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**Discussion 3-03  
Psychrometrics Review  
(Part 1)**

Willis Carrier, known as the father of air conditioning, defined Air Conditioning as follows:

*"Air conditioning is the control of the humidity of the air by either increasing or decreasing its moisture content. Added to the control of the humidity are the control of temperature either by heating or cooling the air, the purification of the air by washing or filtering the air, and the control of air motion and ventilation."*

The point is that air conditioning is not simply the process of cooling air for environmental comfort; and to simply cool air (i.e. reduce the temperature of it) will change the humidity characteristics and in a warm humid climate could cause numerous unwanted effects including discomfort, mold growth, mildew and related undesirable health, comfort, and odor problems.

Thus, whether for environmental comfort or a manufacturing or healthcare process, air conditioning requires control of humidity. The physical concepts related to control of the temperature and humidity properties of the air is called the science of psychrometrics. This discussion is a review of the principles of psychrometrics.

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### **DALTON'S LAW**

The science of psychrometrics (and of course, a clear understanding of that science) is based upon what is known as Dalton's Law, which states:

*Each constituent in a mixture of perfect gases behaves as though the other constituents were not present (at least as far as pressure is concerned).*

Visualize two tanks of equal volume (say 1 cubic foot including connecting pipe) connected by a large pipe with a valve in it. The valve is closed, and tank No. 1 is filled with a gas (let's call it gas X) at an absolute pressure of  $p_{x1}$  psia; tank No. 2 has no gas molecules in it; therefore, its absolute pressure is 0 psia; the entire system is at the temperature of the room,  $t_r$ . If the valve is then opened, after a very short time period, the X gas molecules will fill both tanks equally, and since it now occupies both tanks, the pressure will be less but it will be the

same in both tanks; actually, after returning to the equilibrium temperature ( $t_r$ ) that existed before the valve was open, since the volume has doubled, the pressure in each tank,  $p_{x2}$ , will be one half of the original pressure,  $p_{x1}$ .

Now, let's start the experiment again. This time, again with the valve closed, the same number of gas X molecules will fill tank No. 1 and at the same temperature as before. The pressure will, again, be  $p_{x1}$ . But now, in tank No. 2 is gas Y at a pressure of  $p_{y1}$  psia. When the valve is opened, some of the molecules of gas X will flow into tank 2, and some of the molecules of gas Y will flow into tank 1 until, after some finite time (depending upon the relative size of the tanks and the connecting pipe), the pressures in both tanks 1 and 2 will be equal. Furthermore, in each tank, the pressure read on a pressure gauge will be the sum of the pressure exerted by the gas X molecules ( $p_{x2}$ ) and by the gas Y molecules ( $p_{y2}$ ). In this case, the total pressure would be  $p_{T2}$  psia where:

$$p_{T2} = p_{x2} + p_{y2}$$

Following a return of the system to the initial temperature, the partial pressure of gas X,  $p_{x2}$  will be just as before; i.e., one half of the initial  $p_{x1}$  pressure (Dalton's Law) and the pressure of gas Y,  $p_{y2}$  will be one half of the original gas Y pressure,  $p_{y1}$ .

And both  $p_{x2}$  and  $p_{y2}$  would be called the partial pressure of each of these gases respectively. Also, according to Dalton's Law, both partial pressures would be equal in each tank.

(Think of this fundamental concept and convince yourself of its validity before reading on.)

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## **THE AIR**

Air is a mixture of the gases - *dry air* and *water vapor*.

Dry air is actually a mixture of several gases, containing approximately (by volume) 21% oxygen, 78% nitrogen and 1% numerous "rare" gases. These gases, at ambient temperatures and pressures are well into the superheat range of stable gas phase and far from the vapor boundary.

The water vapor, however exists at conditions near and at the liquid vapor boundary (i.e., saturation point) as defined in the steam tables. Just as a refresher, let's consider some of the saturated liquid/vapor state points regarding the properties of pressure and temperature, taken from the steam tables.

Saturation temperature - pressure relationships**Temperature,  $t_s$  approx. pressure,  $p_s$** 

<u>°F</u>	<u>psia</u>
40	0.12
60	0.25
80	0.50
100	1.00
150	4.00
212	14.70
300	67.00
350	135.00

Based upon this data, if tank No. 1 in the first example above was filled with water vapor that was at a temperature of 80°F and a pressure of 0.50 psia, that would represent the maximum water vapor pressure that could exist at that temperature. If molecules were removed, the pressure would drop, but if molecules were added (at no change in temperature) they would simply condense to water (i.e. change phase). Now, with no water in the tank (i.e., only gas), and with a perfect vacuum in tank 2, if the valve were opened, half of the molecules would flow into tank No. 2 and after returning to temperature equilibrium, the pressure in both tanks would be  $\frac{1}{2}$  of 0.50 or 0.25 psia. On the other hand, if tank No. 2 had been filled with "dry air" at the 80° temperature and a pressure of 29.0 psia and tank 1 had been at an absolute vacuum and the valve were opened, after reaching temperature equilibrium (80°), the air pressure in both tanks would be 14.5 psia.

Then, by Dalton's law, since each gas would behave as though the other wasn't present, let's combine the two foregoing experiments, and with the valve closed, the system at 80°F, 0.50 psia of steam (water vapor) in tank No. 1 and 29 psia of dry air in tank No. 2, when the valve is opened, each gas would behave as it had when the other was not present, and the end result would be, after reaching temperature equilibrium (80°F) in each tank, the air pressure would be 14.5 psia, the vapor pressure would be 0.25 psia and the total pressure in each tank would be 14.75 psia.

(Take time to accept and embrace this concept before proceeding.)

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## IDEAL GASES

Prior to discussing psychrometrics, a review of another important relationship in the fundamental concepts of the theory of gases is in order:

It has been observed through extensive scientific study that at "low pressures" the relationship between the pressure, specific volume and absolute temperature of gases is that, for any specific gas, the product of the pressure and specific volume is proportional to the temperature.

The constant of proportionality,  $R \left( \frac{ft}{°R} \right)$ , is called the ideal gas constant and is found to be, numerically, the constant 1545 divided by the molecular weight of the specific gas. Any gas, the behavior of which is consistent with these relationships is called an "ideal gas", and the equation of state of for an ideal gas is then,

$$pv = RT$$

Most real gases at and around ambient pressures and temperatures behave in a manner close enough to ideal gases that in engineering analyses they can be assumed to be ideal gases; this is an assumption that greatly simplifies the engineering practice of gas behavior while preserving an acceptably high level of accuracy. Thus, in the study of air/water vapor mixtures, the assumption of ideal gas behavior is common.

## PSYCHROMETRICS

Psychrometrics is the science of the behavior of air/water vapor mixtures. Before defining the relationships upon which this science is built, let's review the earlier discussions on Dalton's Law.

The atmosphere in which we live consists of "moist air" which is a mixture of dry air and water vapor. At any given temperature, the pressure of the water vapor in the mixture can be any value equal to or less than the saturation pressure at that temperature. This vapor pressure is called the partial pressure of the water vapor ( $p_H$ ). ( $p_s$  if the vapor pressure is at the saturation pressure, the highest possible at any given temperature). The dry air pressure is called partial pressure of the air ( $p_a$ ). And the sum of the two ( $p_H + p_a$ ) is called the barometric pressure,  $p_B$ .

With nothing more, an important but quite logical observation can be made: if a mixture of air and water vapor at 80°F has a vapor pressure of 0.25 psia and it is cooled to a temperature of 60°F the water vapor will be saturated and with any further cooling, some of the vapor will condense to liquid. The 60°F temperature (the saturation temperature at the vapor pressure,  $p_H$ ) is thus called the *dewpoint temperature* of the mixture,  $t_{dp}$ .

Symbols commonly used in the study of psychrometrics include:

<u>Characteristics</u>	<u>Symbol</u>	<u>Units</u>
Partial pressure of dry air	<b>p<sub>a</sub></b>	lb/in <sup>2</sup>
Partial pressure of water vapor	<b>p<sub>H</sub></b>	lb/in <sup>2</sup>
Partial pressure of saturated vapor	<b>p<sub>s</sub></b>	lb/in <sup>2</sup>
Barometric pressure	<b>p<sub>B</sub></b>	lb/in <sup>2</sup>
Density of dry air	<b>d<sub>a</sub></b>	lb/ft <sup>3</sup>
Density of water vapor	<b>d<sub>H</sub></b>	lb/ft <sup>3</sup>
Temperature of the mixture	<b>t<sub>d</sub></b>	°F

Using these characteristics, then, terms are defined that enable us to understand, analyze and control the mixtures. These terms are as follows:

⚡ **Relative Humidity, RH**, is defined as the ratio of the partial pressure of the water vapor in the mixture, **p<sub>H</sub>**, to the partial pressure if the water vapor were saturated at the temperature of the mixture, **p<sub>s</sub>**. In equation form:

$$RH = \frac{p_H}{p_s} \%$$

Example; at a temperature of 80°F (**p<sub>s</sub>** = 0.50 psia), if the partial pressure of the water vapor is 0.25 psia, the relative humidity is

$$RH = \frac{0.25}{0.50} = 0.50 \text{ or } 50\%$$

⚡ **Humidity Ratio, w**, (sometimes called specific humidity) is defined as the ratio of the weight of the water vapor in a fixed volume of mixture to the weight of the air in the same volume. The equation is

$$w = \frac{d_H}{d_a} \frac{\text{lb vapor}}{\text{lb dry air}}$$

If the water vapor is saturated, it is common practice to use the subscript s, so that the specific humidity of a mixture in which the water vapor is saturated would be.

$$w_s = \frac{d_s}{d_a} \frac{\text{lb vapor}}{\text{lb dry air}}$$

Since this is a very small number, it has become an accepted practice to multiply the numerator by 7,000 grains/lb and express the humidity ratio in terms of grains of water vapor/lb of dry air, or grains/pound.

The condition in which the water vapor in the mixture is saturated is called a saturated mixture of air and water vapor. Note that at any given temperature, in a saturated mixture, the vapor pressure, the relative humidity, the vapor density and the humidity ratio are as high as they can be.

≪ **Percent Saturation,  $\mu$** , is defined as the ratio of the humidity ratio of a mixture of air and water vapor to the humidity ratio of a saturated mixture at the same temperature. In equation form

$$\mu = \frac{w}{w_s} \%$$

≪ **Adiabatic saturation temperature (wet bulb temperature,  $t_w$ )**: Imagine a relatively large closed chamber which is partially filled with water, has two openings above the water for air to enter and leave respectively, and is perfectly insulated so that no heat can enter or leave the chamber.

Then a moving stream of an air water vapor mixture which is not saturated is introduced and flows across the water surface. As it does so, some of the water will evaporate, increasing the amount of water vapor in the mixture. Since the chamber will allow no heat transfer, the heat required to evaporate the water will be drawn from the air or the water, thereby decreasing the temperature of both until the water vapor in the air is saturated. In order to allow the process to continue, a stream of water is introduced at the temperature of the leaving air, the flow rate of which must be equal to the evaporation rate. Also, if this water is introduced at the leaving air temperature, then the only source of heat to evaporate the water is the higher temperature air which will decrease in temperature until the air/water vapor stream becomes "saturated". This chamber is called an adiabatic saturation chamber. The entering air temperature is the ambient temperature which, in the science of psychrometrics is called the dry bulb temperature,  $t_1$  or  $t_d$ . The cooler leaving air stream temperature,  $t_2$  or  $t_w$  is the *adiabatic saturation*

*temperature*, the value of which is approximately equal to what is called the *wet bulb temperature*. (The wet bulb temperature is the temperature read on the bulb of a mercury thermometer which has been fitted with a cloth saturated with water and placed in a moving air stream.)

A steady flow energy balance performed on the adiabatic saturation chamber yields the following formula, with subscripts 1 and 2 representing the entering and leaving air streams respectively, and enthalpy (**h**) subscripts those commonly used in the steam tables.

$$w_1 = \frac{w_2(h_{f2}) - c_p(t_1 - t_2)}{h_{g1} - h_{f2}}$$

where **t**<sub>1</sub> is the dry bulb temperature and **t**<sub>2</sub> is the wet bulb temperature; **w**<sub>1</sub> is the humidity ratio of the sampled stream and **w**<sub>2</sub> is the saturated humidity ratio of the leaving stream at temperature **t**<sub>2</sub> or **t**<sub>w</sub>. Thus, if only the entering temperature **t**<sub>d</sub> and the leaving temperature **t**<sub>w</sub> are measured, the humidity ratio of the sampled air, **w**<sub>1</sub>, can be calculated.

#### Other useful relationships.

Combining the above definitions and equations with the perfect gas equation and applying some straightforward algebra reveals the following useful relationships:

Humidity Ratio

$$w = 0.622 \left( \frac{p_H}{p_B - p_H} \right)$$

$$w_s = 0.622 \left( \frac{p_s}{p_B - p_s} \right)$$

Percent saturation

$$\mu = RH \left( \frac{p_B - p_s}{p_B - p_H} \right)$$

Since  $\left( \frac{p_B - p_s}{p_B - p_H} \right)$  is close to 1 at ambient temperatures, then, at temperatures below about 100°F  $\mu$  is approximately equal to **RH**.

✎ Enthalpy of air water vapor mixture. Considering the adiabatic saturation process, since the process is adiabatic, the enthalpy of the leaving mixture (saturated at the wet bulb temperature) is equal to the sum of that at the entering condition plus the difference between the leaving and entering humidity ratios times the enthalpy of the water at the leaving temperature.

If, for the adiabatic saturation process,  $h_{a1}$  is the enthalpy of the entering stream (the ambient air water vapor mixture) in BTU/pound dry air, and  $h_{a2}$  is the enthalpy of the leaving stream (saturated at wet bulb temperatures of ambient air) then:

$$h_{a1} + (w_{s2} - w_{s1}) h_{f2} = h_{a2} \text{ BTU/lb dry air.}$$

Since the deductive term,  $(w_{s2} - w_{s1}) h_{f2}$ , is very small compared to the others, it can be stated that:

*"The enthalpy of an air water vapor mixture is approximately equal to the enthalpy of a saturated mixture at the wet bulb temperature."*

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**Next Month: "Construct your own psychrometric chart."**