[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: So I called the lecture Case Studies. The first case, we're going to do is weather. And the second case we're going to do is particle physics.

So this is the case of weather. OK, air always has some water in it, right? Always.

All right, let's define some terms. Relative Humidity, or RH for short, equals the water vapor pressure normalized to its saturation pressure. In other words, rh, which is normally expressed as a percent, equals 100, because it's a percent, times PH2O, that is the water vapor pressure, over the saturation vapor pressure. Maybe you knew that already from looking at the weather report.

Another term, dew point. Who knows what the dew point is? Can you tell me?

There's a chat. I missed a chat. Let's see. Pro tricks. Thanks, All right--

AUDIENCE: It's like 4 Celsius?

PROFESSOR: Sorry.

AUDIENCE: Just 4 Celsius?

PROFESSOR: I mean, but what's the concept? What is it-- what does it capture?

AUDIENCE: Equilibrium of atmospheric pressure and vapor pressure.

PROFESSOR: Yeah, those concepts are in there. Anybody else? It's the temperature at which water at its current vapor pressure would condense. So this is a little bit of a complicated concept, even though it's in your-- it's right there in your weather report.

You take the current pressure of water, and you find that temperature for which the current pressure of water equals the saturation vapor pressure. Why is it called the dew point? Please, somebody give it a shot. Why is it called the dew point? What's that word come from?

AUDIENCE: So isn't that when water becomes a liquid form on grass and stuff. So it forms dew.

PROFESSOR: Yeah, dew is like wet condensation, typically on grass or leaves. Why does that-- it's not that it rained overnight, right? When you come in the morning, the grass is wet, especially in the summer, even if it didn't rain. What happened?

AUDIENCE: The water condensed onto the grass.

PROFESSOR: The water condensed onto the grass. It spontaneously condensed onto the grass because the temperature fell below the dew point. So there was some humidity in the air. During the day, the dew point was lower than the current temperature. In other words, water was below its saturation vapor pressure.

As the temperature drops, the saturation vapor pressure drops. And at some point, those cross. And then, water condenses out and forms dew.

So let me-- when it's raining-- when it's raining, water is in two phases, vapor and liquid, right? And PH2O equals PSAT 100% humidity. When it's raining, the humidity is 100%. And the dew point, it's just the temperature.

On a sunny day, well, I should just say, otherwise, the water vapor pressure is lower than its saturation vapor pressure. The relative humidity is lower than 100%. And the dew point is greater than or less than the temperature.

AUDIENCE: Less than?

PROFESSOR: Exactly. These are important concepts. So please dwell on these if it's not immediately apparent. Let's look at some data.

All right, so here's what I did. I grabbed the Weather Underground. And I went to Weather Underground, and I grabbed some data. And I grabbed it for a typical day. So I grabbed it for last Tuesday.

And here's some data. So it gives you plots of random things. And then, it gives you a table of time, temperature, dew point, humidity, then wind, wind speed, wind gust, pressure, and all that. then I grabbed that data and I started plotting it.

All right, so first of all, here's the data that it gave me. So the x-axis here is the hours of the day, and the y-axis is temperature in Fahrenheit, and make things familiar for us. So the temperature-- this is a typical day. So temperature started low, and got warm, and then and then cooled down at night. So that's very typical.

The dew point slowly rose throughout the day. So there's more water coming into the air, right? The weather pattern, for whatever reason, is bringing more humid air into the region. The dew point is crawling up.

All right, so the next thing I did is I plotted two things. I plotted the saturation vapor pressure as a function of temperature using the expression, which we derived 10 minutes ago. And then, I plotted the actual vapor pressure.

OK, how did I do that, somebody? The orange curve, please, how did I find the saturation vapor pressure as a function of time throughout the day? How did I do that?

AUDIENCE: You used your model from before and use the temperature at that point.

PROFESSOR: Good. Yeah, let me back up. Exactly right. So I developed this model. Fits the data pretty well.

I just plug-in the temperature. I convert from Fahrenheit to Kelvin, but I plug-in the temperature. And I get this number. So you see it varies monotonically with temperature. That's good.

Temperature goes up. Vapor pressure goes up. I'm plotting in torr by the way. It's convenient to plot in units that are like 1, 5, 10, 20. Does anyone know what a how many torrs in an atmosphere? Anybody know?

AUDIENCE: 7.5?

PROFESSOR: 760. So these are important. You should know such things. So 760 torrs in an atmosphere. Torrs corresponds to a millimeter of mercury. So these are the kind of scientific literacy things.

I didn't want to plot in pascals. I didn't want to be down in like the orders of magnitude away from 1. Great, so now we understand how I got the orange curve, how did I get this blue curve? That's the actual vapor pressure of water throughout the day.

Well, I've got the saturation data. And I've got-- and I've got the dew point. I could have plotted relative humidity. I do that next.

The way I get the blue data is I take the dew point temperature and I plug that into my model, right? That's the meaning of the dew point. The dew point tells you the water vapor pressure in terms of the temperature at which that pressure would be saturated. So I plug the dew point into this model to get the actual water vapor pressure.

All right, last curve, relative humidity. Somebody please volunteer and tell me how do I calculate this relative humidity? Somebody who hasn't volunteered yet today please.

AUDIENCE: Don't you just divide the two lines that we just found? So we would be dividing at each point. The blue line by the red line and then--

PROFESSOR: Thank you. That's exactly right. It's the it's the fraction relative to saturation, right? So it's the actual vapor pressure divided by the saturation vapor pressure. Thank you.

So you see, it's got the kind of-- there's a little bit of wet air coming into the region. Dew point starts creeping up. But then the day starts heating up, right? And the relative humidity falls.

And then, at night, the relative humidity climbs. This is not a day where we're going to form dew, right? This is almost 11:45 at night, and the relative humidity is still just at 50%.

But on summer days, you'll see this climb at night. Really, really come up towards 100. Then we're going to form dew. Or frost if it's winter. Excellent.

So I really want you to become proficient with these sorts of data manipulations. And now you understand the weather a little more. OK, so let me see what comes next.

That was it for the weather and meteorology. The next case study we're going to do is in a totally different topic. So I want to pause for two minutes and gather any questions that you have on the concepts of dew point and relative humidity.

These concepts of vapor, which is sub saturation are really important for materials processing and pretty much everywhere else. So I'm using this very accessible commonplace example of the weather. But this sort of analysis is certainly not limited to meteorology.

AUDIENCE: I was ask about the line we saw in before, which wasn't exactly linear. I think it was like the 1 over T y log pressure. So what's the parameter that if we got like either like the H is constant or that the gas is ideal? Which one of them is like the most efficient to fix and get a better fit of our initial assumptions?

PROFESSOR: Yeah, it's a good question. So first of all, if you look up expressions for the vapor pressure of water, you'll find equations that look like this with correction terms. So you'll find equations that look like this with quadratic terms or logarithmic terms. They're just curve fitting.

There's not really thermodynamics in there, but they're curve fitting, and this model does not exactly fit the data. So that's just an empirical thing. So I encourage you to just go Google for expressions and you'll find different expressions.

What's underlying there? What's the reason for that? The assumption of constant Delta H is the first to break down. So the assumption of temperature independent enthalpy of vaporization is pretty good in a narrow temperature window. But it's not good from 0 to 100 C. It's not good over that whole range.

And so, if you were to analyze more carefully and come up with an expression for the temperature dependence of Delta H, you would get a more accurate model. And it would be more mathematically complicated than this one. Thank you.

All right, so now it's 10:28. I want to move on to particle physics. So the example we're going to look at and we're going to work some-- we're going to work a little bit is out of cloud chambers. So if we were in a classroom, I'd ask how many of you have seen a cloud chamber, or know what a cloud chamber is.

It's a little awkward to resume, so I'll just give you a two minute introduction to cloud chambers. Cloud chambers are-- let's see, they're an expansion apparatus for making visible the tracks of ionizing particles and gases. So this is Charles Wilson Cavendish Laboratory in Cambridge, Nobel Prize for this work in 1927.

And here's what it is. Here's his drawing. You have A is the chamber here. And A is connected via this valve, B, to a vacuum space, C. And C is evacuated by a pump, so there's a pump and gauge.

And there's a voltage across that space. And these are magnets. So there's magnetic field lines. So this space here has electric field lines and has magnetic field lines. And the space is filled with wet air, humid air. And at times 0, what they do is they open this valve, and they cause the air to rapidly expand into this vacuum space. So that's what you do.

And here's a photo of it. So here's the volume here. It's glass so you can see into it. You can see there's this volume here. Here's the vacuum space. Here's the vacuum pump connections. And there's a valve here, and a valve actuator here, the stem-- the valve stem, I guess, they just pull it manually.

And what does this do? It creates a situation where the water is super saturated. It goes from-- you go from relative humidity, less than 100%, to relative humidity, greater than 100%. It's super cooling, right? That's like the instant hot pack.

So you have a super cold situation with greater than 100% relative humidity. Or in other words, the dew point's higher than the actual temperature. And what happens? Condensation will nucleate around any imperfection.

In particular, it will nucleate around ionized molecules created by ionizing radiation. So as radiation that ionizes air passes through the chamber, it leaves a path of cloud. It leaves a path of condensed water vapor. That's a cloud chamber.

From the original paper, he put in a piece of radiation, radioactive material. And, of course, this thing is spewing, ionizing radiation, nucleating cloud everywhere it goes. And you get this kind of starburst pattern.

Here's another Nobel Prize. This is the-- well, it was Fermi, who originally hypothesized the existence of positrons, and Carl Anderson at Caltech verified that. And he got the Nobel Prize for it. And so, this is the first published recorded positron track in a cloud chamber.

And we won't go into how they figure out it's a positron. The point is that you have a piece of ionizing radiation that's normally invisible, and it's made visible because it leaves behind clouds. This is kind of a beautiful concept.

And here's a very long-time exposure photograph of a cloud chamber. All sorts of radiation here. They look pretty beautiful.

And I have a couple examples here of these things actually running. So here's first an example from Harvard. And I don't know whether you'll be able to hear the audio on this. And if you can't, that's perfectly fine.

That's dry ice. So there's a bed of dry ice. And then what they're going to do is put the box over it. And here, they're not going to use water vapor. It's going to be a cloud of ethanol.

So they're going to saturate the-- they're going to saturate the chamber with ethanol. And I think what's happening now is the temperature is slowly dropping, and they're just projecting light through the box. And now, the ethanol is condensing spontaneously in the box.

What are those what are those zing traces? What's going on in there? What's creating those lines of cloud? Those are cosmic rays zinging through the box.

Here's another example. They're slowly introducing a rod with 2% thorium, which is radioactive. That's giving off ionizing radiation and the cloud is nucleating around that. That's really cool.

It's sort of a more, I would say, a slightly prettier example here from a company that sells these as demo kits. And we'll just look at this for a little while because it's really pretty. And so, here, they have a little bit of a cleaner system. I don't know whether this is water, or ethanol, or what have you.

But they have this thing operating continuously. I don't know how they rig that up. But they have it operating continuously. Not one at a time. And all these lines are just the cosmic rays that we're constantly inundated with.

Maybe there's some other radiation in there as well. I'm not sure. And normally this is invisible, right? But it's visible because we've created a situation of greater than 100% relative humidity.

Isn't that cool. It's really cool. So I'll take questions for a minute. And with the remaining time, we're going to set up and solve this problem. And I'll explain what I mean.

So this is 110-year-old technology. Doesn't mean the concepts aren't valid today, right? Now it's mainly used for science museums. Has anyone ever seen one of these? There's one at the Exploratorium in San Francisco.

I haven't been to see it, but I've seen a video of the one they have set up there. There's one in the physics teaching lab here at MIT. Has anyone ever played with one of these?

All right, well, anyway it's cool stuff. When there's a magnet on, you know whether the particle is charged or not by whether it bends because charged particles curve in magnetic fields. Anyway, let me stop this mesmerizing video and move back to the board.

All right, so here's the cloud chamber problem. All right, so we have a cloud chamber. And let's just make it specific initially at 298 Kelvin and 1 atmosphere filled with air with dew point of let's say 288 Kelvin. Let's make it nice and round.

So this is 77 degrees Fahrenheit, and this is-- I don't remember. Now this is 59 degrees Fahrenheit. So this is typical lab conditions you might find in Boston. So it's 77 degrees in the lab. The humid air has a dew point of 59 degrees. And we're going to expand-- expands quickly.

In your thermal class, you're supposed to read that as adiabatically. It expands quickly by-- and we're going to parameterize the expansion by Delta V over V initial. This is going to be the control parameter in our analysis.

So we're going to expand the volume by Delta V over V. And here's the problem, find the Delta V over V initial needed to achieve saturation. I used to give something like this as a homework problem. But I think it's more fun to work through in lecture.

So we have a cylinder with a piston. We have humid air. You have humid air. We're going to withdraw the piston, and we're going to have air with condensable water.

All right, so humid air to air with condensable water vapor. That's the problem. And I'm going to simply step through how you solve this because it's pretty complicated. And if I don't get all the way through, we'll we'll post some notes.

So the first thing is we're going to write an expression for the water vapor pressure as a function of Delta V or V initial. The initial vapor pressure PH2O initial equals the saturation vapor pressure evaluated at the dew point.

And I just plug this in. It's 1,863 pascals. That's using concepts which we learned earlier in the lecture.

The system is initially at P total initial equals atmosphere equals 101,325 pascals. So here's a concept which we're going to learn on Friday. The water vapor pressure equals the total pressure times the mole fraction of water. This is Dalton's law of partial pressures. And we're going to dive into that on Friday, Dalton's law.

OK we know for an adiabatic process-- for an adiabatic process, P final equals P initial volume final over volume initial to the minus gamma. We know that. And so, I want to parameterize in terms of 1 plus Delta V or volume initial, that's my control parameter. That's taking results from a couple of lectures ago.

And then, I apply Dalton's law. And what I get is the water vapor pressure equals the mole fraction of water times the initial total pressure times 1 plus Delta V or volume initial to the minus gamma. And by the way, the mole fraction of water, I solved for it. It's 0.0184.

All right, we introduced this mole fraction concept. We then use our concept of dew point. We used our expressions for adiabatic process. And there we go. OK, this is an expression for water vapor pressure as a function of that expansion.

2, right expression for temperature, right? It's going to cool down as we expand. All right, well, again, for adiabatic process, temperature initial volume initial gamma minus 1 equals temperature final volume final gamma minus 1. In other words, temperature final equals temperature initial volume final volume initial minus gamma plus 1. And I like to parameterize in terms of Delta V over V initial minus gamma plus 1.

OK, good. So now we know how the temperature varies. We know how the pressure varies. And the final thing we do is we solve for saturation.

Solve for saturation. This is the thing we're looking for, the water vapor pressure is saturated. We know that PH2C equals XH2OP total initial plus 1 Delta V over Vi over minus gamma. OK, so that's that.

And we know that p? Saturation equals Ce to the minus B over T. That's our model. And T equals T initial 1 plus Delta V over V initial minus gamma plus 1. So that's the temperature. That's the saturation pressure.

So this is the thing we need to solve. This is parametric in Delta V or V initial. See, it's parameterized by what we chose as our control parameter. So we can solve this numerically, or graphically.

We do need a value for gamma. And I would recommend use value for the diatomic ideal gas, right? Why? Air equals 80% N2, 20% O2, plus small amounts of other things. And N2 and O2 are both diatomic molecules.

All right, CP over CV is actually in the range of 1.4 to 1.7 for air. Whereas its 1.4 for the diatomic gas. So we're not going to worry about this approximation. We're just going to take the value for the ideal gas.

We can adjust it later. This is kind of its own interesting meteorology problem. But we're just going to take the value for the ideal gas.

Now I'm done writing out equations. I want to show you the solution. But I ran through that rather quickly to make sure we'd have time for discussion. So I'm going to pause now and ask for questions on what on Earth just happened.

AUDIENCE: This is a pretty broad question, but without going back through the math again, could you talk about the steps are.

PROFESSOR: Right, so let's start with this. You need to recognize that there's a control parameter here. The control parameter is the thing that you're physically doing, which is expanding the volume.

This is your independent parameter. Everything needs to be a function of this, or else you kind of end up lost. So that's the first thing to recognize.

The next thing to recognize is what on Earth are you trying to solve for? This is the condition you're trying to solve for. All right, you're solving for the condition of saturation. For this pressure and beyond, you can start forming clouds. That's when water is saturated.

So recognizing that we're controlling expansion, and this is a condition we're looking for, you recognize that you have to get expressions for the left-hand side and the right-hand side in terms of the control parameter. So we took it one at a time. The pressure of water vapor was this expression. We got that by thinking about Dalton's rule of partial pressures and the adiabatic expansion process.

OK, so that's the pressure of water. What about its saturation vapor pressure? Its saturation vapor pressure varies with temperature.

We know these parameters for water. We solved them 40 minutes ago. They're also widely available.

All right, so that means that in order to find PSAT, we need temperature. Well, that also is varying as we expand. So now we need temperature parameterized in terms of Delta V over V.

So you see Delta V over V is controlling temperature, which controls PSAT. Delta V over V is controlling the pressure. And so, those connections need to be your starting point before you really dive in to do the solution.

Let me move on to show some slides and we'll come back because I hope the slides illuminate that a little more. Let's see the answer. So this is what I did. I first plotted the saturation vapor pressure of water.

Let me grab a laser pointer here. All right, so this is the saturation vapor pressure of water as a function of temperature. The same data from Wikipedia that I showed previously.

Although, now I'm plotting it on a semi-log scale. Y-axis is log, but x-axis is just temperature. And I'm 1 over temperature.

All right, these are my initial conditions. This is the starting temperature, standard temperature, 25 degrees C, and the initial water vapor pressure, right? If you remember the dew point was 288. So if I scoot over here to 288, I'll find that this water vapor pressure would be saturated at 288. That's the meaning of that term dew point.

So this is my starting condition. Now I'm going to expand. I have Delta V over V. As I expand, the temperature drops. As I expand, the pressure drops.

So as I expand, the temperature drops, and as I expand, the pressure drops. These are adiabats. These are adiabatic curves that you now are somewhat familiar with.

So you see I'm going to plot a parametric curve. I'm going to plot H20 partial pressure versus temperature on this curve, on this plot. There, I did it.

This is the parametric curve of how the water vapor pressure and temperature vary as I expand the volume. So you see as I expand, the pressure drops and the temperature drops. And at some point, it crosses saturation.

At that point, I'm saturated. And you could solve this numerically. You could also just eyeball it if you're in a hurry. It crosses for around 9% volume expansion. So you need to quickly expand this volume by roughly 10% in order for the water pressure to become saturated, or in other words, for to cross the dew point.

Think that's the end of my graphical analysis. OK, again, I don't know if that helped, but others, please, chime in. We have plenty of time to discuss this or anything else.

I think this is a fun problem to work because it leads to these beautiful images. It also is a bridge between the topic of binary phase diagrams and the topic of gas mixtures, which we start on Friday with Dalton's Law of partial pressure. So it's kind of a bridge topic.

Also, just something that everything every scientifically literate person should know. So, yeah, again questions? Please.

AUDIENCE: What is quickly expanding imply adiabatic process?

PROFESSOR: All right, that's excellent. So if you do anything fast enough, then there's no time for heat to transfer. Yeah, it is a confusing point because you haven't had free transfer yet and you haven't had kinetics.

And maybe if you're a Course 2, if you're a junior or senior student in Course 2, that's sort of obvious to you. But it's not necessarily obvious to you at this point. So if you do something very quickly, it can happen adiabatically or in approximate an adiabatic process because heat transfer takes time.

You can withdraw a piston much more quickly than you can equilibrate thermal energy between a volume and its walls. We've seen that a little bit with the free expansion example, or the free expansion problem, a couple of lectures ago. You can see this in many real world engines where things like compression strokes and internal combustion engines are approximated as adiabatic because they happen too quickly for that heat transfer.

So in a problem that you might receive on a problem set or an exam, typically we'll clarify. And, of course, there are corrections. It's not strictly speaking adiabatic. But this model works well.

AUDIENCE: Thank you.

PROFESSOR: Yeah. If you like, you can also just say we thermally insulated the walls. Anyway, I don't want to go far down that path because it gets kind of nitty gritty.

It is a helpful thing to know that in many textbooks and problems, maybe not that you'll receive from me directly, but maybe problems you'll find in other books or in other classes, when something is said to happen very quickly, that is kind of equivalent to saying adiabatically or quasi adiabatically. And you'll find lots of problems discussed in the scientific literature where they discuss the adiabatic solution of that, adiabatic process of this.

It's very common in quantum computing. Very, very common. For those of you who go into work on quantum computing, this becomes second nature. Adiabatic versus fast.

And there is, of course it's because heat transfer is the bane of qubits. And so, you have to operate quickly enough for decoherence not to take effect. So anyway, it's an important concept. Thank you for asking.