The Trailing Edge

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Why Thunderstorms Form in the Summer and Why You Have to Drain Your Air Compressor

"It's not the heat, it's the humidity!" We've all heard this cliché, and you may have even said it yourself. This sentiment directly references your body's primary method of controlling its internal temperature through evaporative cooling. Water is excreted by the skin as sweat, and heat energy from the body is used to evaporate the sweat, and because of the high latent heat of evaporation the water vapor carries away the heat energy, thus cooling the body.

Unfortunately, this method doesn't work very well if the water (sweat) can't evaporate because the atmosphere is already "full" of water vapor, commonly reported as a "relative humidity" at or close to 100 per cent.

But what exactly is humidity, and what do your relatives have to do with it? Our atmosphere consists of a mixture of gases, consisting of nitrogen, oxygen, argon, water vapor, carbon dioxide and other trace gases. Except for water vapor, all of the constituent gases exist in consistent amounts. So consistent that the gas constant for air can be considered to truly be constant.

Water vapor varies greatly in its amount, so much so that we give the amount of water vapor in the atmosphere a special name, humidity. The value of the gas constant for water vapor is significantly different than the value of the gas constant for air, such that if a single gas constant was applied to humid air the value of that gas constant would vary with the amount of water vapor present. Thermodynamically, humid air is treated as a mixture of air and water vapor. Dealing with a gas mixture is much more complicated than dealing with a single, consistent gas.

For many analyses, the amount of water vapor is so small that it can safely be ignored. The standard atmosphere is calculated assuming dry air (no water vapor). For many reasons, there is so much variation between the standard atmosphere and the actual atmosphere from day to day that the small effect of water vapor can be safely ignored. Many parameters, such as lift, drag, thrust, and horsepower are commonly calculated ignoring water vapor.

Table 1
Saturation Pressure of Water (Ref 1 and 2)

Temp (°F)	Saturation Pressure (psia)
-20	0.006189
-15	0.008252
-10	0.010904
-5	0.014293
0	0.018812
5	0.024117
10	0.030993
15	0.039785
20	0.050591
25	0.063853
30	0.080553
32.018	0.08866
35	0.09992
40	0.12166
45	0.14748
50	0.17803
60	0.2563
70	0.3632
80	0.5073
90	0.6988
100	0.9503
110	1.2763
120	1.6945
130	2.225

The Air Sponge, A Flawed Analogy

The mass of water vapor in a given volume of humid air is known as the absolute humidity. For many applications, this value is not that useful, because the limit on the absolute humidity varies with air temperature. For many purposes, it is more useful to consider how much water vapor is present compared to the maximum possible amount of water vapor. This is called "relative humidity" and lines up much better with how humidity "feels".

Frequently, relative humidity is described as a measurement of how much water vapor is present in the air divided by how much water vapor the air can "hold". This description makes the air sound like a sponge soaking up the water vapor. This analogy further breaks down when you consider that the absorbency of the air sponge changes with temperature. This really isn't a good analogy for understanding.

A Better representation

A better approach is to consider air and water vapor as two gases coexisting in the same space. The amount of each gas present can be determined from the partial pressure of that gas. The partial pressure of a gas is the pressure exerted by that gas if it was the only gas in the given volume at the current temperature. The sum of the partial pressures of all constituent gases with be the observed (or measured) pressure of the gas mixture.

For this analysis, humid air will be considered as a mixture of dry air and water vapor. All of the constituent gases of air, such as nitrogen, oxygen, argon, and carbon dioxide, will be considered as a single gas. We can do this because the proportions of these gases are very consistent.

At temperatures above cryogenic temperatures, air is a supercritical fluid, meaning that it will remain in a gaseous state regardless of its pressure. Specifically, the critical temperature of air is around -140°C.

However, the critical temperature for water is 374°C. At ambient temperatures below the critical temperature, as pressure is increased, the water vapor will start condensing into liquid. The pressure at which the water vapor starts to condense is called the saturation pressure, because at this pressure the volume is saturated with water vapor. The saturation pressure limits the amount of water vapor that can exist.

A greater amount of water vapor in a volume will increase its partial pressure. At partial pressures above the saturation pressure, water vapor will condense until the partial pressure is reduced to the saturation pressure. If the partial pressure is below the saturation pressure, the water vapor will remain in a gaseous state.

If the partial pressure of water vapor is equal to the saturation pressure, then the relative humidity is 100 per cent. If the partial pressure of water vapor is half of the saturation pressure, then the relative humidity is 50 per cent.

Why Thunderstorms Form in the Summer

The saturation pressure for water vapor is shown in Table 1 as a function of temperature. The sharp-eyed reader will immediately note that the saturation pressure increases as the temperature increases. The honors students will even note that some water vapor can exist in the atmosphere at temperatures below freezing (32°F), but that isn't significant to this discussion.

Thunderstorm formation is complex, including lifting action from thermals caused by the hotter summer sun. Much of the energy of a thunderstorm comes from the latent heat of evaporation that is released as the water vapor condenses back to the liquid state. The key point for this discussion is that because the saturation pressure is higher at higher temperatures, more water vapor can exist in a volume of air, and more water vapor releases more energy as it condenses. In the winter, there is not enough water vapor available in the air to release sufficient energy to create a thunderstorm.

Another common result of the saturation pressure being a function of temperature is that your air conditioner also works as a dehumidifier. As the warm humid air passes through the cold evaporator, the temperature of the air drops, as does the saturation pressure of the water vapor. If the water vapor partial pressure exceeds the saturation pressure, water vapor will condense until the partial pressure is equal to the saturation pressure at that temperature. This is why the evaporator produces water that must be drained away.

Why you have to drain your air compressor

A large amount of air at atmospheric pressure can coexist with a lot of water vapor, as long as the partial pressure of water doesn't exceed the saturation pressure of water at that temperature. What happens when we compress that large amount of humid air? To keep it simpler, let us assume that the compressed humid air is cooled back to its original temperature. This would be like running your air compressor, then letting the tank sit until it cools back to room temperature.

The dry air is compressed into a smaller volume, raising its partial pressure. Because the air is a supercritical fluid, it remains in a gaseous state.

The water vapor also gets compressed, raising its partial pressure. Because the water vapor is a subcritical fluid, if the partial pressure rises above the saturation pressure for the ambient temperature, the water vapor will condense until the water vapor partial pressure is equal to the saturation pressure. This condensed water will collect at the bottom of your compressor tank, rusting it out from the inside unless you remember to drain it.

It's Time for Recreational Maths!

The effect of temperature on humidity is fairly straightforward, as shown in Table 1. To better understand how increasing the pressure produces condensate, let's drag out some maths to run through an example.

Starting Conditions

Humid Air Volume:	43.53 ft^3
Humid Air Pressure:	14.7 psia
Ambient Temperature:	80°F
Relative Humidity:	100 per cent

(The weird volume comes from working the problem backwards to know how much humid air would compress into my 33 gallon air compressor tank. The humid air pressure is sea level standard pressure.)

Compressed Conditions

Humid Air Volume:	33 gallons
Moist Air Pressure:	125 psig
Temperature:	80°F

The starting conditions are given in customary units, but like any engineering problem, we need to convert into consistent units. In this case, the humid air pressure needs to be converted into pounds per square foot.

$$P_{humid} = 14.7\,\frac{lbf}{in^2} * \frac{144\ in^2}{ft^2}$$

$$P_{humid} = 2116.8\,\frac{lbf}{ft^2}$$

We'll also need the temperature in Celsius in a minute.

$$T(°C) = \frac{(T(°F) - 32)}{1.8}$$

$$T(°C) = \frac{(80 - 32)}{1.8}$$

$$T = 26.67°C$$

We need the water vapor saturation pressure. We could get the saturation pressure from Table 1, which returns 0.5073 psia at 80°F. However, for building a spreadsheet, it would be nice to be able to calculate the saturation pressure for any temperature. There are many curve fits for Table 1 available, and one of the most popular is Tetens' expression (Ref 3). Tetens' expression is a curve fit which requires temperature input in Celsius and returns pressure in millibars.

$$P_{sat} = 6.11 * 10^{\left(\frac{7.5T}{237.3+T}\right)} \qquad T(°C) > 0$$

$$P_{sat} = 6.11 * 10^{\left(\frac{7.5(26.67)}{237.3+26.67}\right)}$$

$$P_{sat} = 34.97\ mbars * \frac{2116.22\frac{lbf}{ft^2}}{1013.25\ mbars}$$

$$P_{sat} = 73.04\ \frac{lbf}{ft^2}$$

The partial pressure of water vapor is the saturation pressure multiplied by the relative humidity.

$$P_{water} = P_{sat} * \text{Relative Humidity}(\%)/100$$

$$P_{sat} = 73.04\ \frac{lbf}{ft^2} * \frac{100\ \text{per cent}}{100}$$

$$P_{water} = 73.04\ \frac{lbf}{ft^2}$$

The dry air partial pressure is what is left after subtracting the water vapor partial pressure from the humid air pressure.

$$P_{air} = P_{humid} - P_{water}$$

$$P_{air} = 2116.8\,\frac{lbf}{ft^2} - 73.04\,\frac{lbf}{ft^2}$$

$$P_{air} = 2043.8\,\frac{lbf}{ft^2}$$

Now that we have the partial pressures, we can calculate the dry air mass using the perfect gas law.

$$m_{air} = \frac{P_{air}V}{R_{air}T}$$

$$m_{air} = \frac{\left(2043.8\,\frac{lbf}{ft^2}\right)(43.53ft^3)}{\left(1716\,\frac{ft^2}{sec^2\,R}\right)(80°F+460)} * \frac{32.2\ lbm}{slug}$$

$$m_{air} = 3.08\ lbm$$

Likewise, we can calculate the water vapor mass using the perfect gas law.

$$m_{water} = \frac{P_{water}V}{R_{water}T}$$

$$m_{water} = \frac{\left(73.04\,\frac{lbf}{ft^2}\right)(43.53ft^3)}{\left(2762\,\frac{ft^2}{sec^2\,R}\right)(80°F+460)} * \frac{32.2\ lbm}{slug}$$

$$m_{water} = 0.0683\ lbm$$

Dividing the mass of water vapor by the sum of the mass of dry air plus the mass of water vapor

$$\text{Water Vapor\%} = \frac{m_{water}}{m_{air} + m_{water}} * 100$$

$$\text{Water Vapor\%} = \frac{0.0683\ lbm}{3.08\ lbm + 0.0683\ lbm} * 100$$

$$\text{Water Vapor\%} = 2.17\ \text{per cent}$$

When we compress the humid air, the dry air mass will remain the same. The compressor shows 125 psig (gauge), so we need to add the atmospheric pressure to get the absolute pressure.

$$P_{humid} = P_{gauge} + P_{atm}$$

$$P_{humid} = 125\ psig + 14.7\ psi$$

$$P_{humid} = 139.7\ psia$$

We need this pressure in pounds per square foot.

$$P_{humid}=139.7\,\frac{lbf}{in^2}*\,\frac{144\ in^2}{ft^2}$$

$$P_{humid}=20117\,\frac{lbf}{ft^2}$$

Since we set up the problem with the same temperature after compressing, the saturated pressure for the water vapor is still the same value.

$$P_{sat}=73.04\ \ \frac{lbf}{ft^2}$$

We will assume that the relative humidity of the compressed gases will be 100 per cent, because the water vapor will condense only just enough to match the saturated pressure.

$$P_{water}=73.04\ \ \frac{lbf}{ft^2}$$

The dry air partial pressure is what is left after subtracting the water vapor partial pressure from the humid air pressure.

$$P_{air}=P_{humid}-P_{water}$$

$$P_{air}=20117\,\frac{lbf}{ft^2}\ \text{-}\ 73.04\ \ \frac{lbf}{ft^2}$$

$$P_{air}=20043\,\frac{lbf}{ft^2}$$

The dry air mass has not changed after compression.

$$m_{air}=3.08\ lbm$$

The compressed volume can be calculated from the dry air partial pressure and dry air mass.

$$V_{comp}=\frac{m_{air}R_{air}T}{P_{air}}$$

$$V_{comp}=\frac{3.08\ lbm\left(\frac{slug}{32.2\ lbm}\right)\left(1716\,\frac{ft^2}{sec^2\ R}\right)(80°F+460)}{20043\,\frac{lbf}{ft^2}}$$

$$V_{comp}=4.42ft^3$$

$$V_{comp}=4.42ft^3\ \left(\frac{7.4805\ gal}{ft^3}\right)$$

$$V_{comp}=33\ gal$$

which is the size of my air compressor tank.

Now we need to recalculate the water vapor mass.

$$m_{water} = \frac{P_{water} V_{comp}}{R_{water} T}$$

$$m_{water} = \frac{\left(73.04 \frac{lbf}{ft^2}\right)(4.42\ ft^3)}{\left(2762 \frac{ft^2}{sec^2\ R}\right)(80°F+460)} * \frac{32.2\ lbm}{slug}$$

$$m_{water} = 0.00697\ lbm$$

Dividing the mass of water vapor by the sum of the mass of dry air plus the mass of water vapor

$$Water\ Vapor\% = \frac{m_{water}}{m_{air} + m_{water}} * 100$$

$$Water\ Vapor\% = \frac{0.00697\ lbm}{3.08\ lbm + 0.00697\ lbm} * 100$$

$$Water\ Vapor\% = 0.225\ per\ cent$$

Note that before compressing, the water vapor was 2.17 per cent of the mixture, but after compressing the water vapor was only 0.225 per cent of the mixture, because water vapor is a subcritical fluid that is limited in its partial pressure.

The amount of water precipitated out is the difference between the water vapor mass before and after compressing.

$$Water\ precipitate = 0.0683\ lbm – 0.00697\ lbm$$

$$Water\ precipitate = 0.0614\ lbm$$

Since we don't usually think of water in pounds, let's convert that to volume, knowing that the density of water is 1.983 slugs/ft^3.

$$Precipitate\ Volume = 0.0614\ lbm \left(\frac{slug}{32.2\ lbm}\right)\left(\frac{ft^3}{1.983\ slug}\right)\left(\frac{fl\ oz}{957.5064 ft^3}\right)$$

$$Precipitate\ Volume = 0.942\ fl\ oz$$

Assume the compressor runs the equivalent of doing the above compression 13 times, a reasonable amount for a day's work session. The amount of water precipitated in the compressor would be 13 * 0.942 fl oz, or 12.2 fl oz. That's slightly more than the liquid in that can of Coke you just drank.

- **Russ Erb**

References

1. Çengel, Yunus A. and Boles, Michael A., *Thermodynamics: An Engineering Approach, Second Edition*, McGraw-Hill, Inc., New York, 1994.

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3. Erb, R. E., *Pitot-Statics and the Standard Atmosphere, Fifth Edition*, http://erbman.org/Pitot%20Statics%20and%20the%20Standard%20Atmosphere%205th%20ed%20signed.pdf , Air Force Test Center, Edwards AFB, 2021.