Applied Thermodynamics for Engineers
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Lecture – 33
Psychrometric Chart

Good morning everyone, may not be the warmest morning to say because it is raining outside a bit of irritating rain is going on and on the best weather to be inside such a closed studio because the air conditioner is not in the most comfortable stage. Now, the temperature is not very high outside and also it is raining, then what do you feel exactly what kind of condition that we should go for, for your air conditioner or what we expect your air condition to do? The requirement from your air conditioner of course, keeps on changing depending upon your requirement of course also, depending on the outside condition. And accordingly, we may have to go for different kind of processes or we may have to instruct the air conditioner to perform different kind of processes. You may have seen that modern air conditioner remote have a button or modes that symbolises something like summer mode or winter mode or spring mode or maybe sleep mode etc. Each of them corresponds to different kind of setting in different states of requirements. And accordingly, your air conditioner to perform different kind of processes. Just like today, here the temperature may not be very high outside quite suitable, for quite comfortable to us. But the because of the humidity is quite high and you probably want your air conditioner not to cool down the air but to dehumidify it. That is the probably to maintain the same temperature but to reduce the moisture content. Whereas in a hot summer day, you may want both. You may want the temperature to cool down, so you want your air conditioner to lower the temperature and also to reduce the moisture level.

Whereas if you go to the northern part of India where the weather generally very dry, there in a summer day, you may want your air conditioner to cool down the temperature but increase the moisture content. So, we may have different kinds of requirements and how that we can perform in a practical air conditioner and also perform certain thermodynamic analyses, that exactly what we are going to study in this lecture. Now, in the previous lecture you have been introduced to different kinds of terminologies associated with the gaseous mixture.

like the dry bulb and wet bulb temperature, temperature of adiabatic saturation, Dew point temperature. Even before that specific humidity and relative humidity that you have learnt.

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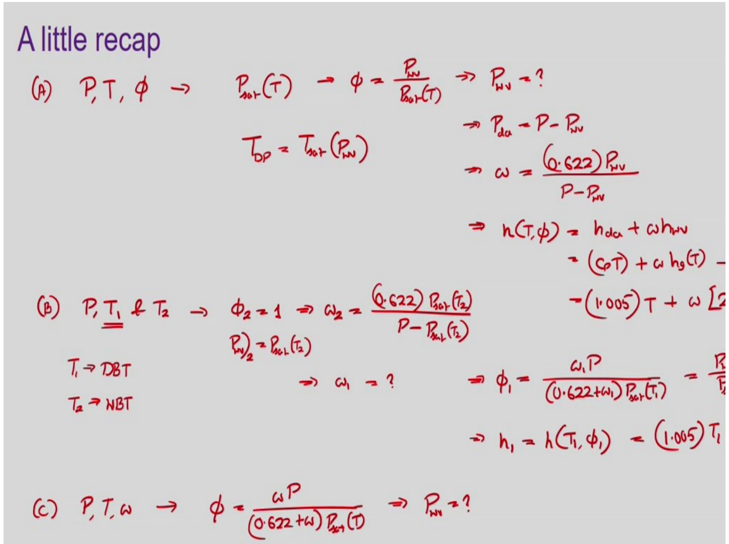

Let us see if we know a few of them how we can calculate other parameters. There can be several situations your air conditioner whether I should say your measurement me provide you different sets of data from there we can generally always calculate others. In most of the situations we need to know three parameters. Let us say we know pressure; we know temperature and we know the relative humidity.

Temperature and relative humidity probably are the two parameters which are reported in most of the weather bulletin and pressure may be the atmospheric pressure. So, if you know these three parameters how can you calculate the others that you have learned yesterday? Once you know the pressure and temperature you can calculate most of the properties. Like using the temperature, you can easily get the saturation pressure corresponding to that temperature. Now, what is this? How can you use this saturation pressure? Using this saturation pressure, you can easily calculate as you know ϕ, we know that the definition of relative humidity is:

$$\phi = \frac{P_{wv}}{P_{sat}\,(T)}$$

So, from here you will be able to calculate the partial pressure for water vapor. And once you know the partial pressure for water vapour you will be able to calculate the partial pressure for the dry air part as well which is:

$$P_{da} = P - P_{wv}$$

and combining this to you will be able to calculate the specific humidity ω. What is the relation that you did yesterday? It was:

$$\omega = (0.622)\left(\frac{P_{wv}}{P_{da}}\right)$$

Or, sometimes instead of your writing this way you just directly write the denominator as the difference of P and P_{wv}, so, that you do not have to calculate the partial pressure for dry air separately. So, you now know the value of specific humidity and now if you want to calculate the specific enthalpy of moist air at this particular condition, at this given combination of temperature and ϕ. You know that it will be:

$$h(T, \phi) = h_{da} + \omega h_{wv}$$

In the same way we can either go by h_g corresponding to the temperature, i.e.,

$$= C_p(T) + \omega h_g(T)$$

or the other way is possible the same thing can be written as the sum of h_g at 0 ^{0}C and c_p multiplied by the temperature of the water vapour for this. i.e.,

$$= \omega[C_p(T) + h_g(0^0C)]_{wv}$$

So, both way it is possible and we know the values also, so we can calculate as follows:

$$= (1.005)T \times \omega[2500.9 + (1.82)T]$$

So, this way we can calculate the enthalpy as well. So, we have all the parameters here. And also, we have got the values of the specific humidity and enthalpy and if I want you to calculate the Dew point temperature how can we get this?

You already know the partial pressure for water vapour, so that Dew Point temperature will be the saturation temperature corresponding to this particular partial pressure of water vapour.

$$T_{DP} = T_{sat}(P_{wv})$$

So, you have all the parameters to measure and if you want to calculate the temperature of adiabatic saturation that also can be calculated, this much longest calculation procedure and so we generally do not go by that route.

So, what we have just discussed is scenario number (A). Let us say scenario (B) I have provided you data for pressure and we have gone for the process of adiabatic saturation. We know the initial temperature of the air sample T_1 and the final temperature T_2 which is nothing but the temperature of adiabatic saturation. Then what can you do from this, how we can get the value of the specific and relative humidity of the original air sample which was at this temperature T_1? Remember T_1 is the temperature of the original air sample at which you want to do all the calculation. And T_2 is the temperature of adiabatic saturation which you have obtained at the exit of that adiabatic saturator. So, we want to calculate the values of all this parameter like specific and relative humidity is enthalpy etc. corresponding to the T_1. So how can you go by this?

We now know that at the exit of the adiabatic saturator the relative humidity is equal to one so corresponding this you can calculate your ω_2. Your ω_2 will be equal to:

$$\omega_2 = (0.622)\frac{P_{sat}(T_2)}{P - P_{sat}(T_2)}$$

Because we know that:

$$P_{wv})_2 = P_{sat}(T_2)$$

using that we got at ω_2. Once we know that ω_2 then from this value of ω_2 you can calculate ω_1. Yesterday, we have derived quite longish formula using the specific heat for water vapour and air and also is value of ω_2 and also enthalpy values for water at temperature T_1 and T_2. So, you know the values of ω_1. Now once you know ω_1 then it is quite straight forward. So, how to get ϕ_1 from ω_1, you know ω_1 then how to get ϕ and corresponding to this your ϕ_1.

$$\phi = \frac{\omega_1 P}{(0.622 + \omega_1)P_{sat}(T_1)}$$

$$= \frac{P_{wv}}{P_{sat}(T_1)}$$

So, from there you get the partial pressure for the water vapour as well. And hence you have again all the parameters okay. If you want to calculate enthalpy at temperature T_1, that is I am talking about this h at condition of this T_1 and ϕ_1, then as we have already obtained ω_1, then we can easily calculate the same as:

$$h_1 = h(T, \phi) = (1.005)T_1 + \omega_1[2500.9 + 1.82T_1]$$

So, actually this is the way we calculate while we are going or the adiabatic saturation. But quite often I have mentioned yesterday that we may not have sufficient time of space to put an adiabatic saturated into picture. Then we go for the wet bulb temperature. In that case your T_1 is the dry bulb temperature the normal temperature and T_2 is taken to be the wet bulb temperature. The wet bulb temperature in practical cases is very close to the temperature adiabatic saturation so, just go by the thermometer like this. Quite often in practice you may get sets of two thermometer one we will be giving you the dry bulb temperature other giving you the wet bulb temperature. Because the second one generally has a piece of cloth or wick wrapped up around the bulb and it is also immersed into a pool of water so that we get the wet bulb temperature.

Let us say third scenario, in the third scenario you are given the value of pressure, temperature and ω, i.e., specific humidity for the air sample. What to do in this kind of scenario? It is given straight forward. As you know the value of ω so you can easily calculate the value of ϕ. ϕ is, as we have used in the previous case also, is:

$$\phi = \frac{\omega\, P}{(0.622 + \omega) P_{sat}\,(T)}$$

So, we have the value of ϕ from there, once we have the value of ϕ from there, as just we have done the in the previous case, you can calculate the partial pressure for water vapour as well. And again, once you have ω then you can directly calculate h as a function of T and ω just like we have done earlier. So, this way depending upon whatever information is available to us whether it is temperature, generally dry bulb temperature and pressure are the two parameters that are always given. Pressure in all these cases you really do not go for a measurement, we can we take the standard atmospheric pressure. You know that the standard atmospheric pressure is 1.01325 bar. So, you can generally take standard atmospheric pressure unless there is significant variation in pressure is expected.

So, the pressure value is generally obtained from the standard barometer. And this dry bulb temperature is another thing, that is also generally specified. So, you will always be getting the pressure and dry bulb temperature and then you need a third parameter. And your third parameter can be your relative humidity or can be your specific humidity or it can be the wet bulb temperature.

Or, in certain specific cases you may have the Dew point temperature given. If the Dew point temperature and dry bulb temperature are given just think how can calculate the other parameters. So, I am leaving this case (D) where you are given with the pressure, you are given with the dry bulb temperature T and you are given with the Dew point temperature T_{DP}. From there, try to find ways of estimating the specific and relative humidity and also the enthalpy of moisture content.

Now, as we can see there are quite a bit of calculations involved, once you are having some information is maybe two or three parameters specified we have to go for quite a bit of calculations to obtain the others. Because there are several parameters of our interest. We generally have to calculate *ω*, the specific humidity, relative humidity, the enthalpy, the partial pressure for water vapour and also some parameters which have not touch here.

We may be interested in specific volume and a few others also. So, once you interested in all these parameters, we have to go for several calculation steps. And if you are designing a real-life air conditioner such calculations may be quite involved. They may be quite cumbersome even for practicing engineers as well. And therefore, there are two options, either we can go for computerization, i.e., we can write a computer program where we shall put some inputs and the program will using the same formulas. And also, some property tables of property relations. It is going to give you back the desired quantities.

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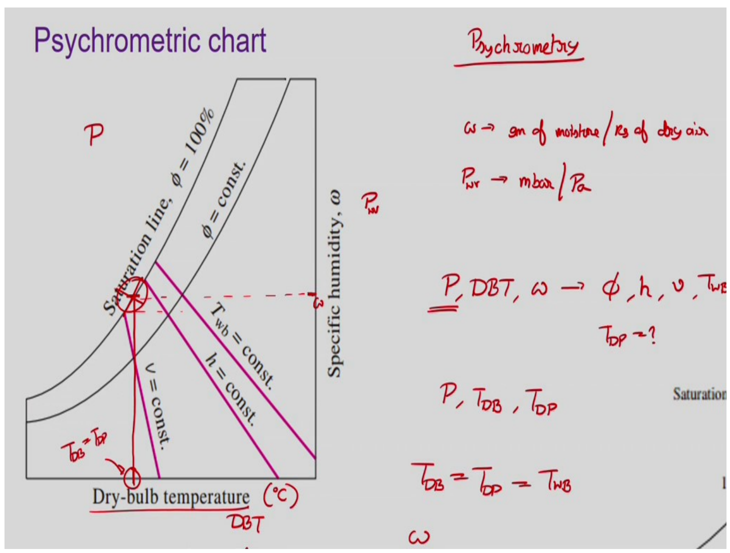

And the second option is the graphical option, which is this. This is called the psychrometric chart. Psychrometric chart is something that is extensively used in case of air conditioning applications. It is in fact it is so much used, that the study of the properties of gas vapour mixture is generally referred to as psychometry. So, whatever you are studying this week that is actually the psychometry. The psychometry is the science of studying the mixture of gas and vapour, i.e., non-condensable gases and condensable vapour. And it is process identification of properties and also analysis of different processes involving gas vapour mixture. Now, psychrometric chart, just look at this chart, it is quite similar to that Mollier diagram that we can sometimes use in conjunction with the steam or maybe similar properties. Like that, compressibility chart also we have seen.

Similarly, here also from two known information or three known information we generally can obtain whatever other parameters that we are looking for. Just look at the chart, on the horizontal axis you have the dry bulb temperature. So, the dry bulb temperature in horizontal axis commonly specified in degree Celsius. And generally, as we are looking for air conditioning application, this change generally ranges from -10 ^{0}C to 50 ^{0}C and in certain situations just 0 ^{0}C to 50 ^{0}C.

On the vertical axis we have the specific humidity, ω. So, we have specific humidity, you may also find some charts where the partial pressure for water vapour is given or may be both. We may be having two vertical scales, one giving the specific humidity, other giving the partial pressure for water vapour.

So, while the dry bulb temperature is given in Celsius the specific humidity is commonly specified in terms of gram of moisture/kg of dry air. So far, we have used kg of moisture/kg of dry air we have generally seen that the ω value is coming too small, that is why most of the charts commonly give within grams. So, we have to be very careful about what you need. If it is given in partial pressure for water vapour, you may find this is given in millibar or just in Pascals, may be in Pascals as well. So, these are the two axes and look at the left-hand side of the graph instead of having a straight line, we are having a curve. This curve is the curve corresponding to 100% relative humidity, it is also called the saturation or line saturation curve. Now what we have on this chart? On this chart, we have several lines of each corresponds to different value of ϕ, that is shown here.

Like this line is corresponding to some ϕ. This is the ϕ is equal to 100% on the extreme end. We may have several such lines like this, each one corresponding to different values of ϕ. So, we are having the lines for constant relative humidity. Specific and relative humidity are done. Then look at the three other lines shown here. This line is the line corresponding to wet bulb temperature.

Similarly, we will be having several such inclined lines which gives you wet bulb temperature and these are lines which are much steeper compared to the wet bulb temperature lines. These are the lines corresponding to the specific volume. So, we have lines corresponding to the wet bulb temperature and also the specific volume. Specific volume lines are generally must steeper compared to the wet bulb temperature lines. And there is the third line corresponding to enthalpy.

Look at this wet bulb temperature line and constant enthalpy line, they are almost parallel to each other. Therefore, you may find certain charts where the same line indicates both the temperature and enthalpy, their magnitude will be given separately. However standard charts generally have both kinds of lines, that is set of lines for wet bulb temperature and also sets of line corresponding enthalpy.

And be very sure which one you are looking into because there almost parallel to each other, as I shall be showing shortly. Such charts are generally given corresponding to certain pressure. So, each are corresponding to one pressure and therefore once you are given any sets of data points you can easily identify the corresponding state on this particular chart.

Like, suppose as the cases you were analysing, if you are given with pressure, the dry bulb temperature and the specific humidity. It is very easy to plot; you just have to identify the chart corresponding to this particular pressure and most of the standard charts are given under atmospheric pressure only and that is the one that you also have to use in 99% of situations. Only in very special cases it may use the chart corresponding to other pressures.

So, from this moment you are not going to talk about pressure only, as you mean everything to be done at atmospheric pressure. Now dry bulb temperature and ω are given then you can easily identify that on this chart because you know, your horizontal is giving the dry bulb temperature in Celsius and vertical axis giving you the specific humidity.

So, we can easily identify the point maybe somewhere here is a point that looking for. Then you can identify the corresponding wet bulb temperature lines and enthalpy lines that is passing through this point and you will get the value of enthalpy and wet bulb temperature, similarly specific volume and also the relative humidity. You can directly get all other properties like the relative humidity, specific enthalpy, specific volume and also the wet bulb temperature. That directly can be obtained from this chart.

Now suppose we have line corresponding to each of the four quantity that I have written here. Now, if I want to calculate, say the Dew point temperature. How can we do this? The Dew point temperature, there is no line corresponding to this. Then how can we do this? What is the definition of dew point temperature? Dew point temperature refers to a process, during which we are keeping the moisture content the same but you looking the temperature till that sample of moist air becomes saturated by its own moisture content. Then how we can do this on this curve? So, this is the state point that we are talking about. If you want to maintain the specific humidity constant then we have to proceed along a horizontal line, a line somewhat like this.

So, along with this particular dotted line, specific humidity that is a moisture content in the sample remains constant. Now we are talking about a process during which the temperature is reduced. So, we have to go in this particular direction and we have to continue till we reach the saturation curve where the relative humidity becomes 100%. This is the point; the sample may become saturated or should become saturated by its own moisture content because I have not changed ω.

Remember as you are moving towards left, moving in this particular direction, your ω is remaining constant, but your relative humidity is continuously increasing. We have seen yesterday also, we have discussed that as the temperature of a moist air sample is reduced, its specific humidity is constant but relative humidity increases. As the reverse is true when we heat up the sample.

So, we have now reach at this point on the saturation curve. Now draw the vertical projection for this and the temperature that you get here, this temperature will be the Dew point temperature that you are looking for. Because this is the temperature at which a sample should become saturated by its own moisture content, which is precisely the definition of the Dew point temperature.

If any other properties are given just the same way we can specify it on the chart also. Let us take the case, the case that I just left out in the previous slide. To say you are given with the pressure which is the standard atmospheric pressure, the dry bulb temperature and Dew point temperature and we have to identify others. So, identifying others is not difficult. You just have to spot the corresponding state point.

Now, the dry bulb temperature is given, let us say this is your dry bulb temperature. This is the dry bulb temperature that is specified to us. Then you have to identify the Dew point temperature. How can identify the Dew point temperature on the chart? Just draw a vertical line, Dew point temperature may be somewhere here. So, this is your dry bulb temperature, this is your Dew point temperature. Draw two vertical lines, two constant temperature lines.

So, this is the constant temperature line corresponding the Dew point temperature. This is the constant temperature line in corresponding to the dry bulb temperature. So, Dew point temperature line cut the saturation curve at this point. If we draw a horizontal projection on the vertical axis then this is actually will be the value of the specific humidity given in a sample because just, we have in the previous case, that is the way we have identified the Dew point temperature going in the reverse way. As in the previous case was given, we identified the Dew point temperature by taking a projection on the horizontal axis. Here the Dew point temperature is given. From the Dew point temperature, we have identified the corresponding specific humidity using the saturation curve.

And now we have taken the position on the vertical axis to get the value of the ω. Now where this ω and dry bulb temperature lines are coinciding or intersecting., this is the point. So, this one is going to the state point that you are looking for. So, this way we can identify even if the dry bulb temperature and Dew point temperatures are given. And just follow the same procedure to get the other properties. Now this is special scenario, when you are talking about a saturated mixture. For a saturated mixture, just the one I specified, the dry bulb and Dew point temperature are given. But in this case, they are same. That is your dry bulb temperature and your Dew Point temperature equal to each other. What does it indicate? Let us erase this line. Let us say this is the temperature that is given to us and this temperature corresponds to both the dry bulb temperature and the Dew point temperature. Now starting with this, is dew point temperature, draw a projection on the saturation curve.

Then we get the value of the corresponding ω. Corresponding to the Dew point temperature, now it is the dry bulb temperature as well. So, this will be the value of the sample only, so I get the specific humidity and this is the state that we are looking for. That means here when the Dew point temperature and dry bulb temperature are the same, also comes from the definition of dew point temperature of the mixture, actually saturated by its own moisture content.

And it can also be shown that this will be equal to the wet bulb temperature as well. Because the sample cannot take more moisture so, if you allow the sample to pass through an adiabatic saturator, then what will happen? Remember in adiabatic saturator, we are supplying an unsaturated mixture and when passing over the water surface it picks up the moisture from this. And as it is picking of the moisture because of the latent heat transfer the temperature of both water and the air sample that reduces. But here as the supplied air as it is already saturated solution, it will not be able to pick up any more moisture from this and therefore there will be no latent heat transfer, no mass transfer between water and moist air. Accordingly, it will come out with the same temperature. Therefore, the adiabatic saturation temperature will be the same as the initial temperature and hence the dry bulb temperature and wet bulb temperature will be same just like shown here for a saturated mixture. Therefore the dry bulb, wet bulb and Dew point temperatures are equal to each other.

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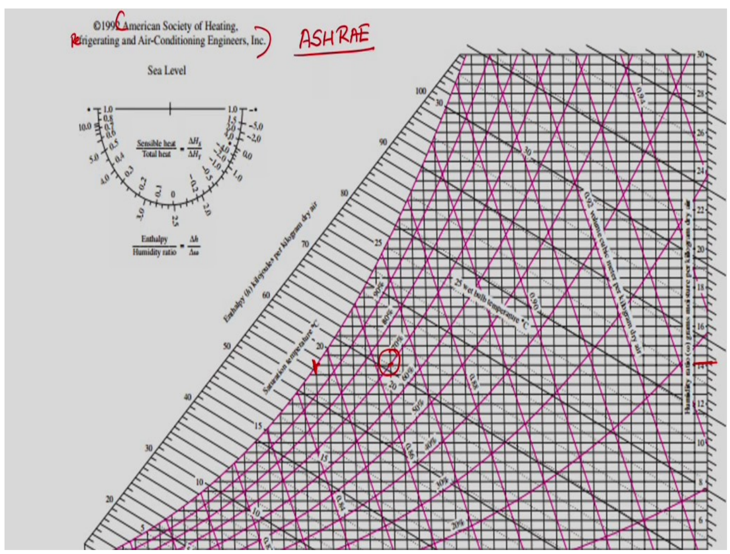


This is a real life such psychometric chart that we can identify. Here look at this, it is important for you to get this name American Society of Heating, Refrigerating and Air-Conditioning Engineers, in short ASHRAE. It sets up the global standard in the field of air conditioning and refrigeration and also any kind of similar applications which was the heating and heating is also a part of air conditioning only. And this is a psychometric chart that has been devised by ASHRAE for standard atmospheric pressure. Just look at this, the horizontal axis is the dry bulb temperature given in Celsius at the range starts from 0 to 50. On the vertical axis you have the humidity ratio. This is given here, humidity ratio ω and it is the unit is given in font-size is quite small.

But you can check it out. I have adopted this particular chart from the book of Cengel and Boles, you can refer to the book also or you can search on Internet to get a much clear chart in terms of the axis caption. The unit is given here in gram of moisture per kg of dry air. So, this value this 2, 4, 6,.. these values correspond to the value of ω. But there is another vertical axis also. Here another scale is given which gives you the sensible heat to the total heat loss.

This is something that you can ignore for the moment because this is something related to pure air-conditioning design and we are not going there at the moment. Look at the other lines are there. So, this is your saturation curve corresponding to 100% relative humidity. This is a 90% curve, 80% curve. This is the 50% curve, this is the 10% curve, 10% relative humidity. This way each of these pink lines corresponding to different humidity levels of the lines. Of course, the lines are shown in 10% gap but

What we can also have lines much closer to each other as well. Then other lines. the enthalpy lines are starting from there. It is given in kJ/kg of dry air. Always take a note of the units of the data they are using and these continuous straight lines which are given, they correspond to different value of enthalpies. Like this particular line corresponds to 70 kJ/kg, it is given here. It is also given here. You just have to follow the line. This particular continuous black straight line corresponds to 50 kJ/kg of dry air. These are the units for this, even the smaller units are also given. Can you identify the specific volume lines here? Now we have got the enthalpy and that to axis another relative humidity. Now we got the specific volume lines, they will be much steeper.

And the straight pink lines, these lines which corresponds to specific volume lines. So here it is 0.92 m^3/kg of the dry air. This is 0.9, 0.88, 0.86, this is 0.80, 0.78, each of the inclined pink line corresponding to the specific volume lines. There is a 0.94, this line does not have a caption, this is 0.93 between 0.94 so, this way we have the specific volume line as well.

And finally, the wet bulb temperature, so where is the wet bulb temperature? You can see four kinds of black lines that are shown here. The vertical one corresponding to the dry bulb temperature, the axis, these vertical lines, the horizontal line corresponds to the specific humidity ratio These are the horizontal black lines. So, this is there now among two sets of inclined black lines, one corresponds to the enthalpy.

The continuous black straight line inclined that corresponds to the enthalpy. But there is also a set of dotted black straight lines, which are virtually parallel to the enthalpy lines, these are the wet bulb temperature lines. Like you can see this is a 25 ^{0}C wet bulb temperature line, here you have the 20 ^{0}C. So, what about these dotted lines? This is 25, this is 24, this is 23, this is 22, this is 21 and here I have the 20.

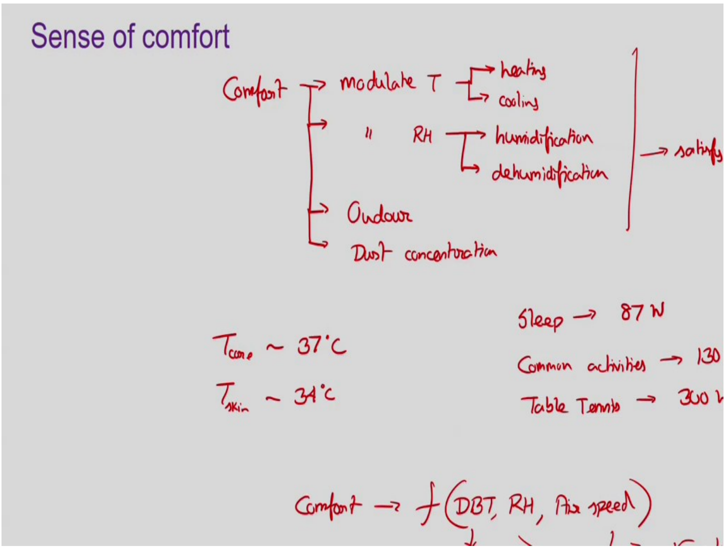
These are the different wet bulb temperature lines. And just follow any one of the wet bulb temperature line, let us follow the 20 ^{0}C temperature line. So, this is a 20 ^{0}C temperature line, just follow this line and see where it intersects the 100 % relativity line or saturation line. It intersects at this particular point. From this point, you take the vertical projection on the horizontal axis and you reach here which gives you the dry bulb temperature which is the same. Because we know that the dry bulb temperature and wet bulb temperature line in the same magnitude of dry bulb temperature and wet bulb temperature, these lines intersect only at the saturation card and that is also going to be, if you are dealing with saturated mixture, this also going to be the Dew point temperature.

Suppose I have given a case where you are dealing with the sample which is maintained at 25 ^{0}C and relative humidity of 70%. Can you spot it on the chart? So, first identify 25 ^{0}C dry bulb temperature. So, this is your 25 ^{0}C so you have the corresponding vertical line and 70% of relative humidity, that line is also there. So, this is your 70% relative humidity. So, you just want to identify where intersect. These two lines 70% relative humidity and 25 ^{0}C dry bulb temperature, if I follow the line they intersect at this particular point, so, this is the point. From this point if you follow the continuous black horizontal line, observe the straight line, then we reach here. So corresponding ω directly you can get this ω will be equal to 14 g/kg of dry air and also what other lines you are getting? So what will be the wet bulb temperature?

You can see the 21 ^{0}C wet bulb temperature is also passing through that point, at least nearly to this point. So, wet bulb nearly equal to 21 ^{0}C. What will be the Dew Point temperature at this particular point? You just, continue the constant to ω line with the saturation curve that you are following this line and at this particular point. So whatever value are getting if you take the projection, we reach here.

So, that the Dew point temperature is 19 ^{0}C so you can clearly see which should be the case for all samples. The dry bulb temperature is the highest, then you have the wet bulb temperature and the lowest is the Dew point temperature because the Dew Point temperature is the one with the mixture becomes saturated by its own moisture content. So, the value of enthalpy can also be obtained.

The enthalpy lines, that is if the enthalpy, seems to be it is difficult to identify it is in something like 61 kJ/ kg of dry air. So, this is 25 ^{0}C and 70% relative humidity and atmospheric pressure using that you please try to use a mathematical part also to check whether you are getting the similar values are not, at least for ω in enthalpy and also the Dew point temperature. Then, you will be able to verify this results in terms of this psychrometric chart as well. **(Refer Slide Time: 34:37)**



The next we have to talk about the sense of comfort. The term comfort of course, a very much quality of term. The term comfort refers to how comfortable a human is the feeling in a particular environment. Of course, it is not possible for us to control the outside environment. But the maybe we can control the indoor just like the environment inside the studio and make ourselves feel comfortable. Now there are several things that comes on this comfort. Like comfort does not mean that controlling temperature alone. The primary concern of comfort is the modulation of temperature but there was also go into is we can go by heating if the temperature of the interior is too low for us then we have to go for heating it is too high for us we can go for cooling. But comfort also refers to the modulation of the relative humidity or moisture content.

Because quite often the moisture content may not suitable for us. So, in that case, if the moisture content is too low, we have to go for a humidification where we add more moisture into the air sample. If the moisture content is too high, we have to go for dehumidification. But modern air conditioners, our modern definition of comfort does not restrict only to this, that can be several others too.

Like a very common thing can be the control of odour or control of the dust concentration. Even in certain cases maybe the controlling the sound like in a studio like this it has to be soundproof. And sometimes it also comes under the part view of this air conditioning and that is why we specifically used the term air conditioning not air cooling because we have two condition the air in terms of several parameters.

Just a few of them I have mentioned here which are the most common functions of modern air conditioners. Where we have the modulation of temperature relative humidity, also removal of bad order, sometimes also adding some fragrance to the room here and also the removal of dust concentration, sometimes adding certain biologically comfortable volatile material to the air so that the air becomes much fresher. All this comes under the sentence we call it air conditioning. Now, the objective of this entire air conditioning is to satisfy the new need of human being. And actually, I should not restrict the term to human because you may be inside this a controlled condition control room or inside your condition room probably you are engaged in some kind of scientific experiments which requires a particular level of temperature and relative humidity. And therefore, here the need actually is coming from the process that you are performing. So, the idea of comfort is to force the air conditioner to perform something so that it can modulate your interior environment to suit the need of hours. Need of the corresponding human or corresponding process or corresponding maybe some animals to store their which requires a certain temperature to maintain and that we have to ensure. Now, restricting ourselves to human only, our body can always be visualised like a heat engine because we consume the food and was the food goes inside that participates in the metabolic processes and the chemical energy stored in the food comes out in the form of thermal energy and that provides us the enough energy to perform different kinds of activities.

But once we have performed the energy then what happens? Once you perform the work then the amount of energy that is released by the metabolic processes is only a small fraction of that gets converted to work. Actually, the efficiency of a body as a heat engine is extremely poor can be even less than 1% that is the total energy that is getting released maybe only 1% of that is getting converted to work and remaining has to be rejected to the immediate surrounding. And therefore, we are always radiating energy to our surroundings. Just to mention some very common activities like even when you are sleeping, a common person on an average radius 87 kW of energy to the surroundings. Even just like I am sitting inside this room and giving lecture and writing, this kind of common activities it can be easily in the range of 130 to 200 watts.

If suppose someone is participating some kind of indoor games or maybe something game of table tennis. It can be extremely high it can easily go in the range of 300 watts or even higher. When someone is going for a very quick run, someone is running a sprint, then that temperature will be much higher Sorry not the temperature that energy value that we are talking about that is much higher.

And now your air conditioner has to remove this amount of energy and also to maintain the conditioned environment. And therefore, we have to remove this heat and sometimes also removal of heat may not be sufficient like suppose you for indoor temperature is too low then the body will be losing too much of heat therefore we shall be feeling quite chilled and hence the conditions heat up the room.

Where the room temperature is too high then we may not be able to receive it sufficient amount of energy and we may feel very much uncomfortable, very much stuffy and so the air conditioner has to lower the temperature. We know that our core temperature is in the range of 37 ^{0}C whereas the skin temperature is generally in the range of 33 to 34 ^{0}C almost for all the human beings.

When the outside temperature is too high then we may struggle, like if outside temperature is too close to is 34 ^{0}C and higher than that we may not be able to reject heat to the surroundings. Now what happens in that case? We start to perspire; we start to sweat and this sweating is a way of removing heat in the form of latent heat where the moisture gets converted to liquid water and as that water evaporates from your body it takes the latent heat from the body thereby cooling the body. So, when the temperature is too high this heat removal by the latent heat that keeps on increasing. Whereas at low temperature, the sensible heating is more important. So, in a nutshell the sense of comfort can be identified as a function of three parameters. It is the function of the dry bulb temperature; it is a function of the relative humidity and also function of the air speed.

It has been identified from studies that the most comfort temperature for human being ranges between 20 to 27 ^{0}C that is whether you are talking about an extremely for a person who is residing in a desert used to of 50 ^{0}C temperature or we are talking about an eskimo who is always a custom with sub-zero temperature, but this is generally the comfort temperature.

Relative humidity requirement keeps on changing depending upon what activity level you are indulged in. But commonly 40 to 60% relative humidity is advantages or comfortable to most of the persons in most of the situations. Air speed again, we do not want to air speed to be high because we shall be having some problems in breathing, where the air speed is too low feels stuffy because the latent heat removal stops.

Something in the range of 15 m/min is generally quite comfortable level of speed that have been identified. And therefore, the air conditioner should perform psychrometric processes which are able to monitor the dry bulb temperature and relative humidity, particularly within this particular range.

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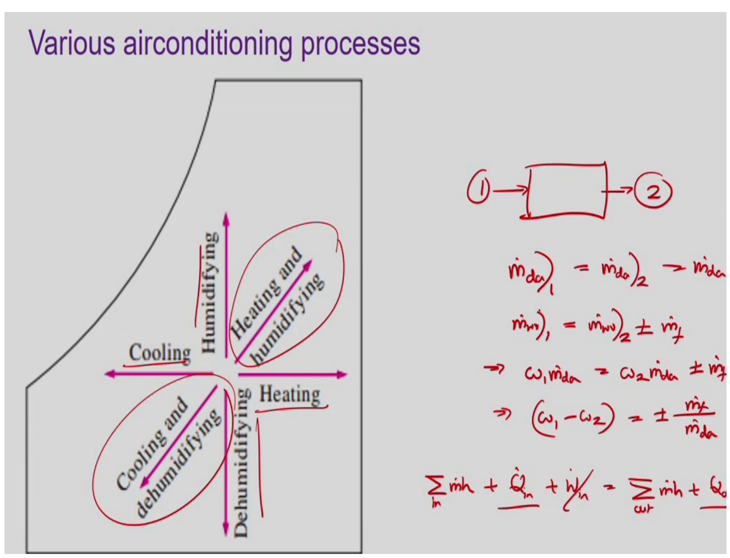

And accordingly, we have to perform different kinds of air conditioning processes. And these are different kind of air conditioning processes we may have. We may have heating process, cooling process, we may have dehumidification and humidification where only the ω change and the temperature remains constant. Whereas we can have heating and cooling, humidification and dehumidification with simultaneously temperature and relative humidity are modulated.

If we perform a simple energy balance or mass balance first on an air conditioner. Then performing the mass balance over the dry air, let us say it enters with state 1 and comes out with state 2. Then generally during the process, this psychometric process, all this air conditioning process called the psychrometric processes. So, during them generally the mass of dry air remains the same.

$$\dot{m}_{da})_1 = \dot{m}_{da})_2 = \dot{m}_{da}$$

But mass of water vapor may change if you are going for some kind of humidification and dehumidification option.

So,

$$\dot{m}_{wv})_1 = \dot{m}_{wv})_2 \pm \dot{m}_f$$

$\dot{m}_f$ corresponds to the amount of water added or removed from it.

Or we can write this one as:

$$\omega_1 \dot{m}_{da})_1 = \omega_2 \dot{m}_{da})_2 \pm \dot{m}_f$$

or

$$(\omega_2 - \omega_1) = \pm \frac{\dot{m}_f}{\dot{m}_{da}}$$

Similarly, if you perform an energy balance then the total energy content plus if there is some heat addition and work addition that should be equal to summation of what is with which it is going out plus if there is any heat rejection and work rejection.

$$\sum_{in} \dot{m}\, h + \dot{Q}_{in} + \dot{W}_{in} = \sum_{out} \dot{m}\, h + \dot{Q}_{out} + \dot{W}_{out}$$

So, these are general energy balance equation for steady flow device. That is work transfer terms are generally negligible for most of the situations because apart from the fan work, there is hardly any work transfer to the system. We can have either heat addition or heat rejection or maybe none of them.

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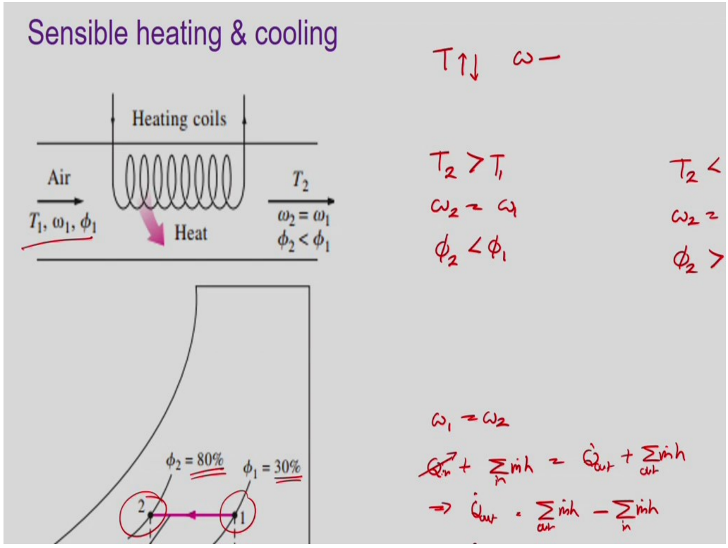

Let us see a few special situations, first is the sensible heat transfer, sensible heating and cooling. We are referring it to the modulation of temperature either increasing during heating or decreasing during the cooling, but the moisture continuation remaining the same, that is ω remaining the same. But temperature is changing accordingly the relative humidity may also change this is a scenario where we are talking about heating air is supplied with certain properties like this and when it is going out the temperature is higher. So, in this case heat is being supplied in the form of some heating coils or maybe electrical heaters. So,

$$T_2 > T_1$$

$$\omega_2 = \omega_1$$

then what will happen to ϕ_2. As the temperature is increasing but moisture content is same ϕ will decrease. So,

$$\phi_2 < \phi_1$$

this kind of scenario in the relative humidity becomes too low may have problems with drying of skin, we may have some respiratory problem, we may also have seen some dry conditions the formation of static electricity on a dry surface, this problem can happen if this value of ϕ_2 becomes too low. When you are talking about a cooling process, then

$$T_2 < T_1$$

$$\omega_2 = \omega_1$$

in this case

$$\phi_2 > \phi_1$$

Like one example of a cooling process is shown where the air in its initial state at 30 ^{0}C and goes through a sensible cooling process where there is no change in moisture content to the lowest final temperature of 12 ^{0}C. So you have to identify the state initial ϕ is 30% using this 30 ^{0}C and 30% have identified state 1 on psychrometric chart and then you have to draw a horizontal line moving towards the lowest temperature till we reach this 12 ^{0}C. So this is at final state point 2, finally getting to is 80% which is a significant increase in the relative humidity despite no change in the value of ω. Suppose for this cooling process if we perform an energy balance, then what we are going to get? So, in this case,

$$\omega_2 = \omega_1$$

and just the energy balance that we wrote earlier if we write here,

$$\dot{Q}_{in} + \sum_{in} \dot{m}\, h = \dot{Q}_{out} + \sum_{out} \dot{m}\, h$$

Here, energy is being removed from this so $Q_{dot\ in}$ is not there and therefore total heat removal is equal to:

$$\dot{Q}_{out} = \sum_{out} \dot{m}\, h - \sum_{in} \dot{m}\, h$$

Here generally this ṁ's are written for dry air, so if we divide that,

$$\frac{\dot{Q}_{out}}{\dot{m}_{da}} = q_{out} = h_2 - h_1$$

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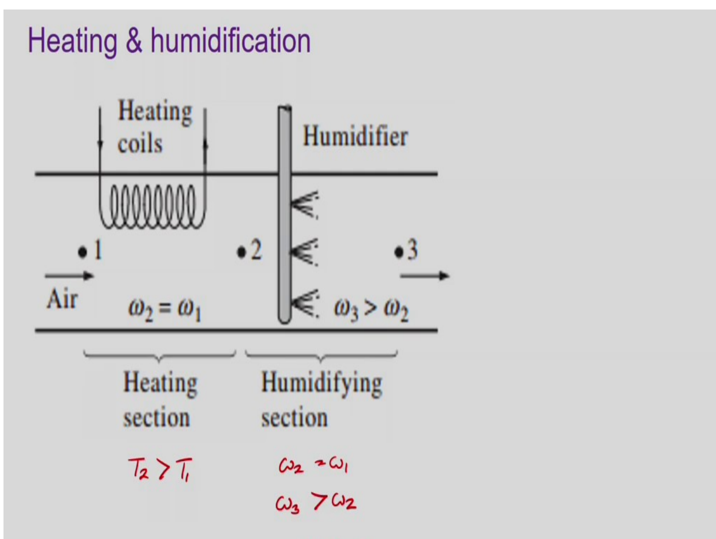

This is the process, where I mentioned we may have heating process, we may have significant reduction relative humidity. Then we may have to go for a separate humidification process where that is a two-step process. Just you can see in the first step ω_1 and ω_2 are equal to each other. That is there is no change in specific humidity. It is just sensible heating process.

So, the temperature is increasing,

$$T_2 > T_1$$

then we have a humidifier where either steam or maybe liquid water is sprayed into this. So accordingly,

$$\omega_2 = \omega_1$$

but

$$\omega_3 > \omega_2$$

But T_3, whether T_3 will be greater than T_2 or equal to T_2 or less than T_2 that will depend upon the nature of the humidifier. Like say if we are spraying steam, spring steam. If you are going for a steam spray, then steam will be having an additional amount of energy, which is the going to be added to the moist air stream. In that case

$$T_3 > T_2$$

So, in the second stage we are having both humidification plus heating. Whereas if you are having a water spray usually sprinkling water inside this then this water has to be evaporate by picking up latent heat from the body of moist air only and therefore, the temperature will reduce in that case,

$$T_3 < T_2$$

So that depends upon the nature of humidification process.

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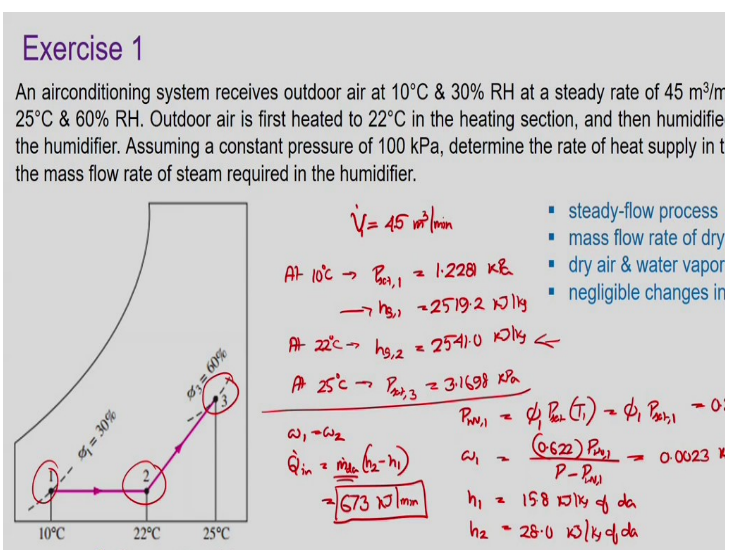

Let us quickly solve a numerical problem to check this out. The process is also shown. It is a heating and humidification process where the air conditioner receives outdoor air at 10 ^{0}C and 30% RH. It is shown on the chart at this point, at a steady rate of 45 m^3/min. So the volume flow rate is

$$\dot{V} = 45\ m^3/min$$

and conditions it to 25 ^{0}C and 60 % RH. So final status is this: 25 ^{0}C and 60 % RH. Outdoor air is first heated to 22 ^{0}C in the heating section. So, first we have the sensible heating 1 to 2, that ends up at point number 2 and then humidified by injecting steam in the humidifier. And then we have the humidification option. So, during the humidification part the temperature is also rising. So, the second part is not pure humidification that is both heating and humidification. Pressure is constant 100 kPa and we have to determine the rate of heat supply in the heating section and the mass flow rate of steam required in the humidifier.

So, we need certain properties at this given temperature. So, let us note down the properties, but before that we assume something as a steady flow process, we assume the mass flow rate of dry air to remain constant which is a very logical assumption. Dry air and water vapour of course we are treating as ideal gases and neglecting any changes in kinetic and potential energies. Now at 10 ^{0}C, P_{sat1} that is saturation pressure of water vapor at T_1.

$$P_{sat1} = 1.2881 \text{ kPa}$$

and

$$h_{g1} = 2519.2 \text{ kJ/kg}$$

At 22 ^{0}C we do not need the proper pressure value at this point. We just need the enthalpy so I am just noting that,

$$h_{g2} = 2541.\ 10 \text{ kJ/kg}$$

and at 25 ^{0}C we have

$$P_{sat3} = 3.1698 \text{ kPa}$$

So, these are the property values we need to use. So, during the first step

$$\omega_2 = \omega_1$$

and

$$\dot{Q}_{out} = \dot{m}_{da}(h_2 - h_1)$$

or if we write the other way where it is a heating process, so taking that into account we should write,

$$\dot{Q}_{in} = \dot{m}_{da}(h_2 - h_1)$$

So, we have the energy balance for the first part. Now to calculate this. We know how to calculate the process I am not going to show all the steps.

So, the partial pressure for water vapour at state 1 can be calculated as:

$$P_{wv,1} = \phi_1 P_{sat}(T_1) = \phi_1 P_{sat,1} = 0.368\,kPa$$

As you know, the partial pressure of water vapour, we can calculate partial pressure for dry air. Here,

$$\omega_1 = \frac{(0.622)P_{wv,1}}{P - P_{wv,1}} = 0.0023 kg/kg\ of\ dry\ air$$

So, the state 1 is completely defined and

$$\omega_1 = \omega_2$$

so, you need to know the mass of this dry air. How can you estimate the mass of the dry air? You know dry air can be treated as an ideal gas, so specific volume state point 1 can be obtained as:

$$v_1 = \frac{R_{da} T_1}{P} = \frac{0.287 \times 283}{100} = 0.815\,m^3/kg$$

and accordingly, the mass flow rate for dry air, therefore the volume flow is given total volume flow rate and dry air will be occupying the entire volume so divided by specific volume. This should be written as without 1 because the total volume may keep on changing as it flows through this and it is expressed as:

$$\dot{m}_{da} = \frac{\dot{V}_1}{v_1} = 55.2\,kg/min$$

So, we know now ω_1, using ω_1 we can calculate h_1 and because at state 1 we know temperature and both ω and state 2 was also known temperature and both ω, we can get both h_1 and h_2 putting this $\dot{m}_{da}$ we have just calculated. So total heat requirement will be coming as:

$$\dot{Q}_{in} = \dot{m}_{da}(h_2 - h_1) = 673\,kJ/min$$

So, this is the rate of heat addition that is recurring in the heating section.

I have the final numbers; I am just showing the values for h_1 and h_2:

h_1 = 15.8 kJ/kg of dry air

h_2 = 28 kJ/kg of dry air

You have the value of h_{g1} and h_{g2}. From this is also C_p for air is 1.005 using this we get h_1 and h_2. So, we have the rate of heat transer. Now we have to get the second part of the mass flow rate of steam required for this. How can you do this? Just perform a mass balance over the second part.

So,

$$\dot{m}_{da}\,\omega_2 + \dot{m}_f = \dot{m}_{da}\,\omega_3$$

therefore,

$$\dot{m}_f = \dot{m}_{da}\,(\omega_3 - \omega_2)$$

Now how to identify ω_3? For state number 3, you know 25 ^{0}C dry bulb temperature, you know the value of ϕ, so ω_3, you can directly obtain using the value of ϕ corresponding to T_3 and ϕ and in this case it is coming as:

$$\omega_3 = \omega(T_1, T_1) = 0.01206\ kg/kg\ of\ dry\ air$$

so, putting this

$$\omega_2 = \omega_1$$

we have calculated. So, from there we get the mass flow rate requirement as:

$$\dot{m}_f = 0.539\ kg/min$$

So this way we can do the calculation for a heating and humidifying air conditioning system.

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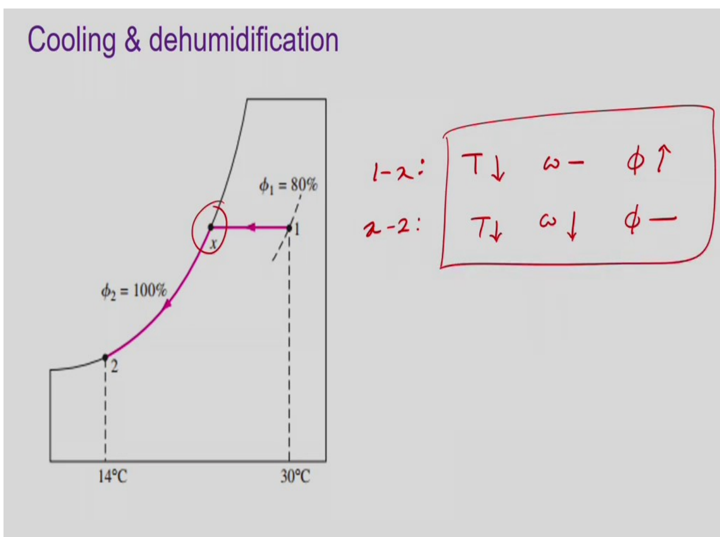

Similarly, we can also have a cooling and dehumidification process which is probably the most relevant process in a warm and humid country like ours whereas the heating and humidification is more suitable for cold and dry countries, but in a warm and humid place like ours cooling and humidification is most preferable. But now I have already seen sensible cooling, in case of sensible cooling here is no change in relative humidity, but here we want the temperature to decrease but also the relative decrease, how can you have it? At what condition the moisture starts separating from the sample? Of course, if the temperature becomes lower than the Dew point temperature and that precisely what we have to do to have a cooling and dehumidification process.

Here, we have to perform the process initially following a sensible cooling of things so that we are able to reach the saturation point. And once it reaches a saturation point any further cooling will lead to the dehumidification process. The mixture will remain saturated but its moisture content will keep on coming down as well as its temperature also be coming down. So, this is a cooling and dehumidification process during which temperature decreases. During the first part, this process, 1 to x, temperature is decreasing, ω is remaining constant and your ϕ is increasing. Now in the second part, x to 2, you can see here temperature keeps on decreasing, ω also keeps on decreasing but ϕ remains constant because it is constant at this 100%. So, both temperature and specific humidity are decreasing over the entire process, once we combine this together.

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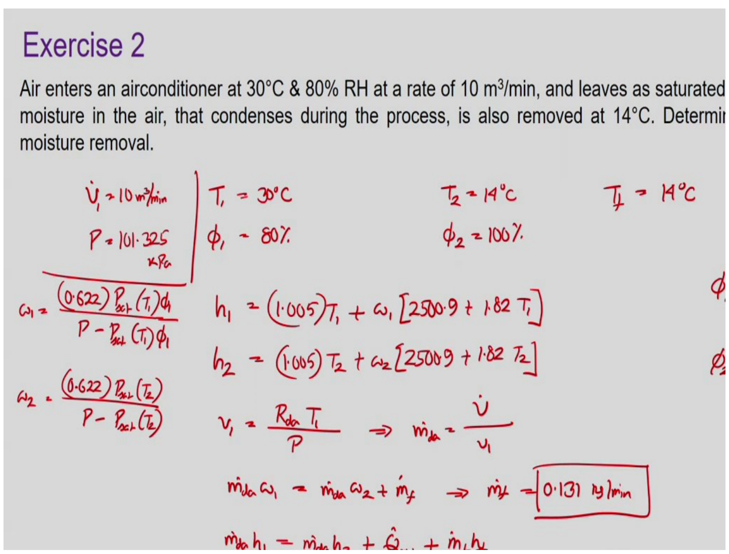

This is the cooling and dehumidification which are the most common kind of application that we can see. I have put here one numerical problem. Again, the solution I shall be leaving to you. Just I shall be discussing the process of solving this and giving the final answer. Here we have an air conditioner, here air is entering at 30 ^{0}C and 80% relative humidity, the assumption that you took in the previous case they are valid here as well.

So,

$T_1 = 30\ ^0\text{C}$

$\phi_1 = 80\%$

$$\dot{V}_1 = 10\ m^3/min$$

And it leaves the saturated air. So, the final state let us say at the state 3.

$T_3 = 14\ ^0$C

$\phi_3 = 100$ %

that is saturated air. Part of the moisture in the air that condenses during the process also removed at 14 ^{0}C. That is, during the process the water gets condensed over this entire process.

The condensate that happens that also has to be removed at 14 ^{0}C. So, let us say T_f is the temperature at which is the condensate which has been removed that is also at 14 ^{0}C.

$T_f = 14\ ^0$C

So, we have to calculate the rate of heat and moisture removal. So how can we achieve this? We can easily get the property values from the table, but instead of getting the property values, let us directly calculate h_1 as:

$$h_1 = (1.005)T_1 + \omega_1[2500.9 + 1.82T_1]$$

Now what is your ω_1? ϕ_1 is also known.

$$\omega_1 = (0.622)\frac{P_{sat}(T_1)}{P - P_{sat}(T_1)}$$

total pressure is not given here. So, let us consider the pressure to be atmospheric pressure, i.e., 101.325 kPa which is the atmospheric pressure.

So, from there we get ω_1 and using the ω_1, you get the value of h_1. Now h_2 which is the final state, let us go directly, let us say this is T_2 and this is ϕ_2. Now state 2

ϕ_2 is 100 %. So we can calculate ω_2 to be equal to:

$$\omega_2 = (0.622)\frac{P_{sat}(T_2)}{P - P_{sat}(T_2)}$$

Is whatever I am doing is right? No, I am not doing right, ω_2 is correct, because here we are dealing the situation of saturated thing. But ϕ_1 is:

$$\phi_1 = \frac{P_{wv1}}{P_{sat}(T_1)}$$

We have to multiply the ϕ_1. Because where we actually have partial pressure of water vapour in this. But in the second case ϕ_2, which is equal to 1 is:

$$\phi_2 = \frac{P_{wv2}}{P_{sat}(T_2)}$$

So, ϕ_1 will be coming into the first expression for ω_1. So, once we have ω_2, h_2 is:

$$h_2 = (1.005)T_2 + \omega_2[2500.9 + 1.82T_2]$$

So, you have h_1 and h_2, specific volume, again you can calculate easily specific volume for the entire mixture also can be calculated or specific volume for the dry air part also can be calculated. Let us calculate the dry air. So, for the specific volume of the dry air can be calculated as:

$$v_1 = \frac{R_{da}T_1}{P}$$

which is going to give you the mass of dry air as:

$$\dot{m}_{da} = \frac{\dot{V}_1}{v_1}$$

Now once we have this numbers, then we can go for the mass balance for the water vapour part. So,

$$\dot{m}_{da}\omega_1 = \dot{m}_{da}\omega_2 + \dot{m}_f$$

You are going to get the m value of $\dot{m}_f$.

And how much is your $\dot{m}_f$ in this case?

$$\dot{m}_f = 0.131 \text{ kg/min}$$

So, this is the rate of moisture that has been removed from this. So,

$$\dot{m}_{da}h_1 = \dot{m}_{da}h_2 + \dot{Q}_{out} + \dot{m}_f h_f$$

where total amount of energy that has been added is on the left hand side and on the right hand side is the sum of the energy that comes out, heat that has been removed and $\dot{m}_f\ h_f$ because this water has also been removed and enthalpy of h_f can be taken equal to the saturation enthalpy of liquid water at 14 ^{0}C.

So, from this:

$$\dot{Q}_{out} = \dot{m}_{da}(h_1 - h_2) - \dot{m}_f h_f$$

$$= 511\ kJ/min$$

So, this way we can perform for cooling and dehumidification process as well. So that is the discussion that you wanted to have about the different psychrometric processes because these are the most common psychrometric processes that you encounter in air conditioning applications.

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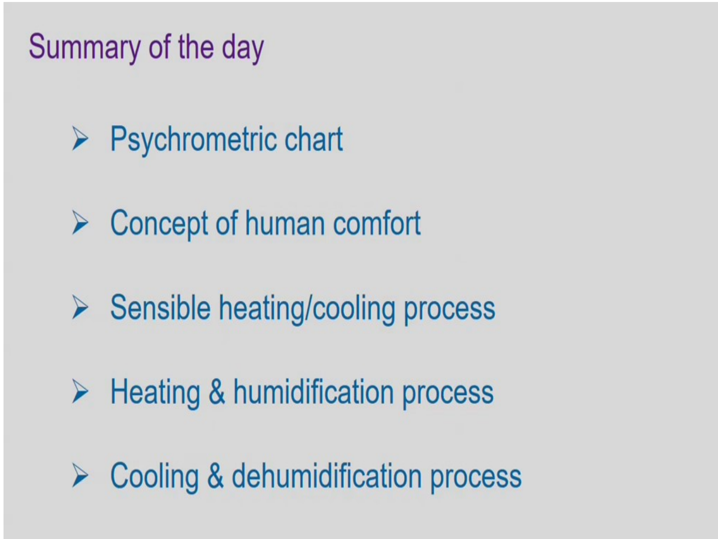

So, today you are being interest to the psychometric chart, the concept of human comfort and the requirement for the psychrometric processes that we have discussed. Then we have discussed about different kind of psychrometric processes like the sensible cooling and heating process. I have briefly mentioned about the humidification and dehumidification process, then we have analysed one heating and humidification process and a situation of cooling and dehumidification process.

So, that is it for today's discussion, in the third and last lecture for this week. I shall we take it forward to get a few more scenarios related to the psychometry. Till then you please try to solve a few more problems from the text books. Thank you very much.