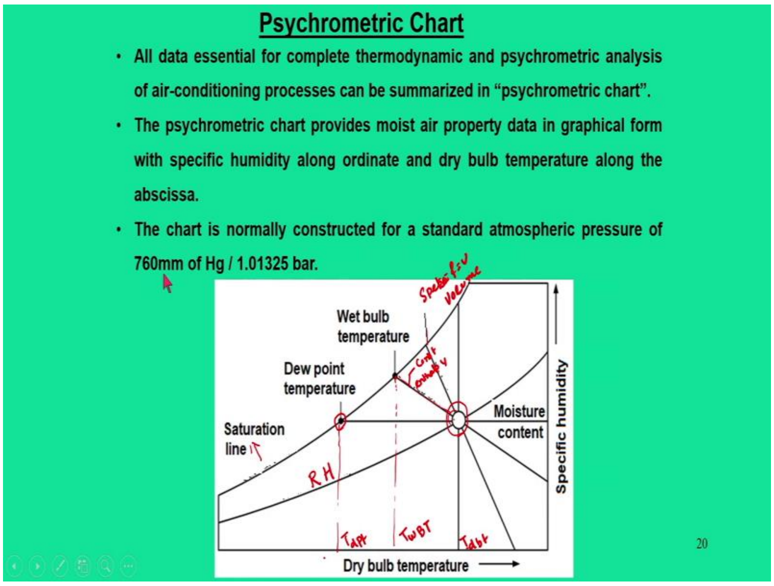

Psychrometric Chart

- All data essential for complete thermodynamic and psychrometric analysis of air-conditioning processes can be summarized in "psychrometric chart".
- The psychrometric chart provides moist air property data in graphical form with specific humidity along ordinate and dry bulb temperature along the abscissa.
- The chart is normally constructed for a standard atmospheric pressure of 760mm of Hg / 1.01325 bar.

Now, till this point of time, we discussed about the all the psychrometric properties. Now, we are going to say that how these psychrometric properties can be utilized or discussed in a psychrometric chart. So, psychrometric chart is nothing but locating the thermodynamic properties in a chart. So, you have a particular state which is denoted by this circle.

So, we have a dry bulb temperature axis, we have a specific humidity axis and for any state within this, we require two property. That means, you will be given with the two property value at the initial state and that point we can locate on this chart.

Now, on this chart, there are lines what you call as relative humidity lines. And this particular line is known as saturated line. Now, from this point if you drop a vertical, we reach the dry bulb temperature on the temperature axis and when you drop a vertical on specific humidity axis, we get the moisture content and wherever it cuts this inclined line, we call this as a relative humidity value at that point. And from this if you go along same specific humidity line; that means, until you reach the saturated point and drop a vertical on the temperature axis. So, this will denote the dew point temperatures. Another way is that when we go along the adiabatic saturation curve, it is nothing but your constant enthalpy curve.

So, if you go along this and reach the saturation point and drop a vertical, this will give you T_{WBT}. So for a given state, there are three temperatures. And there is another line which is goes in this manner and this line is called as a specific volume line. So, all these things is plotted at standard atmospheric pressure that is 760 mm of Hg.

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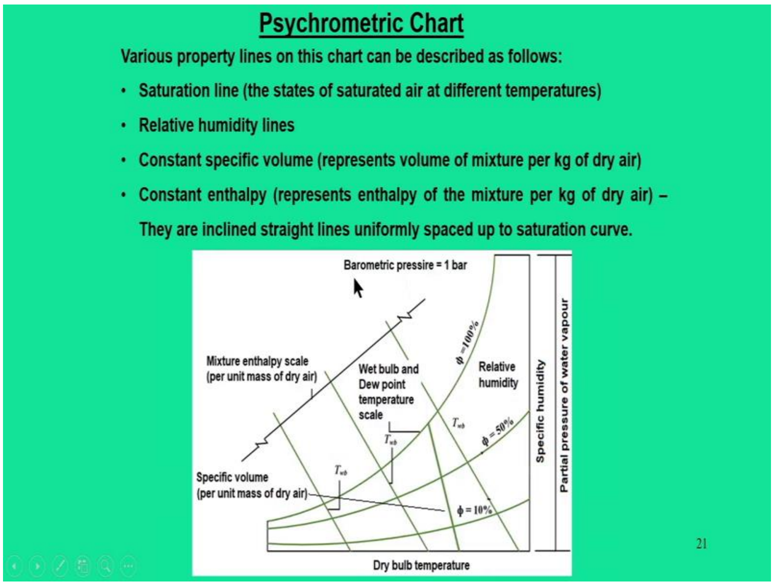

Psychrometric Chart

Various property lines on this chart can be described as follows:

- Saturation line (the states of saturated air at different temperatures)
- Relative humidity lines
- Constant specific volume (represents volume of mixture per kg of dry air)
- Constant enthalpy (represents enthalpy of the mixture per kg of dry air) – They are inclined straight lines uniformly spaced up to saturation curve.

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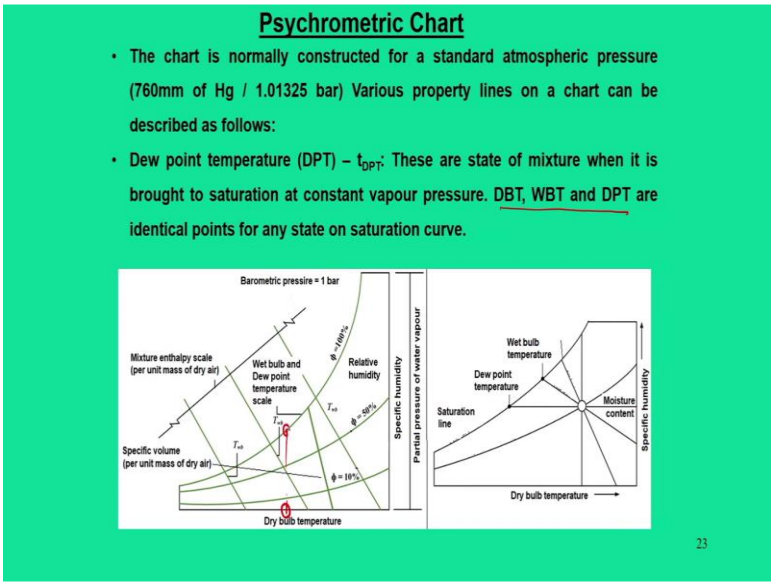

Psychrometric Chart

- The chart is normally constructed for a standard atmospheric pressure (760mm of Hg / 1.01325 bar) Various property lines on a chart can be described as follows:
- Dew point temperature (DPT) – t_{DPT}: These are state of mixture when it is brought to saturation at constant vapour pressure. DBT, WBT and DPT are identical points for any state on saturation curve.

And a more clear picture is shown here. In a psychrometric chart how you can calculate the value of DBT, WBT and DPT.

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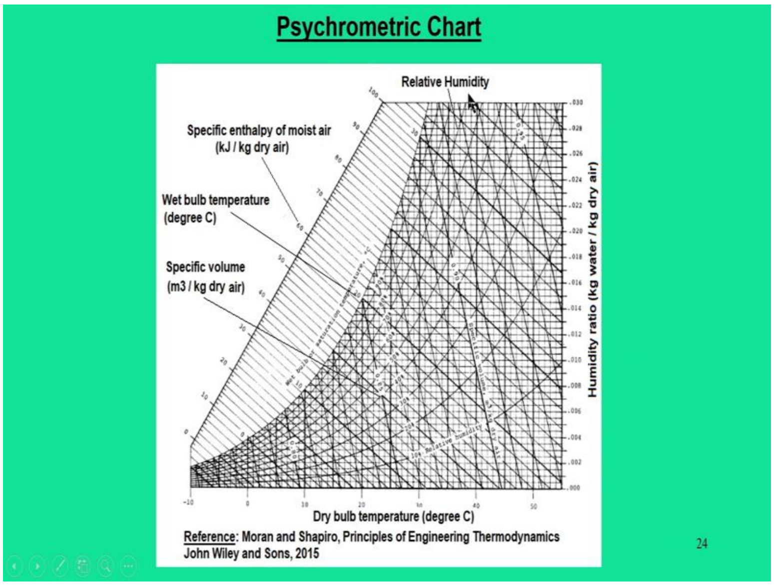

Psychrometric Chart

Reference: Moran and Shapiro, Principles of Engineering Thermodynamics John Wiley and Sons, 2015

And the realistic version of a psychrometric chart is going to look like this. So, here we can see these charts and it is plotted for standard atmospheric pressure of 1 bar.

And for which all the lines with their actual quantification is denoted here. So, basically any processes or change of state of moist air can be located on this psychrometric charts and their approximate values can be found out. Now, we are going to solve a simple problems which we discussed right now.

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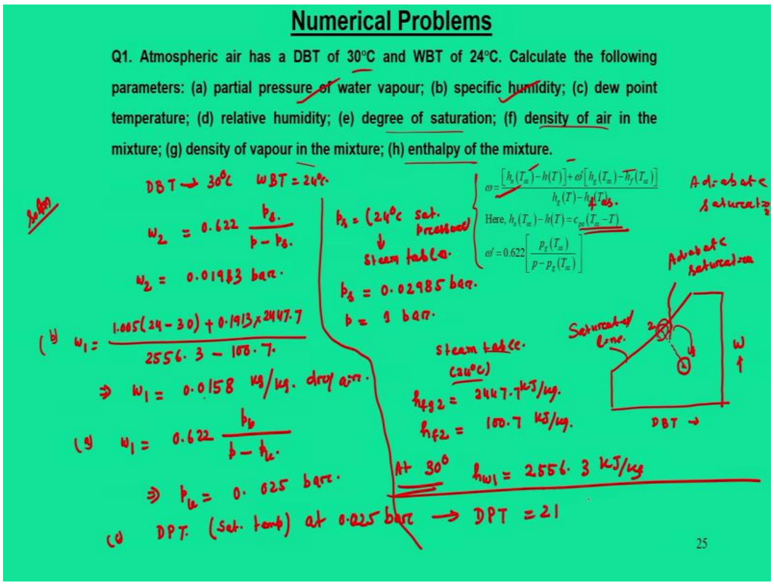

Numerical Problems

Q1. Atmospheric air has a DBT of 30°C and WBT of 24°C. Calculate the following parameters: (a) partial pressure of water vapour; (b) specific humidity; (c) dew point temperature; (d) relative humidity; (e) degree of saturation; (f) density of air in the mixture; (g) density of vapour in the mixture; (h) enthalpy of the mixture.

Soln

DBT → 30°C WBT = 24°C.

$w_2 = 0.622 \frac{p_g}{p - p_g}$

$w_2 = 0.01913$ bar.

p_g = (24°C sat. pressure)
↓
steam table.

$p_g = 0.02985$ bar.

$p = 1$ bar.

$$\omega = \frac{[h_a(T_{as}) - h(T)] + \omega'[h_g(T_{as}) - h_f(T_{as})]}{h_g(T) - h_f(T_{as})}$$

Here, $h_a(T_{as}) - h(T) = c_{pa}(T_{as} - T)$

$$\omega' = 0.622\left[\frac{p_g(T_{as})}{p - p_g(T_{as})}\right]$$

Adiabatic saturation

(b) $w_1 = \frac{1.005(24-30) + 0.1913 \times 2447.7}{2556.3 - 100.7}$

$\Rightarrow w_1 = 0.0158$ kg/kg. dry air.

(a) $w_1 = 0.622 \frac{p_v}{p - p_v}$

$\Rightarrow p_v = 0.025$ bar.

(c) DPT (Sat. temp) at 0.025 bar → DPT = 21

Steam table.
(24°C)

$h_{fg2} = 2447.7$ kJ/kg.

$h_{f2} = 100.7$ kJ/kg.

At 30° $h_{w1} = 2556.3$ kJ/kg

So, we are given with atmospheric air which has a DBT of 30°C and wet ball temperature of 20°C. And we have to calculate the parameters like partial pressure of water vapour, specific humidity, dew point temperature, relative humidity, degree of saturation, density of air in the mixture, density of vapour in the mixture and enthalpy of the mixture.

So, first thing is that as I mentioned there are two ways in which properties values can be calculated. One way is through the expressions that we defined so far, other way we can use the directly psychrometric charts. So, although it is very difficult to remember most of the expressions, but on the other hand for learner or beginner, it is advisable to use the formula to understand the problem.

And later on when you have understand the problem then you can use the psychrometric chart directly. So, in this case, first thing we have to draw this psychrometric chart to locate this state.

So, we have DBT, we have ω and we have state which is this point. And the point 2 is nothing but your adiabatic saturation. Now, why I should go here? Because, to calculate all these degrees of saturation and enthalpy, we require the corresponding values when air is saturated, because this is the saturated line.

So, the solution that we can start is DBT is given 30°C and WBT 24°C. Now, first thing we have to find out this ω. So, here you have to use $\omega = 0.622\left[\dfrac{p_s}{p - p_s}\right]$. So, p_s is calculated at 24°C, we can calculate using steam table. And this value is equal to 0.02985 bar.

And then we also have p = 1 bar. So, from this we can calculate ω_2 as 0.01913 bar then using this equation we can first thing what we are going to calculate, ω_1. Before that, from the steam table at 24°C we can find out h_{fg2} is 2447 kJ/kg, h_{f2} enthalpy value at liquid state 100.7 kJ/kg. And again at 30°C we can calculate h_{w1} as 2556.3 kJ/kg.

$$\omega = \frac{\left[h_a\left(T_{as}\right) - h\left(T\right)\right] + \omega'\left[h_g\left(T_{as}\right) - h_f\left(T_{as}\right)\right]}{h_g\left(T\right) - h_f\left(T_{as}\right)} = \frac{1.005\left(24 - 30\right) + 0.1913 \times 2447.7}{2556.3 - 100.7} = 0.0158$$

So, this will give you ω1 as 0.0158 kg/kg of dry air.

$$\omega_1 = 0.622\left[\frac{p_v}{p-p_v}\right] \Rightarrow p_v = 0.025\text{bar}$$

Then we have to find dew point temperatures. So, DPT can be find out at saturation temperature at 0.025 bar. So, DPT is equal to 21°C.

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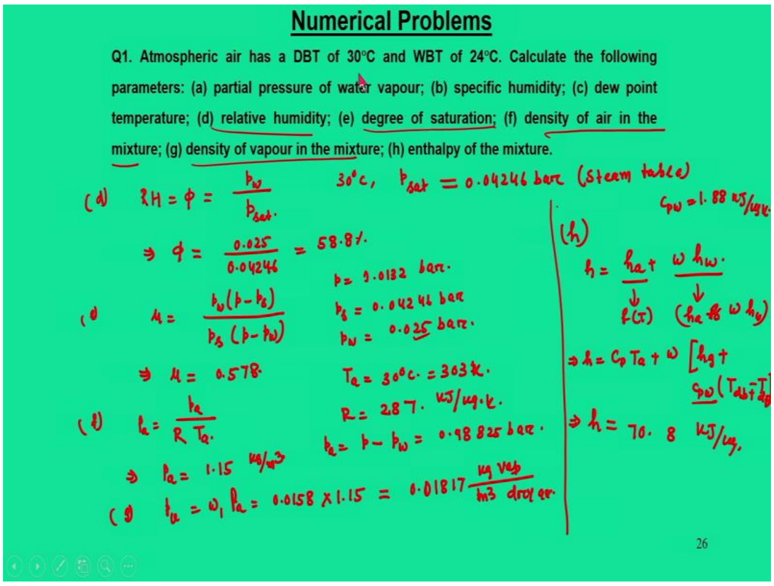

Numerical Problems

Q1. Atmospheric air has a DBT of 30°C and WBT of 24°C. Calculate the following parameters: (a) partial pressure of water vapour; (b) specific humidity; (c) dew point temperature; (d) relative humidity; (e) degree of saturation; (f) density of air in the mixture; (g) density of vapour in the mixture; (h) enthalpy of the mixture.

(d) $RH = \phi = \frac{p_w}{p_{sat}}$ 30°C, $p_{sat} = 0.04246$ bar (Steam table)

$\Rightarrow \phi = \frac{0.025}{0.04246} = 58.8\%$

(e) $\mu = \frac{p_w(p-p_s)}{p_s(p-p_w)}$

$p = 1.0132$ bar.

$p_s = 0.04246$ bar

$p_w = 0.025$ bar.

$\Rightarrow \mu = 0.578$

(f) $\rho_a = \frac{p_a}{R T_a}$

$T_a = 30°C = 303$ K.

$R = 287$. kJ/kg.K.

$p_a = p - p_w = 0.98825$ bar.

$\Rightarrow \rho_a = 1.15$ kg/m³

(g) $\rho_v = \omega_1 \rho_a = 0.0158 \times 1.15 = 0.01817 \frac{\text{kg vap}}{\text{m3 dry air}}$

$c_{pw} = 1.88$ kJ/kgK

(h)

$h = \underline{h_a} + \underline{\omega h_w}$

$\downarrow f(T)$ $\downarrow (h_a\ \cancel{fg}\ \omega h_g)$

$\Rightarrow h = c_p T_a + \omega\,[h_g + \underline{c_{pw}}(T_{dbt} - T_{dp}$

$\Rightarrow h = 70.8$ kJ/kg.

The next thing is we have to find out relative humidity RH, for that we need p_{sat} at 30°C. From steam table we get it as 0.04246 bar.

$$\phi = \frac{p_w}{p_{sat}} = \frac{0.025}{0.04146} = 58.8\%$$

$$\mu = \frac{p_w\left(p-p_s\right)}{p_s\left(p-p_w\right)} = 0.578$$

$$\rho_a = \frac{p_a}{RT_a} = 1.15\text{kg/m}^3;\ p_a = p - p_w = 0.98825$$

$$\rho_v = \omega_1\rho_a = 0.0158\times1.15 = 0.01817\frac{\text{kg vap}}{\text{m}^3\text{dry air}}$$

$$h = h_a + \omega h_w = c_p T_a + \omega\left[h_g + c_{pw}\left(T_{dbt} - T_{dpt}\right)\right] = 70.8\text{kJ/kg}$$

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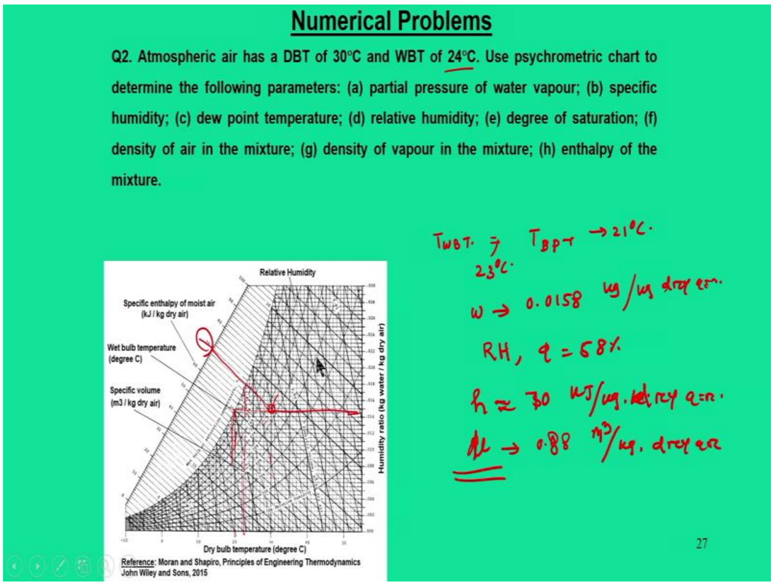

Numerical Problems

Q2. Atmospheric air has a DBT of 30°C and WBT of 24°C. Use psychrometric chart to determine the following parameters: (a) partial pressure of water vapour; (b) specific humidity; (c) dew point temperature; (d) relative humidity; (e) degree of saturation; (f) density of air in the mixture; (g) density of vapour in the mixture; (h) enthalpy of the mixture.

Reference: Moran and Shapiro, Principles of Engineering Thermodynamics John Wiley and Sons, 2015

$T_{WBT} \neq T_{DPT} \to 21^\circ C.$

$23^\circ C.$

$\omega \to 0.0158$ kg/kg dry air.

RH, $\phi = 58\%$

$h \approx 70$ kJ/kg. dry air.

$v \to 0.88$ m^3/kg. dry air

So, the next problem that lies here, for same problem we want to use this psychrometric chart. So, first thing 30°C somewhere here and 24°C wet bulb temperature. So, you go along this we will have enthalpy close to 70. This particular cuts it T_{WBT} and on this line if you go further we can reach T_{DPT}, this is about 21°C, T_{WBT} will be about 23°C.

And from this if you drop a vertical this is about ω 0.0158 kg by kg dry air and this point we have RH, relative humidity is about 58 percent. Enthalpy of the mixture is approximately 70 kJ per kg dry air. And of course, we can say density close to 0.88 kg m^3 per kg dry air. So, if you know the specific volume then you can infer the information about density. So, this is just to demonstrate that how a psychrometric chart is a valuable tool to estimate the thermodynamic properties of moist air. So, with this I conclude this lecture for today.

Thank you for your attention.