Material and Energy Balances
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Lecture - 51
Energy Balances using Psychrometric Charts

Welcome to today's lecture on Energy Balances using Psychrometric Charts. In the last lecture we looked at what psychrometric charts are. Briefly these are cross-plotted charts where you can get information about different parameters for a gas-vapor mixture. The most common gas-vapor mixture which is usually looked at is air-water vapor mixture. We looked at what information can be obtained from these psychrometric charts in the previous lecture.

Today we will try to use the values which we can obtain from these charts to perform simple energy balance calculations. We have two example problems which will help us illustrate how these charts can be used for performing energy balances and how we can actually get enthalpy values directly from these charts while you perform energy balance calculations. Here is the example.

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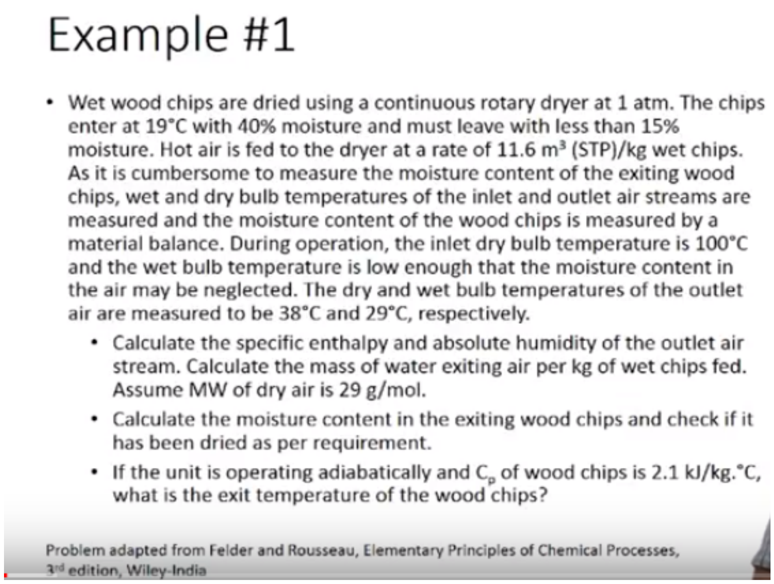

Wet wood chips are dried using a continuous rotary dryer at 1 atmosphere. The chips enter at 19 degree Celsius with 40% moisture and must leave with less than 15% moisture. Hot air is fed to the dryer at a rate of 11.6 meter cube STP per kilogram wet chips. As it is cumbersome to measure the moisture content of the exiting wood, wet and dry bulb temperatures of the inlet and outlet air streams are measured and the moisture content of the wood chips is measured by material balance.

During operation, the inlet dry bulb temperature is 100 degree Celsius and the wet bulb temperature is low enough that the moisture content in the air inlet may be neglected. The dry and the wet bulb temperatures of the outlet air are measured to be 38 degree Celsius and 29 degree Celsius respectively. You are asked to calculate the specific enthalpy and absolute humidity of the outlet air stream.

You are also asked to calculate the mass of water exiting with air per kilogram of wet chips fed. You can assume that molecular weight of dry air is 29 grams per mole. You are also asked to calculate the moisture content in the exiting wood chips and check if it has been dried as per the requirement. So if the unit is operating adiabatically and CP of wood chips is 2.1 kilojoules per kilogram degree Celsius what is the exit temperature of the wood chips?

Now, this is a problem which is a very practical problem because as they have said measuring the moisture content in a wood chip would be very tedious. You would have to perform some analytical techniques which would be very tedious and you would actually take a lot of time performing these experiments. Instead by measuring the dry and wet bulb temperature you can actually identify how much moisture is present in the air which is leaving the system.

Thereby you can actually perform simple material balance calculations to identify the moisture content in the wood chips and confirm if it meets the specification which is that it should be dried to less than 15% moisture. So what you have here is the wood chips are entering from one side and dry air is entering from the other side. So the flowchart for this process would look like this.

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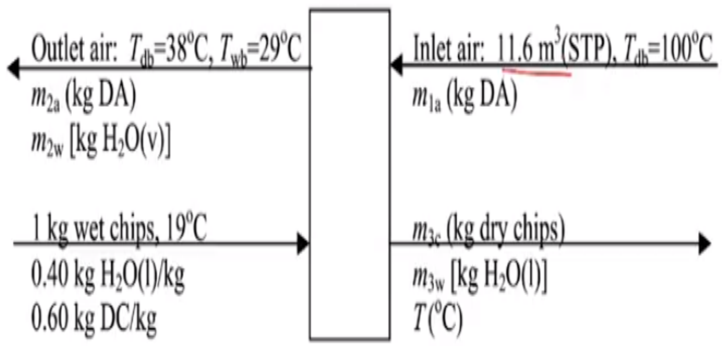
Example #1: Flowchart



You have wet wood chips, let us say 1 kilogram of wet wood chips entering at 19 degree Celsius and the composition is given as 0.4 kilograms of water liquid and the rest 60% is dry chips which I am just representing as DC and you have inlet air which is shown here. So the inlet air here is coming in as 11.6 meter cube STP. As I have mentioned in one of the earlier lectures STP does not mean that the air is coming in at STP but this is just a way to measure volumetric flow rate and molar flow rate for gases.

So if the gas were at STP conditions the volume would have been this. So using this we can convert the volume given to the number of moles from where we can convert it to the mass. Because psychrometric chart gives all the information in terms of masses. So we will be using this value and converting it into mass so that it can actually be used for performing the calculations.

So it is also given that the dry bulb temperature of the inlet gas is 100 degree Celsius which is given here and it is coming in at 100 degree Celsius. It is leaving at 38 degree Celsius but the wet bulb temperature has now become 29 degree Celsius whereas here it has been told that the wet bulb temperature is low enough that we can actually ignore the moisture content. So what we can assume is whatever is coming in through the inlet air is pure air which does not contain any water or dry air bone dry air which is entering.

So as you see the wet bulb temperature and the dry bulb temperature are close enough indicating that there is a high amount of moisture present in the outlet air stream. So you have an inlet wet chip which is coming with 40% moisture content and it would be leaving with some amount of water and we do not know at what temperature it is leaving the system. So we need to now calculate all this information which is required from the problem.

How do we go about doing this? So let us first take the psychrometric chart. So this is the psychrometric chart for SI units.

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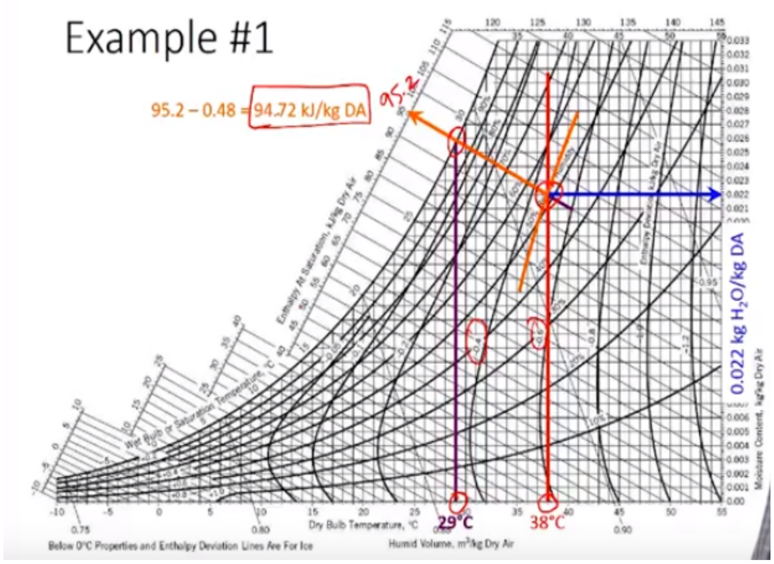

So as you see here you have all the SI units listed in terms of, the temperature is listed in terms of SI units and you have the moisture content and so on. Now, what information do we have from the problem? We know that the air that is coming in is dry air entering at 100 degree Celsius. So for dry air we do not need to use the psychrometric chart. However, we have air which is exiting which is a moist air which contains air-water vapor mixture.

So now for information for this exit air can be obtained from this psychrometric chart. Let us see what information we can obtain. We know that the dry bulb temperature is 38 degree Celsius. So we mark this on this chart which is 38 degree Celsius is here and from this dry bulb temperature of 38 degree Celsius we can draw a straight line where depending on the relative humidity the point of interest has to be identified. So this is the line on which the point of interest would lie.

However, we do not have the relative humidity given to us. Instead what has been given is the wet bulb temperature. The wet bulb temperature has been given as 29 degree Celsius which is here. So once we identify the wet bulb temperature as 29 degree Celsius we can again draw a line straight all the way up to the saturation curve. So once we do this we can draw a line parallel to the slanting axis which are there and identify at what point it intersects.

So this point is the point of interest. So why we do this is if we were given relative humidity what we would have done is we have drawn this line up to the curve for relative humidity and from there we would have identified the wet bulb temperature using this slanting line and then dropping back down to the temperature at which the wet bulb temperature can be identified.

Or we can also do this where we identify the temperature on the wet bulb or saturation temperature curve which is the 100% saturation curve seen here and from there we could draw a line which is parallel to the slanting lines. So the point of intersection for these 2 lines is the point of interest. Now that we have identified the point of interest we can actually identify enthalpies and the other information about what is the composition of the air which is leaving the system. So the first information we need to know is how much water is being carried out.

The next information we would want is what would be the enthalpy of this air-water mixture which is leaving the system. So for enthalpy we just draw the line all the way to this point to obtain the first information which is the amount of water accompanying the air which is leaving the system we would need to know the absolute humidity of the exit stream. So that can be obtained by drawing a line parallel to the x axis all the way to the intersection of the y axis.

To identify the first information which is the amount of water which is leaving the system along with the air or the moisture content in the air, we need to know the absolute humidity of the air which is leaving the system. This can be obtained using the curve given here. So all you need to do is from this point you draw a straight line parallel to the x axis till you intersect at the y axis where you can actually measure the moisture content or the absolute humidity.

So for this particular point the absolute humidity is identified as 0.022 kilograms of water per kilogram of dry air. So for every kilogram of dry air which is leaving the system, you would have 0.022 kilograms of water which has evaporated from the wet chips leaving the system. So similarly we can also identify the enthalpy term. So the enthalpy term you would use this particular line which goes along the axis parallel to the wet bulb temperature.

You go all the way to the enthalpy at saturation curve where you can identify what the enthalpy at saturation is. And to this you would have to use the enthalpy deviation and the sum of this value you get plus the enthalpy deviation would give you the actual enthalpy of air-water mixture at this point. So the curves which you see here are the -0.4 curve and the -0.6 curve. So this value, this point lies in between these two enthalpy deviations.

So we can identify the enthalpy deviation for this point as 0.048. So using interpolation we have identified this as 0.048 and at this point it is 95.2. So using these two values we can calculate the enthalpy of the outlet gas stream as 94.72 kilojoules per kilogram of dry air. So with this we got all the information we need for performing calculations using the psychrometric chart. Now let us go ahead and perform the regular material and energy balance calculations.

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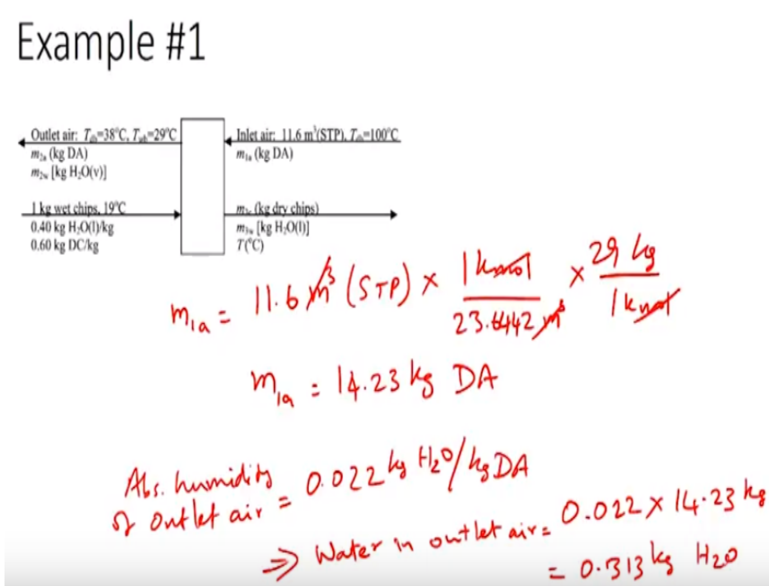

Before we start performing the material and energy balance calculations the first information we need is the mass of air which is entering into the system. So we know that 11.6 meter cube at

STP air is entering into the system. So this is the volume. We need to convert this volume into mass. So we can convert the volume to number of moles using ideal gas law. So based on the latest definition by IUPAC for STP we know that 1 kilo mole of any ideal gas occupies 23.6442 meter cube or 1 mole actually occupies 23.6442 liters.

So using this we can convert the mass to kilo mole sorry the volume to kilo moles. Once we have the number of moles of air entering we can convert it to the mass of air using the average molecular weight of air which has been given as 29 grams per mole. So now let us do that so the mass of air entering which is m 1a = 11.6 meter cube STP times 1 kilo mole/23.6442 meter cube times 29 kilograms per kilo mole. So this gets converted to mass.

And we can calculate the mass of air entering as 14.23 kilograms. So this is the mass of dry air which is entering at 100 degree Celsius into the system. So based on simple material balance we know that the same amount of air would be leaving the system. So m 1a = m 2a. So the mass of air leaving, the pure dry air leaving the system would still be the same. However, we need to calculate the mass of water which is leaving the system along with the air which is m 2w.

So we know that the absolute humidity for the air-water mixture leaving the system is 0.022 kilograms of water per kilogram of dry air. So this is the absolute humidity of the exit stream which is outlet air. So the outlet air stream has this absolute humidity. So we know the mass of dry air which is entering and leaving the system.

And we know the amount of water present per kilogram of dry air in the outlet air stream which means water in the outlet air stream would be equal to 0.022 times 14.23 kilograms which would be roughly equal to, this is equal to 0.313 kilograms of water. So 0.313 kilograms of water leaves with the air. So we know that 40% of the mass of the wet chips which was coming in was water.

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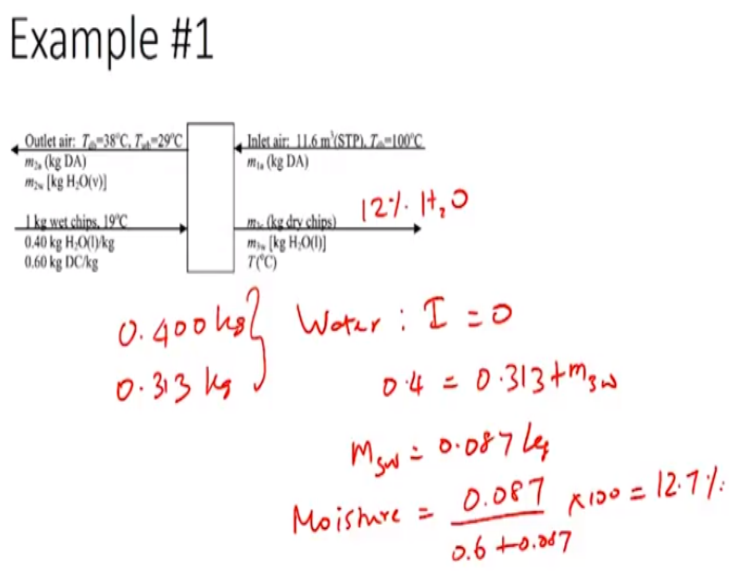

So now using that we know 400 grams or 0.4 kilograms of water is entering into the system and of which 0.313 is leaving with the outlet air. So these are the masses of water entering and leaving the system through the streams. So now we can write a water balance. So the water balance would be input equals output. So input is 0.4 and output basically has two streams. One is the 0.313 kilograms leaving through the outlet air and the rest is leaving through the dry air chips which are leaving. So now, the wood chips which are leaving.

So this would be 0.313 + m 3w. So therefore m 3w = 0.087 kilograms. So what we have now is the wood chips which are leaving the system contain 0.087 kilograms. We need to first identify whether this is meets the required specification. We were told that the chips which are leaving should have less than 15% moisture. Let us see if that holds good. So what we have is the moisture content is equal to so the moisture content would be 0.087/0.6 + 0.087 times 100 and this value is equal to 12.7%.

So this 12.7% is less than the required specification which is 15% moisture. So we would have the dry air wood chips which are leaving the system, the dried chips contain less than 15% moisture and the equipment has been designed as per the required specifications.

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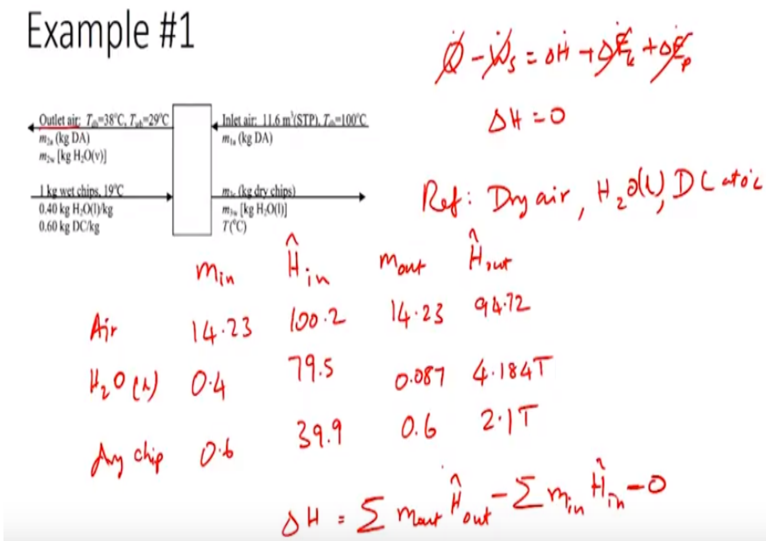

For the next part of the problem, we are asked to identify the temperature at which the wood chips would be leaving. So for identifying that we would have to perform energy balance calculations. So here all the required material balances have been done. So we will start with identifying what the equation would be. So this is an open system which means the general energy balance equation would have enthalpy instead of internal energy.

So the equation would be Q dot - W s dot = delta H dot + delta E k dot + delta E p dot. So since it has been shown that there is no moving parts and kinetic and potential energies are 0, the equation simplifies to Q dot = delta H dot and as the system is operating under adiabatic conditions Q dot also goes to 0 giving you delta H dot = 0. Since the flow rates are not given and only masses are given we can write this as delta H = 0.

So we can use this equation to perform calculations and identify the temperature of the exit stream. So let us start writing the enthalpy table before which we will have to identify the reference states. So here since we are using the data from the psychrometric charts for the enthalpy of the exit stream which is outlet air, we should use the reference states from the psychrometric chart only.

So the reference state for dry air and water vapor would be dry air and water liquid at 0 degree Celsius and I have also used dry chips at 0 degree Celsius. You could use it at different temperatures as well. This would mean that the reference states are dry air, water liquid and dry chips at 0 degree Celsius. This is the reference state we have used. So the table would be air, water liquid and dry chips.

So we are not accounting for water vapor separately because the air which we are accounting for is not dry air which we are accounting for. It is air which is coming in and leaving. So the inlet air does not contain water or any moisture. However, the outlet air contains the moisture. So this air accounts for water vapor which is leaving the system. So we do not have to explicitly write water vapor while we are performing the calculations.

So we now have to have the m in H cap in and m out and H cap out. So mass of air entering in is 14.23 kilograms. Water liquid entering along with the wet chips is 0.4 kilograms and dry chip is 0.6 kilograms. The mass of dry chip does not change. It still remains 0.6. Mass of water liquid leaving with the chips, wood chips would be 0.087 based on the material balance calculations.

Now for performing energy balance calculations we also need to identify the mass of air which is leaving the system. This value would again have to be written in terms of mass of dry air because the enthalpy value we get from the psychrometric chart is given as kilo joules per kilogram of dry air. It is not given as kilo joules per kilogram of humid air. So we will write the mass of dry air here also which means this would also be 14.23 and let us calculate, identify which enthalpies have to be calculated.

Since the reference states are at 0 degree Celsius and none of the inlet and outlet conditions are actually at 0 degree Celsius, we have to calculate all these enthalpies, H 1 cap, H 2 cap, H 3 cap, H 4 cap, H 5 cap and H 6 cap. So now let us see if we can find out the enthalpy values for all these specific enthalpies. H 1 cap would be integral CP VT using CP of air as 1.002 kilo joules per kilogram degree Celsius.

We can calculate this for 0 degree Celsius to 100 degree Celsius and the value would be 100.2 kilo joules per kilogram. For water liquid, using the CP of water liquid as 4.184, we can calculate this H 2 cap as 79.5 which is basically 4.184 times 19 – 0. So 19 being the temperature of the water coming in and 0 being the reference state. So similarly for the H 3 cap we can use the CP of wood chips which has been given as 2.1 kilo joules per kilogram degree Celsius and we would be able to get this value as 39.9 kilo joules per kilogram.

So for the outlet streams we do not know the temperature for the wood chips and water liquid. So we will just use temperature, final temperature as T as initial temperature based on the reference state is 0 and because of this it will just be CP times T, 4.184 T for water liquid and 2.1 T for the dry chips which are leaving. Now this H 4 cap, where do we get this H 4 cap? So this is the value which we obtain from the psychrometric chart.

So the psychrometric chart gave us the value for this air water mixture which is leaving as the outlet air and this was identified to be 94.72. Now that we have completed this table we can actually calculate delta H as basically sigma of m out H cap out - sigma of m in H cap in and this value is equal to 0. So using this we would be able to get the equation for temperature.

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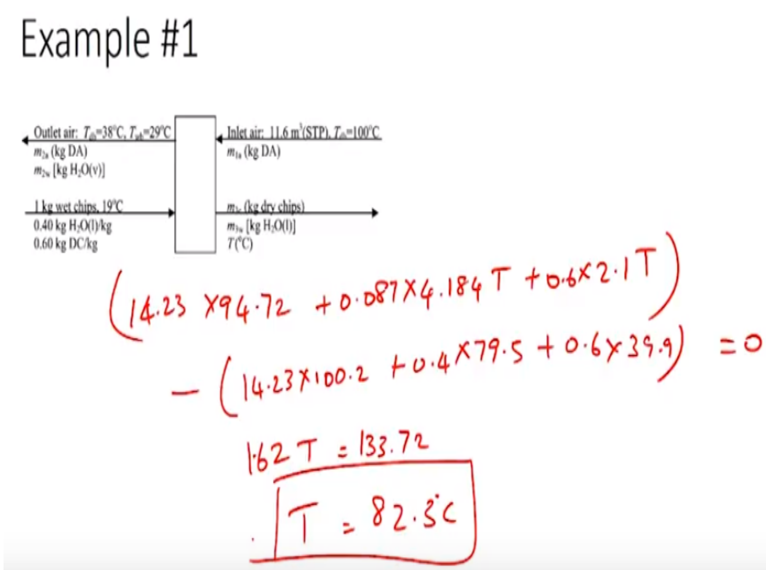

14.23 times 94.72 + 0.087 times 4.184 T + 0.6 times 2.1 T. This is the total enthalpy of the outlet streams minus the total enthalpy of the inlet streams which would be 14.23 times 100.2 + 0.4 times 79.5 + 0.6 times 39.9 = 0. So with this the equation comes down to 1.62 times T = 133.72. So T = 82.3 degree Celsius. So the temperature of the wood chips which are leaving the system is 82.3 degree Celsius.

With this we have performed the required material and energy balance calculations using the psychrometric charts. Let us look at one more example problem on how to use psychrometric charts for performing energy balances.

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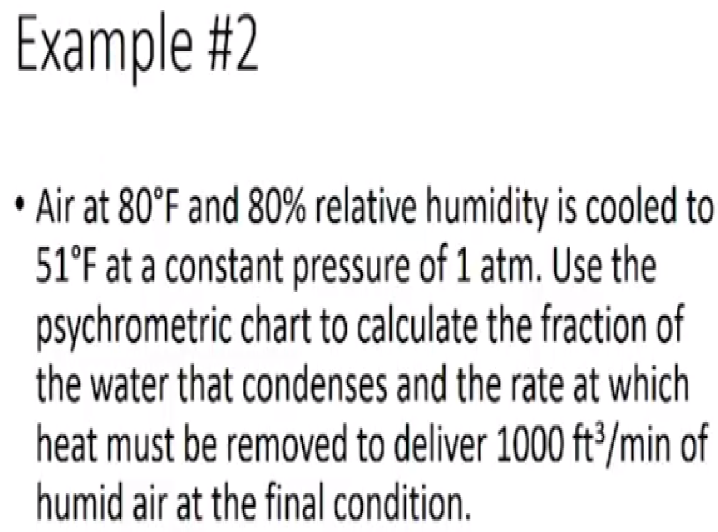

This time, so this time we are going to look at problem which uses American Engineering System. So the problem statement goes as air at 80 degree Fahrenheit and 80% relative humidity is cooled to 51 degree Fahrenheit at a constant pressure of 1 atmosphere. Use the psychrometric chart to calculate the fraction of water that condenses and the rate at which heat must be removed to deliver 1000 feet cube per minute of humid air at the final condition. Let us look at how we would solve this problem. So here is the flow chart for this system.

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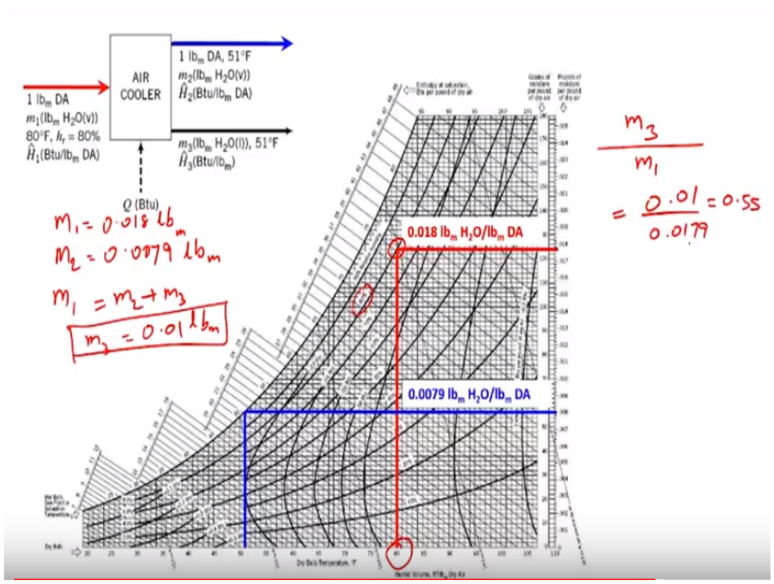

So we are assuming that 1 pound mass of dry air is actually entering into the system and this contains m 1 pound mass of water vapor which is because it is 80 degree Fahrenheit with a relative humidity of 80%. It enters into the air cooler and it gets cooled where some of the water condenses and leaves and the other rest leaves as the air water mixture which must be the saturation air water mixture at 51 degree Fahrenheit.

Because liquid and water exist in the same condition of the outlet stream we would assume that this is in equilibrium and the air which is leaving is saturated with water vapor at 51 degree Fahrenheit. So using this let us see what we can calculate. We first need to identify all the masses and also identify the enthalpies so that we can perform energy balances to identify the amount of heat which needs to be removed.

Once we have that we can actually calculate what is asked for which is the heat required to be removed for 1000 feet cube per minute of humid air in the final condition. Now let us start. First thing is to identify the condition given which is the inlet condition, 80 degree Fahrenheit and 80% relative humidity, so which is this curve. So using this we can first identify the absolute humidity of the air which is entering which is given in the y axis.

So the absolute humidity is identified as 0.018 pounds of water per pound of dry air. So this means we have 1 pound of dry air entering. So m 1 would be equal to 0.018 pounds. So next information we need to look at is m 2. So again we have information about the exit stream here. So 51 degree Fahrenheit and as I said this should be at saturation. So we go all the way till the 100% saturation curve and identify the absolute humidity as 0.079 pounds of water per pound of dry air.

So that would mean that you have 1 pound of dry air leaving which means 0.0079 pounds of water is accompanying this implying m 2 = 0.0079 pound mass which is the mass of water vapor leaving with the dry air. So from here we can calculate m3 using simple material balance. So your water balance would be input equals output which is m 1 = m 2 + m 3. So from here you can calculate m 3 as 0.01 pound mass.

So this is the liquid water which is obtained because of condensation. As we have been asked to identify the fraction of water which is condensed that would be the mass of water liquid which is condensed and leaving divided by the total mass which is entering which is 0.01/ 0.0179 which is roughly 0.55. So roughly 55% of the water entering gets condensed because of this process.

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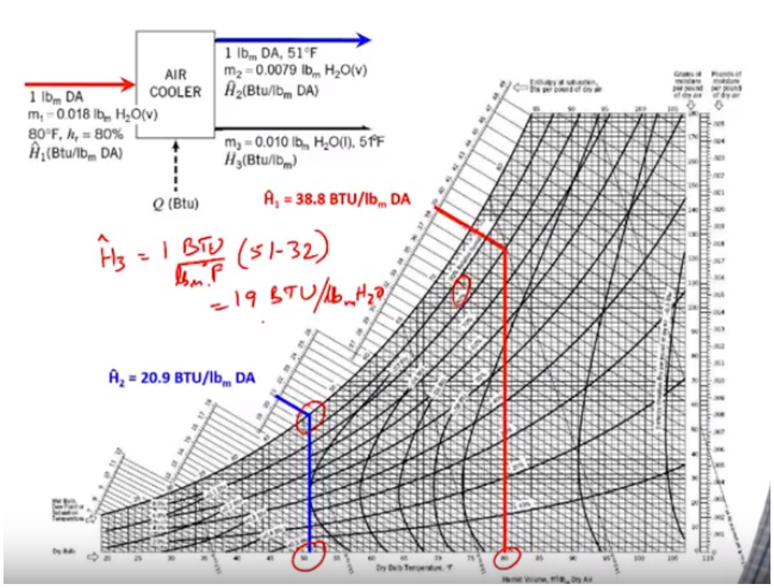

Now that we have identified the masses of water vapor coming in, water vapor leaving and water liquid leaving, we need to identify the enthalpies of the inlet and outlet streams. So the inlet stream you have air water mixture coming in at 80 degree Fahrenheit and 80% relative humidity so which would mean again we can draw the same line from 80 degree Fahrenheit to 80%

relative humidity which is this line and to identify the enthalpy, specific enthalpy we can actually go to this axis using the slanting line and identify this particular value which is 38.8 BTU per pound mass of dry air.

If you remember we have been using another quantity called enthalpy deviation based on these curves that we are observing here. However, if you see, if you observe this here what you see is these curves actually start here and end at about here. They are not going beyond this point. However, after this point it goes all the way up to this to the end.

So for the first few points it goes here indicating that the enthalpy deviation of this region which we are looking at is probably very small and hence we do not have to worry about enthalpy deviation and whatever we are measuring here is good enough to look at. So that is what we have done. We have just looked at the value which is 38.8 BTU per pound mass of dry air.

So similarly for the exit stream which is the cooled air leaving the system, you can identify 51 degree Fahrenheit here and 100% relative humidity and we can identify the enthalpy at saturation as 20.9 BTU per pound mass of dry air. So the H 3 cap is the only thing which needs to be identified. H 3 cap can be identified directly because it is liquid water and we know the CP value for liquid water which would be 1 BTU per pound mass degree Fahrenheit.

And from there you can actually calculate the enthalpy change as H 3 cap = CP which is 1 BTU per pound mass degree Fahrenheit times 51 – 32 which is equal to 19 BTU per pound mass of water. So why did I use 51 to 32 as the range? So the reference state for the psychrometric chart in American Engineering System is air and water liquid at 32 degree Fahrenheit. So the enthalpy which we calculate has to be from this reference state to the final condition which is 51 degree Fahrenheit. So it is 51 – 32 which is being used and the value we have is 19 BTU per pound of water.

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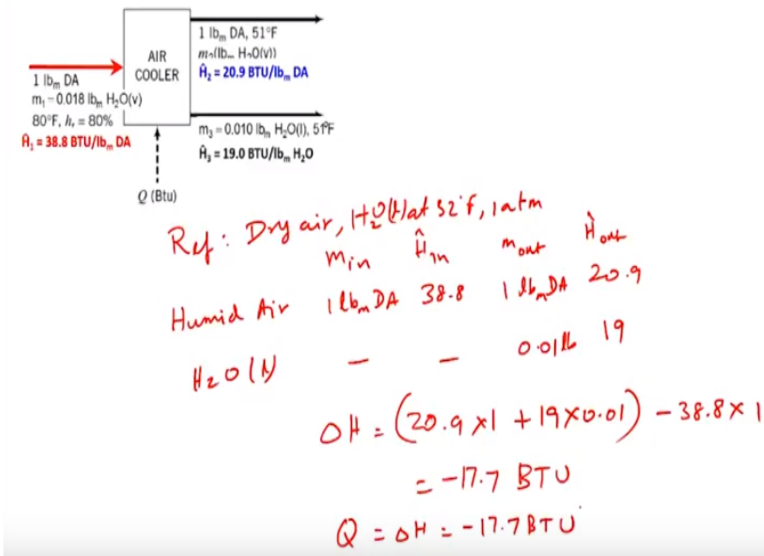

Now that we have all the masses and enthalpies for the inlet and the outlet stream we can perform energy balance calculations so that we can get the amount of heat that needs to be removed or Q. So how do we do that? So first we again have to build the specific enthalpy table. So for that we will have to identify the reference states. As I had mentioned the reference state for the psychrometric chart is dry air and water at 32 degree Fahrenheit and 1 atmosphere.

So water is at liquid and dry air is obviously at gas phase. So your components which are there is humid air and water liquid which are entering and leaving the system you have m in H cap in m out and H cap out. So the enthalpies which we got were in terms of BTU per pound mass of dry air. So we will only account for the mass of dry air in this table. We will not write the mass of humid air in this table.

So this is 1 pound of dry air and entering and leaving and you do not have any liquid water entering. You have 0.01 pounds of liquid water leaving. So using the calculations which we have already done for the psychrometric charts we can fill the enthalpy table where this H 1 cap would be 38.8 BTU per pound mass of dry air. This would be 20.9 BTU per pound mass of dry air and this value would be 19 BTU per pound mass of water.

So now using this table we can calculate the delta H value. Delta H would be 20.9 times 1 + 19 times 0.01 – 38.8 times 1. So this value is – 17.7 BTU. So fitting this back into the general energy balances equation, you would have Q = delta H which equals -17.7 BTU. So the amount of heat that needs to be removed would be 17.7 BTU.

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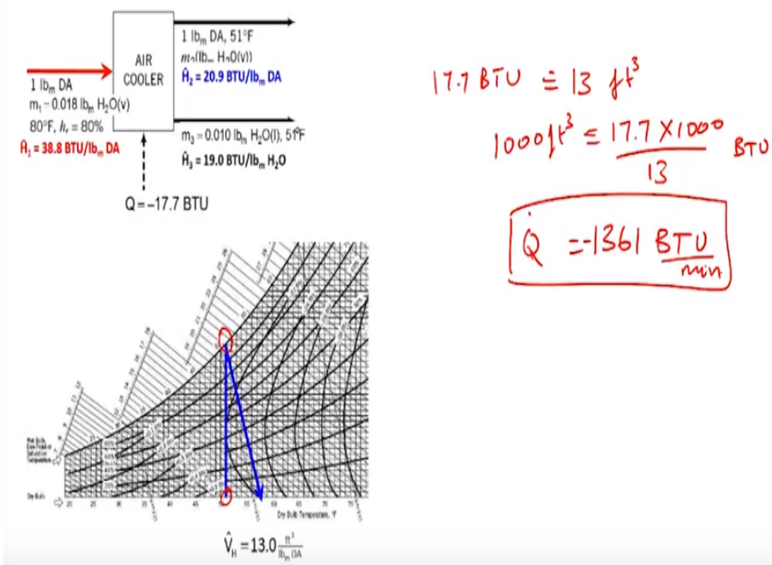

The problem asks us to identify how much of heat needs to be removed for producing 1000 feet cube of humid air. So we know the mass of dry air which is leaving the system. However, we do not have the volume of humid air which is leaving the system directly. So that we can identify using the humid volume data. So the exit stream is at 51 degree Fahrenheit and 100% relative humidity.

So the humid volume can be identified using a line drawn parallel to these slanting lines which you are seeing here and using that you would have the humid volume or the air water mixture which you are having is roughly 13 feet cube per pound mass of dry air. So there is 13 feet cube of humid air which is leaving the system. Now that we have this value we need to identify how much heat needs to be removed for 1000 feet cube of humid air to be produced.

So what we have is 17.7 BTU should be removed to produce 13 feet cube of humid air. So now we want to produce 1000 feet cube. So how much heat needs to be removed? To produce 1000 feet cube we need to remove 17.7 times 1000/13 BTU of heat. So this value is Q that needs to be removed would be so this, the amount of heat that needs to be removed would be roughly 1361 BTU. So Q would be negative because you are removing heat.

So this is the heat being removed. As the flow rate has been given Q dot would be this BTU per minute. We want to produce 1000 feet cube per minute of humid air leaving the system. So the amount of heat, the rate at which the heat needs to be removed would be 1361 BTU per minute. So with this we have performed a couple of example problems to illustrate how psychrometric charts can be used for performing material and energy balance calculations where you have the air water mixture as one of the components in the system.

So in the next lecture, we will look at a different concept which is the mixing and solution. Thank you.