PDHonline Course M135 (4 PDH)

HVAC Made Easy - Overview of Psychrometrics

Instructor: A. Bhatia, B.E.

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

An Approved Continuing Education Provider

HVAC made easy- Overview of Psychrometrics

Course Content

Introduction

Psychrometrics (derived from the Greek: *psukhros* = cold) is study of air-water vapor mixtures at different conditions. To quote the 1989 ASHRAE Handbook of Fundamentals, *"Psychrometrics deals with the thermodynamic properties of moist air and uses these properties to analyze conditions and processes involving moist air."* Take a note; it is not the same as *psychometric*, which your *spell checker* may offer you as an alternative!

While the study of pure psychrometrics involves a number of different aspects, we shall restrict this course to the application of psychrometrics for use on human comfort in the air-conditioning system. In air-conditioning system, we use psychrometric properties for environment control.

Human comfort

The common notion is that as long as cooling or heating (in winters) takes place, the environmental conditions are comfortable or the air conditioning is effective. Over a period of time, experience as well as research has shown that there is much more to human comfort than just temperature. There are *four* major factors that determine comfort

- Air temperature (dry bulb temperature or DBT)
- Humidity (relative humidity RH)
- Air movement (velocity fpm or m/s)
- Internal Quality of Air

1. **Air temperature (DBT)**

   The dry-bulb temperature is the temperature of the air around us and is the most important of all of the above factors. The human body's primary response is towards the changes in temperatures and it is this temperature that we attempt to keep within comfort conditions while designing structures for habitation.

2. **Humidity (RH %)**

   The atmosphere always contains moisture in the form of water vapor. The maximum amount of water vapor that may be contained in the air depends on the temperature;

'higher the temperature of the air, the more water vapor may be contained'. At high temperatures and high moisture contents extreme discomfort is experienced as the evaporation of moisture from the body into the atmosphere by the process of perspiration becomes difficult. Saturated air at 100% prevents any evaporative cooling.

3. Air movement (v)

The air movement can produce different thermal effects at different air temperatures, in the following two ways:

- It increases convective heat loss, as long as the temperature of the moving air is less than the skin temperature.
- It provides cooling through evaporation at low humidity levels and at higher humidity's above 85%, air movement cannot help add vapor to the already highly saturated air.

'Pleasant' ranges of air movements induce skin evaporation, more significantly in medium (40%-50%) humidity's.

4. Air quality

The air quality is important. In order to control the air purity the air supply to the space is filtered. The degree of filtration will depend on specified requirements for the environment within the room.

In addition to the dust control, the air-quality demands precise temperature and RH levels. Too low RH irritates respiratory organs and dust populations increase rapidly at RH levels above 50% and fungal amplifications might occur above 65% RH. Standard is 30% to 60%.

Other factors that influence comfort that are subjective, non-quantifiable individual factors include the metabolic rate of an individual, type of physical activity, clothing, body build, conditions of health, acclimatization to new environments, food and drink etc. Generally speaking, the thermal comfort is associated with the metabolism rate of an individual that led to the production of heat.

Comfort zone

It is an area plotted on the psychrometric chart that pertains to those conditions of dry-bulb temperature, wet-bulb temperature, wind speeds etc. in which most people wearing specified cloths and involved in specific activity will feel comfortable, i.e., neither too cold nor too warm. *The comfort range of temperature varies between 70 to 76°F dry bulb temperatures and 45 - 65% relative humidity.* This applies mainly to summer air-conditioning. During cold winters the comfort condition would be in the range of 65 to 68°F dry bulb temperature and relative humidity of a minimum of 30%.

Studies of personal comfort have shown that relative humidity ranges between 30% and 65% can be considered 'comfortable' depending on activity. However, from the standpoint of indoor air quality, upper ranges should be maintained below 50% (dust mite populations increase rapidly at relative humidity levels above 50% and fungal amplification occurs above 65%). Below 30% respiratory irritation occurs or static electric currents is a concern.

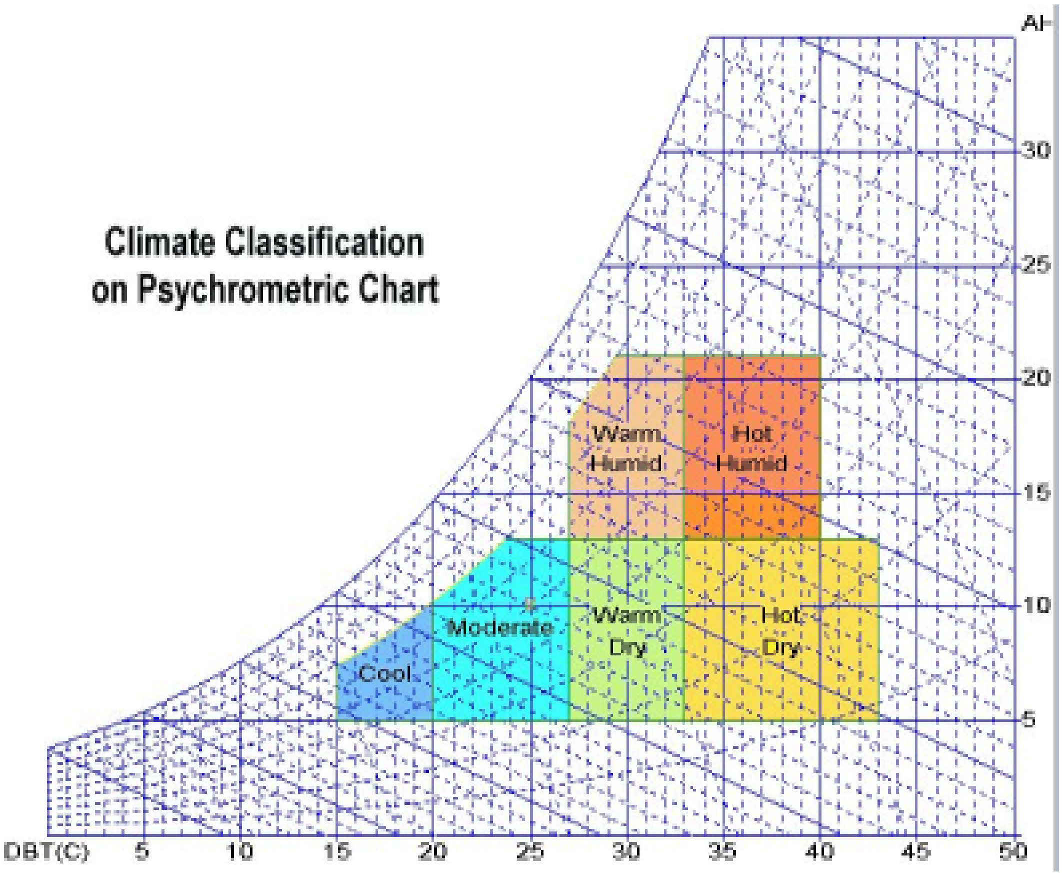


Figure Showing Psychrometric Chart Climate Classification

A B C of Psychrometrics

The most common traditional way to evaluate air properties is with the use of a psychrometric chart showing thermodynamic properties of air at a sea level barometric pressure of 29.921 inches of mercury. To a novice, psychrometric chart seems a dizzying maze of lines and curves going every which way. This appearance stems from the fact that a psychrometric chart conveys an amazing amount of information about air. For any given point on a psych chart, one can read the dry and wet bulb temperatures, relative humidity, humidity ratio, enthalpy, and specific volume. Once a few fundamental things are understood, it is not really that difficult to understand the psychrometric chart.

Dry bulb temperature: The temperature of air as registered by an ordinary thermometer

Wet bulb temperature: The temperature registered by a thermometer whose bulb is covered by a wetted wick and exposed to a current of rapidly moving air

Dew point temperature: The temperature at which condensation of moisture begins when the air is cooled.

Relative humidity: RH is an expression of the moisture content of a given atmosphere as a percentage of the saturation humidity at the same temperature.

Absolute humidity or moisture content: The weight of water vapor in grains or pounds of moisture per pound of dry air or grams of water vapor per kg of air, i.e. g/kg. It is also known as moisture content or humidity ratio.

Saturation Humidity: Air at a given temperature can support only a certain amount of moisture and no more. This is referred to as the saturation humidity.

Enthalpy: A thermal property indicating the quantity of heat in the air above an arbitrary datum, in Btu per pound of dry air. The datum for dry air is 0 deg F and, for the moisture content 32 deg F water.

Enthalpy deviation: Enthalpy indicated above, for any given condition is the enthalpy of saturation. It should be corrected by the enthalpy deviation due to the air not being in the saturated state. Enthalpy deviation is in Btu per pound of dry air. Enthalpy deviation is applied where extreme accuracy is required; however, on normal air conditioning estimates it is omitted.

Specific volume: The cubic feet of the mixture per pound of dry air or cubic meter of the mixture per kg of dry air represented in m^3/kg. It is the reciprocal of density

Sensible heat: is the heat content causing an increase in dry-bulb temperature.

Latent heat: is the heat content due to the presence of water vapour in the atmosphere. It is the heat, which was required to evaporate the given amount of moisture.

Total heat: is the sum of sensible and latent heat.

Sensible heat factor: The ratio of sensible to total heat.

The dry-bulb, wet-bulb, and dew point temperatures and the relative humidity are so related that, if two properties are known, all other properties may then be determined.

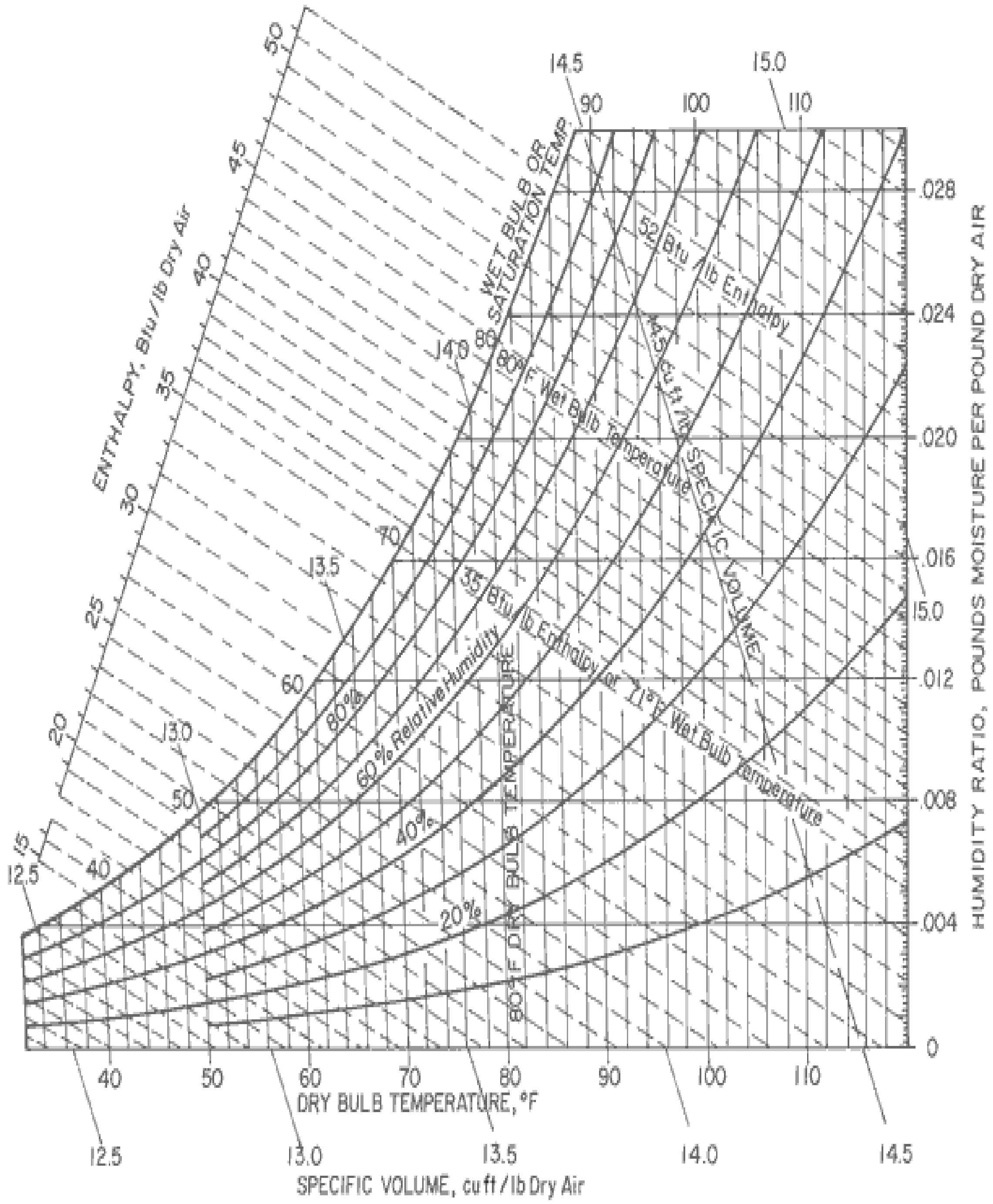
Psychometrics Chart

A psychrometric chart presents physical and thermal properties of moist air in a graphical form. Calculations of air properties otherwise are not very straightforward. Many different equations are often needed to obtain one single point. Standard psychrometric charts are therefore welcome tools to perform psychrometric analysis.

Psychrometric properties are dependent on the atmospheric pressure, so their determination at different elevations is filled with errors that may be considerable at higher altitudes. Psychrometric charts developed for specific atmospheric conditions eliminate errors but lack general applicability. The computer programs to handle these tasks greatly help reduce errors and allow fast and reliable psychrometric calculations for any given atmospheric pressure.

Psychrometric charts are printed mostly for sea level atmospheric pressure. Since virtually all psychrometric air processes involving HVAC design occur within a 30° F and 120°F range, most psychrometric charts only show this range as a practical measure. Psychrometric properties are also available as data tables, equations, and slide rulers.

Figure below is a psychrometric chart in customary units, which describes the important moist air properties: dry-bulb and wet-bulb temperatures, relative humidity, humidity ratio, specific volume, dew point or saturation temperature, and enthalpy.



Psychometrics Explanation

A psychrometric chart contains a lot of information packed in an odd-shaped graph.

The psychrometric chart highlights seven properties of air:

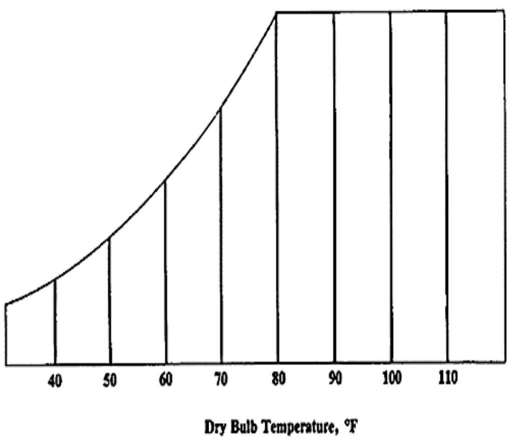
1. Dry Bulb Temperature (DBT)
2. Wet Bulb Temperature (WBT)
3. Saturation Temperature
4. Relative Humidity
5. Humidity Ratio
6. Volume
7. Enthalpy

At first glance, the chart appears complex; however, separating the various lines and scales on the chart simplifies understanding their location, meaning and use.

Before we go further, we need to pause and review the definitions of these 7 terms piece by piece on the psychrometric chart.

Psychrometric Chart Boundaries

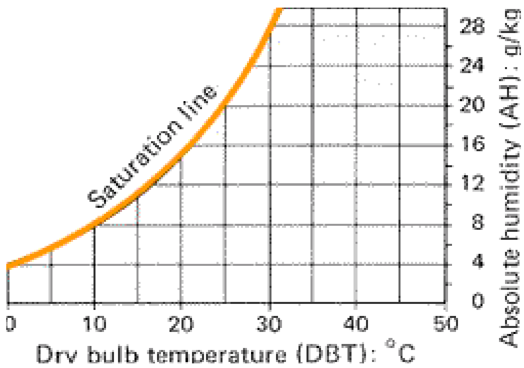
The horizontal X-axis denotes ***dry bulb temperature (DBT)*** scale. Vertical lines indicate constant dry bulb temperature. DBT is the air temperature measured in °C or °F and determined by an ordinary glass thermometer. It is called "dry-bulb" since the sensing tip of the thermometer is dry (see "wet bulb temperature" for comparison). Since this temperature is so commonly used, it can be assumed that temperatures are dry-bulb temperatures unless otherwise designated.



Dry bulb temperature lines

Y-axis indicates ***humidity ratio or absolute humidity***, which is the weight of the water, contained in the air per unit of dry air. This is often expressed as pounds of moisture per pound of dry air or (g/Kg). Since the humidity ratio of moist air is not dependent on temperature, as is relative humidity, it is easier to use in calculations. Humidity ratio is found on the vertical, y-axis with lines of constant humidity ratio running horizontally across the chart.

Curved boundary represents ***saturated air line or dew point temperature line***. Saturation line is a temperature condition at which water will begin to condense out of moist air. Given air at a certain dry-bulb temperature and relative humidity, if the temperature is allowed to decrease, the air is no longer able to hold as much moisture. When air is cooled, the relative humidity increases until saturation is reached and condensation occurs. Condensation occurs on surfaces, which are at or below the dew-point temperature. Dew-point temperature is determined by moving from a state point horizontally to the left along lines of constant humidity ratio until the upper, curved, saturation temperature boundary is reached.



Saturation Line, Absolute Humidity and Dry bulb temperature lines

---

Let's study this a little further…

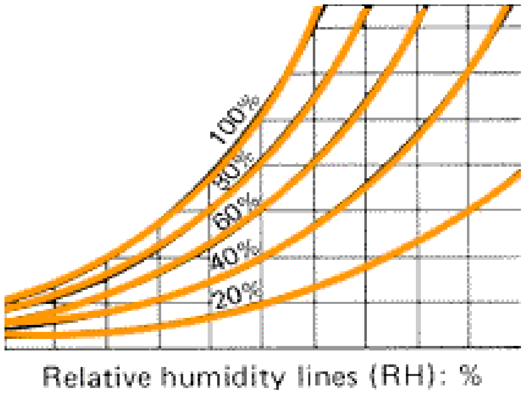
Relative humidity (RH) **:** The term relative humidity is simply a ratio between the actual moisture content of the air compared with the moisture content of the air required for saturation at the same temperature, i.e. at 100% relative humidity (also known as saturation point).

In practice, relative humidity indicates the moisture level of the air compared to the air moisture-holding capacity.

RH = 100 x AH/SH (%)

The curved lines running from the bottom left and sweeping up through to the top right of the chart represent lines of constant relative humidity. The line for 100 percent relative humidity, or saturation, is the upper, left boundary of the chart.

Relative humidity is a relative measure, because the moisture-holding capacity of air increases as air is warmed.



Relative Humidity Lines

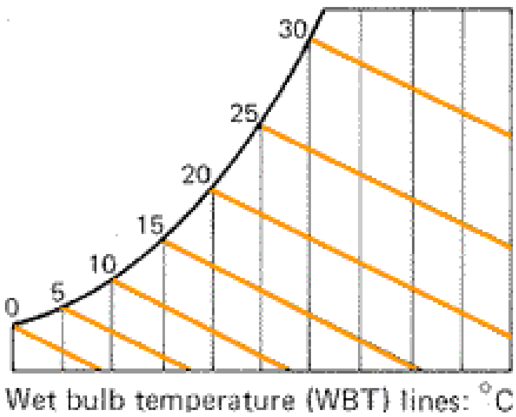
Wet-bulb temperature (WBT) is determined when air is circulated past a wetted sensor tip. It represents the temperature at which water evaporates and brings the air to saturation. Inherent in this definition is an assumption that no heat is lost or gained by the air.

This is different from dewpoint temperature where a decrease in temperature, or heat loss, decreases the moisture holding capacity of the air, and hence, water condenses.

The 'status point' is determined at the intersection of the vertical DBT line and the sloping WBT line of the psychrometric chart.

When the air is fully saturated, the DBT and WBT readings are identical and there is no evaporation.

Determination of wet-bulb temperature on this psychrometric chart follows lines of constant enthalpy but values are read off the upper, curved, saturation

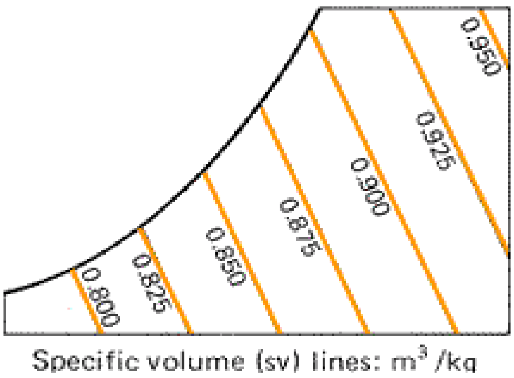


Wet Bulb Temperature Lines

temperature boundary.

Wet-bulb temperature represents how much moisture the air can evaporate.

Specific volume indicates the space occupied by air. It is the reciprocal of density and is expressed as a volume per unit weight in ft^3/ lb or m^3/kg (density is weight per unit volume). Warm air is less dense than cool air, which causes warmed air to rise. This phenomenon is known as thermal buoyancy. By similar reasoning, warmer air has greater specific volume and is hence lighter than cool air. On the psychrometric chart, lines of constant specific volume are almost vertical lines with scale values written below the dry-bulb temperature scale and above the upper boundary's saturation temperature scale. Greater specific volume is associated with warmer temperatures (dry-bulb).

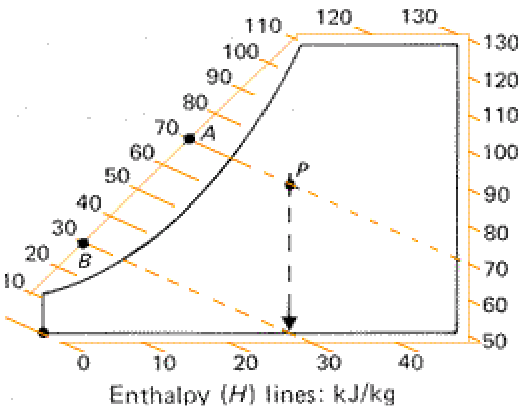


Specific Volume Lines

Specific volume is indicated by another set of slightly more sloping lines on the psychrometric chart. This will be useful for the conversion of volumetric airflow quantities into mass-flow rates, e.g. in air conditioning calculations.

Enthalpy (E) is the heat energy content of moist air. It is expressed in Btu per pound of dry air (or kJ/Kg) and represents the heat energy due to temperature and moisture in the air. Lines of constant enthalpy run diagonally downward from left to right across the chart. Lines of constant enthalpy and constant wet-bulb are the same on this chart but values are read off separate scales. More accurate psychrometric charts use slightly different lines for wet-bulb temperature and enthalpy.

For air condition point (P) the enthalpy is read at point A. The sensible heat component can be read at point B, corresponding to the enthalpy of dry air at the same temperature. The remainder, i.e. A - B, is the latent heat content.



Enthalpy Lines

The Psychometrics Processes

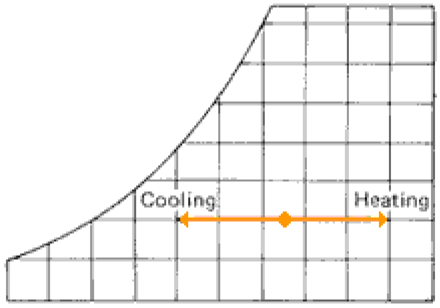
Psychrometric processes bring about changes in air-water vapor properties. The movement of the state point on the psychrometric chart represents changes. Common processes include:

- Sensible Heating and Cooling
- Cooling and Dehumidification
- Heating and Humidification
- Evaporative Cooling
- Air Mixing

1) Heating or cooling:

The addition or removal of heat, without any change in the moisture content (AH), resulting in the change in DBT. The status point will move horizontally to the left (cooling) or to the right (heating).
Note that while the AH (represented on the y axis) does not change, the change in temperature means the relative humidity (RH) changes.

The relative humidity increases if the temperature lowers and vice versa.

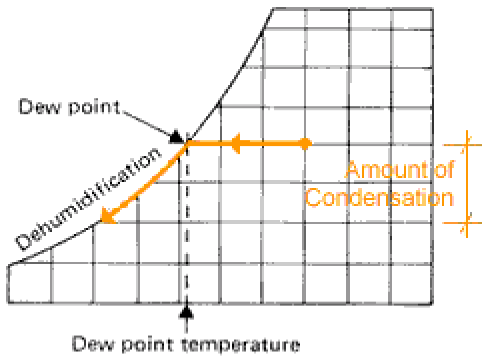


Sensible Heating & Cooling Process

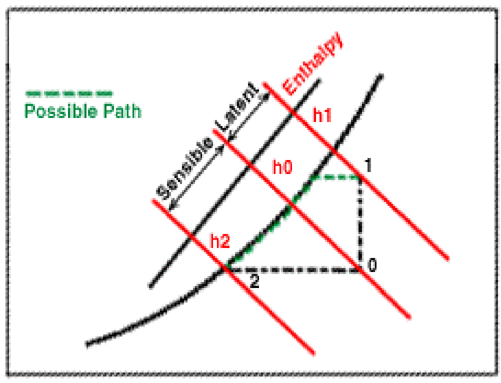
2) Dehumidification by cooling:

If, as a result of cooling, the status point moving towards the left reaches the saturation line, some condensation will start. The DBT corresponding to this point is referred to as the *dew-point temperature* of the original atmosphere. If there is further cooling, the status point will move along the saturation line and condensation will occur. The reduction in the vertical ordinate (on the AH scale) represents the amount of moisture precipitated, i.e., condensed out. This process will reduce the absolute humidity, but will always end with 100% RH.

State 1 is warmer and humid. Cooling and dehumidification shall result in state 2. The total heat absorbed is shown broken into a sensible and latent heat portion.



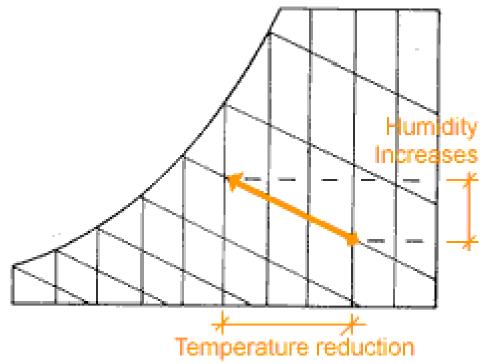
Dehumidification By Cooling



3) Adiabatic humidification (evaporative cooling):

If moisture is evaporated into an air volume without any heat input or removal (this is the meaning of the term *'adiabatic'*), the latent heat of evaporation is taken from the atmosphere. The sensible heat content - thus the DBT - is reduced, but the latent heat content is increased. The status point moves up and to the left, along a WBT line. This is the process involved in evaporative cooling.

Note that this process increases the relative humidity. It increases only until it hits the saturation line, at which it becomes 100%. Beyond it there is no decrease in sensible temperature. This is the reason why during hot and humid months, evaporative cooling is ineffective and uncomfortable.

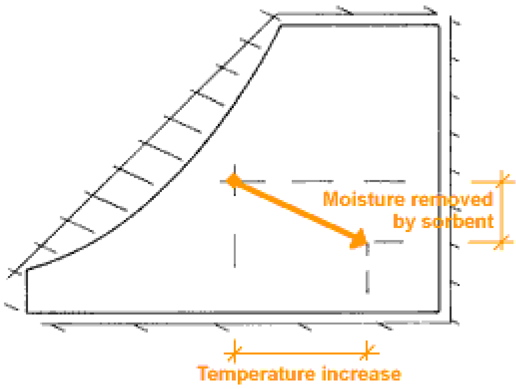


Humidification (Evaporative Cooling)

4) Adiabatic dehumidification (by absorbents):

If the air is passed through a chemical absorbent material (e.g., silica gel), some of the moisture is removed and the latent heat of evaporation is released. There will be an increase in sensible heat content, in the system (i.e., if the process is adiabatic), the state point will move down and towards the right along an enthalpy line.

This process, in effect is the reverse of the previous one.



Dehumidification (By Absorbents)

5) Mixing:

When air streams are mixing the properties of the resulting stream can be determined by mass balances or graphically on the psychrometric chart. Exceptions occur close to the saturation line.

If two air streams are mixed, having:

-Mass flow rates m_1 and m_2,

-dry bulb temperatures $t_1$and t_2,

-enthalpies $H_1$and H_2,

The result will be:

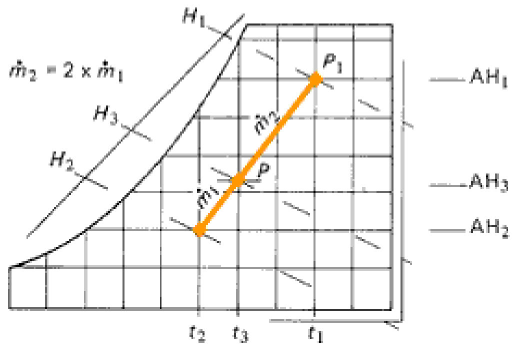
$m_1t_1 + m_2t_2 = [m_1 + m_2]\ t_3$,

$m_1H_1 + m_2H_2 = [m_1 + m_2]H_3$

Therefore:

$t_3 = (m_1t_1 + m_2t_2) / m_1 + m_2$

$H_3 = (m_1H_1 + m_2H_2) / m_1 + m_2$



Mixing Process

The psychrometric chart can be used to establish the value of t_3 and H_3. The two state points are connected by a straight line, which is then divided in inverse proportions of m_1 and m_2. If the mass flow rate m_1 is the greater, the resulting point P will represent the state of the combined air stream.

Air mixing problems must be solved on a mass basis because "volume will change, mass will not". This usually requires changing a volumetric flow to a mass airflow.

Methods of Measuring Psychrometric Variables

The versatility of the psychrometric chart lies in the fact that by knowing just two properties (three if barometric pressure is considered) of moist air, the other properties can be determined. The points of intersection of any two-property lines define the state-point of air. Once this point is located, the other air properties can be read directly. The accuracy of data/readings on chart depends on accurately locating the state point, which in turn depends on precise measurement of two air properties.

Dry-bulb temperature and wet-bulb temperature are relatively most simple to measure though relative humidity can also be found out easily.

Dry-bulb temperature

Dry-bulb temperature can simply and inexpensively be measured by an alcohol-in-glass or a common mercury thermometer.

More sophisticated, hand-held thermistor, resistance bulb, or thermocouple thermometers can also be used. These are more expensive than a glass thermometer but are not necessarily more accurate. However these instruments provide digital reading and have advantages; for instance can be purchased with a probe allowing them to be used for measuring product or skin surface temperatures.

When taking readings, the thermometer should be shielded from radiant heat sources such as motors, lights, external walls, and people. The reading must be taken in an area protected from these sources of radiation or thermometers must be shielded from radiant energy. The thermometers must be calibrated and in field situations, an ice-water mixture is an easy way to check calibration at 32°F

Wet-bulb temperature

Wet bulb temperature (WBT) is usually measured with a sling or aspirated psychrometer consisting of two mercury thermometers, one of which is wrapped with a wick around the mercury bulb. The other is used to measure dry bulb temperature. To use this instrument, the wick is saturated with clean water and the psychrometer is whirled for approximately 10 to 15 seconds. The process is repeated two or three times until there is no further temperature drop on the wicked thermometer.

'Web bulb depression' is noted as the difference between the wet bulb and the dry bulb temperatures. The difference happens as the wet wick thermometer is cooled down by the evaporation on the wick. *The greater the wet-bulb depression (Tdb - Twb), the lower shall be the RH.*

The amount of evaporation is a direct indication of the moisture carrying capacity of the atmospheric air at that temperature.

The key to accurate wet bulb temperature reading depends on:

1) Sensitivity and accuracy of the thermometer,

2) Maintaining adequate air speed past the wick,

3) Shielding of the thermometer from radiation,

4) Use of distilled or de-ionized water to wet the wick, and

5) Keeping wick saturated and use of a cotton wick.

The thermometer sensitivity required to determine an accurate humidity varies according to the temperature range of the air. More sensitivity is needed at low than at high temperatures. For example, at 150°F a 1°F error in wet-bulb temperature reading results in a 2.6 percent error in relative humidity determination, but at 32°F that same error results in a 10.5 percent error in relative humidity. Before wetting the wick of the wet-bulb thermometer, operate both thermometers long enough to determine if there is any difference between their readings. If there is a difference, assume that one is correct and adjust the reading of the other accordingly when determining relative humidity.

The rate of evaporation from the wick is a function of air speed past it. A minimum air speed of about 500 feet per minute is required for accurate readings. An air speed much below this will result in an erroneously high wet-bulb reading.

A buildup of salts from impure water or contaminants in the air affects the rate of water evaporation from the wick and results in erroneous data. Distilled or de-ionized water should be used to moisten the wick. Wick should be replaced if there is any sign of contamination. The wick material should not have been treated with chemicals such as sizing compounds that affect the water evaporation rate.

Special care must be taken when using a wet-bulb thermometer in near freezing conditions. At temperatures below 32°F, touch the wick with a piece of clean ice or another cold object to induce freezing, because distilled water can be cooled below 32°F without freezing. The psychrometric chart must use frost-bulb, not wet-bulb temperatures, below 32°F to be accurate with this method.

Under most conditions wet-bulb temperature data is not reliable when the relative humidity is below 20 percent or when wet-bulb temperature is above 212°F.

At low humidity's, the wet-bulb temperature is much lower than the dry-bulb temperature and it is difficult for the wet-bulb thermometer to be cooled completely because of heat transferred by the glass or metal stem. Water boils above 212°F, so wet-bulb temperatures above that cannot be measured with a wet-bulb thermometer.

In general, properly designed and operated wet- and dry-bulb psychrometer can operate with an accuracy of less than 2 percent of the actual relative humidity. Improper operation greatly increases the error.

Relative humidity

Direct relative humidity measurements can be achieved through an electric sensing hygrometers or a mechanical system. As the humidity of the air around the sensor increases, its moisture increases, proportionally affecting the sensor's electrical properties. These devices are more expensive than what computed by measuring wet- and dry-bulb psychrometer. An accuracy of less than 2 percent of the actual humidity is often obtainable. Sensors lose their calibration if contaminated, and some also lose calibration if water condenses on them. Most sensors have a limited life.

Electric hygrometers are based on substances that absorb or lose moisture with changing relative humidity and exhibit changes in electrical characteristics as a function of their moisture content. The electrical hygrometers are further classified as impedance/resistive hygrometers and capacitive hygrometers.

Polymer film hygrometers are based on the fact that a hygroscopic organic polymer is deposited on a water permeable substrate. Both capacitance and impedance sensors exist with this technology. The advantages of polymer film hygrometers include:

- Small in size
- Low cost
- Low hysteresis
- Fast response (τ = 1 to 120 sec)
- Long-term stability

Mechanical or Hair hygrometer: Mechanical hygrometers usually employ human or animal hairs as a sensing element. Hair changes length in proportion to the humidity of the air. The response to changes in relative humidity is slow and is not dependable at very high relative humidity. These devices are acceptable as an indicator of a general range of humidity. These require frequent calibration and are not suitable for instantaneous accurate measurements.

A mechanical device known as 'Thermo-hydrograph' measures and plots the temperature and RH with 2 colors tip pen on a paper for long durations. The instrument finds use in energy auditing surveys and is useful in recording the temperature/RH curves up to 7 days interval.

Dew point Measurements

Dew point products use chilled mirror hygrometers. These can measure dew/frost points from -80 °C to 85 °C that is obtained by cooling a solid surface usually a mirror, until condensation occurs on the surface. High accuracy (±0.15 °C) platinum RTD is embedded in the mirror surface to measure the reading. Various methods used to cool the mirror include ice, refrigerants (freon), thermoelectric cooling (Peltier device) etc.

These are often used as a secondary standard to calibrate other humidity transducers.

Performance largely defined by accuracy of temperature measurement.

- ±1% RH from 40 % to 90% RH
- ±0.5% RH from 1% to 40% RH

Sample Examples

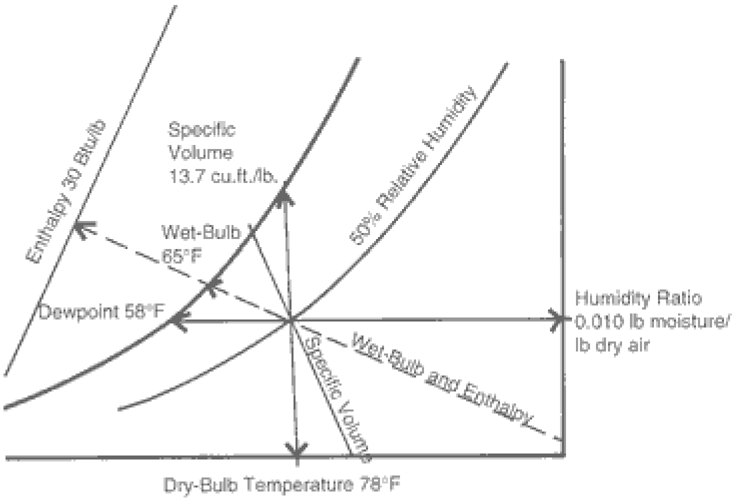
Example Problem # 1: (Find air properties)

A sling psychrometer gives a dry-bulb temperature of 78°F and a wet-bulb temperature of 65°F. Determine other moist air properties from this information i.e. find

- Relative Humidity
- Dewpoint Temperature
- Humidity Ratio
- Enthalpy
- Specific Volume

- Vapor Pressure
- Percentage Humidity

Solution



This example is shown in figure above, so you may check your work.

Step#1: Find the intersection of the two known properties, dry-bulb and wet-bulb temperatures, on the psychrometric chart.

Step#2: The dry-bulb temperature is located along the bottom horizontal axis. Find the line for 78^{o}F, which runs vertically through the chart. Wet-bulb temperature is located along diagonal dotted lines leading to scale readings at the upper, curved boundary marked "saturation temperature".

Step#3: The intersection of the vertical 78^{o}F dry-bulb line and the diagonal 65^{o}F wet-bulb line has now established a "state point" for the measured air.

Step#4: From this state point determine read all of the other values:

- Relative humidity as 50 percent (curving line running from left to right up through the chart)
- Follow the horizontal line, moving left towards the curved upper boundary of saturation temperature; Dewpoint temperature is 58^{o}F
- Follow the horizontal line to the right until it intersects the humidity ratio scale. Read humidity ratio as 0.010 lb (~72 grains) of moisture per pound of dry air.
- Take a straight edge. Revolve it about the point until its edge intersects the same numerical value on the enthalpy scale at the bottom and the enthalpy scale outside of the 100% RH line. Read ~ 30 Btu per lb of dry air as the enthalpy.
- Interpolate between the specific volume lines. Read 13.7 cubic feet per pound of dry air.

- Follow the horizontal line to the right until it intersects the vapor pressure scale. Read ~ 0.48 inches of mercury.
- Percentage humidity equals actual humidity ratio found in step 4 c), divided by humidity ratio at saturation for same DB temperature.

  At 78°F and 100% RH read W= 146

  Percentage Humidity = 72/146 = 0.493

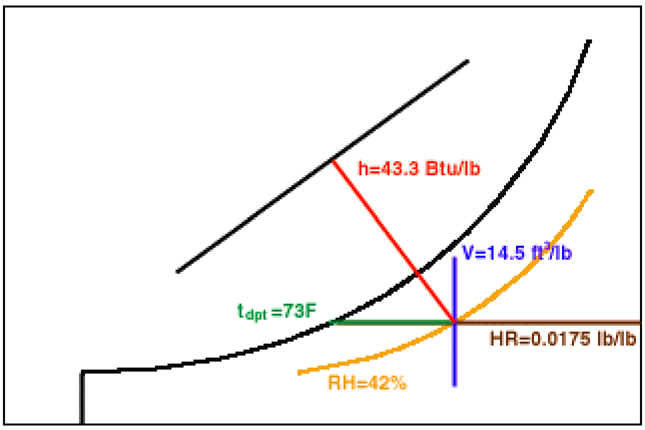
What might we conclude from this information? The relative humidity of 50 percent is acceptable for comfort. If we allowed the air temperature (dry-bulb) to decrease to 58°F (dewpoint) or below, the air would be 100 percent saturated with moisture and condensation would occur. The humidity ratio, as seen on the vertical, y-axis scale, is a reliable indicator of air moisture level since it reflects the pounds of moisture contained in a pound of dry air and does not fluctuate with dry-bulb temperature readings as does relative humidity.

Example Problem # 2:

Given: Consider air at t_{db} = 100°F & t_{wb} = 80 F

Find: %RH, Humidity Ratio, t_{dp}, enthalpy, specific volume

<u>Solution</u>:



RH = 42%

HR = 0.0175 lb/lb of dry air

T_{DP} = 73°F

Enthalpy = 43.3 Btu/lb

Specific Volume = 14.5 cuft/lb

Example Problem # 3:

A wet-bulb thermometer reads 60°F and a dry-bulb thermometer reads 72°F. If the air is heated to 120°F, what will be its relative humidity?

Solution:

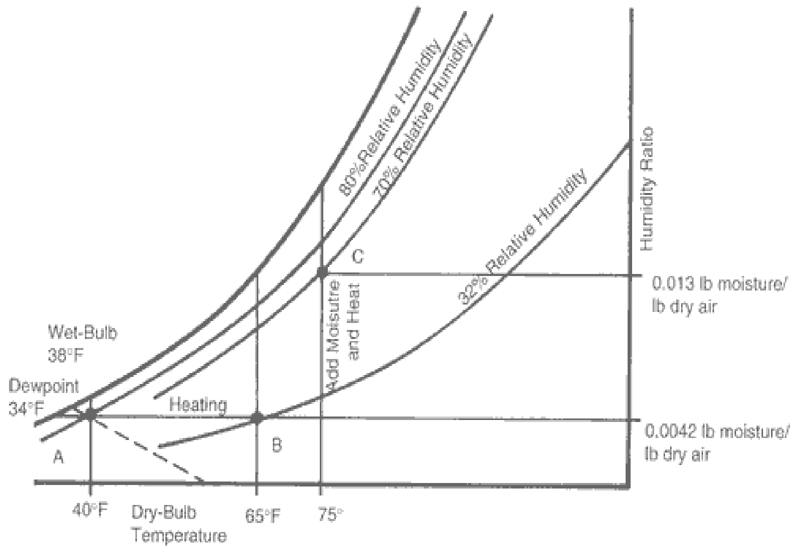
Heating is represented by moving horizontally to the right from the initial temperature conditions. The horizontal line intersects the vertical 120°F line at about 12% RH.

On calm, clear nights the air cool by radiation, following a horizontal line to the left. If the air cooled to 52°F (and 100% RH), it would still produce the same RH after heating to 120°F. If it cooled to less than 52°F, it would cause dewfall and the air would have less moisture content. If this air (even though its relative humidity is 100%) were heated to 120°F it would have less than 12% RH.

Example Problem # 4: **(Sensible Heating / Winter Ventilation)**

Air at 40°F dry-bulb temperature and 80 % relative humidity is heated by passing through a heating coil to 65°F dry-bulb. For a 65°F air, find its percentage RH, DP temperature and Humidity Ratio.

Solution:



Air at 40^{o}F, 80 percent relative humidity (point A) is heated to 65^{o}F (point B).

Step#1: Find the state point for the incoming cool air on the lower left portion of the psychrometric chart (point A, figure above) Note that other properties of the 40^{o}F air include a wet-bulb temperature of 38^{o}F a dewpoint temperature of about 34^{o}F and humidity ratio of 0.0042 lb moisture/ lb dry air.

Step#2: Heating air involves an increase in the dry-bulb temperature with no addition or reduction in the air's water content. The heating process moves horizontally to the right along a line of constant humidity ratio. Heating process is shown between points A and B.

Step#3: Heating the air to 65^{o}F (dry-bulb) has resulted in decreasing the relative humidity to about 32 percent. Heated air at point B continues to have a dewpoint of 34^{o}F and humidity ratio of 0.0042 lb moisture/ lb dry air.

The Wet bulb temperature at point B is ~ 50^{o}F… (check it yourself)

The amount of heat added to the air per pound of dry air can be found by reading the enthalpy scale for point A and B and see the differential. For this example, the heat added is approx 6.5 Btu per pound of dry air… (check it yourself)

Let's put the above example in practical use.

Imagine the outside air at 40^{o}F dry-bulb temperature and 80 % relative humidity is heated to 65^{o}F dry-bulb before it is distributed throughout a building shed containing material for drying say plantation leaves.

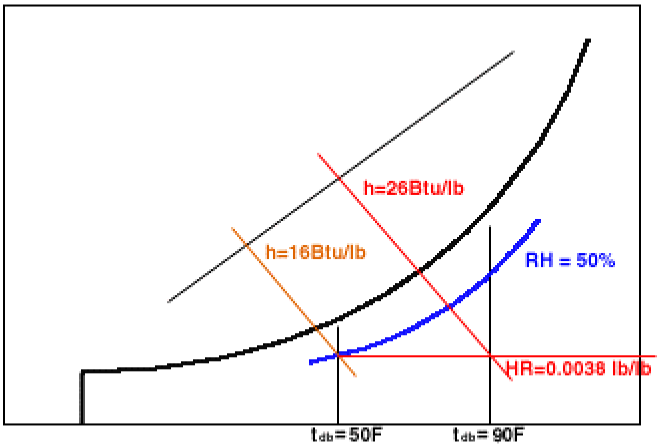
From the results above, the heated air entering the building is dry enough to be useful in absorbing moisture from the interior spaces. The heated air, with its lower relative humidity, shall be mixed with moist, warm air already in the building.

As the air moves in indoor environment, it will pick up additional moisture before it reaches the ventilation system exhaust. We might measure the exhausted air conditions at 75°F (dry-bulb) and 70 percent relative humidity, represented by point C in the Figure. Note that in this exhausted air, the humidity ratio has tripled to 0.013 lb moisture/ lb dry air or in other words the exhaust air contains three times the moisture of fresh air. This means that a lot more water is ventilated out of the building in the warm, moist exhaust air than was brought in by the cold, high relative humidity incoming air. This is one of the major functions of a winter ventilation system: removal of moisture from the indoor environments.

Example Problem # 5:

Determine the amount of sensible heat needed to increase the temperature of air from 50°F and 50% RH to 90°F.

Solution:



Enthalpy (50°F, 50% RH) = 16 Btu/lb (HR = 0.0038 lb/lb da)

Enthalpy (90°F, same HR) = 26 Btu/lb

Heat added = 26 - 16 = 10 Btu/lb

Example Problem # 6: **(Evaporative Cooling)**

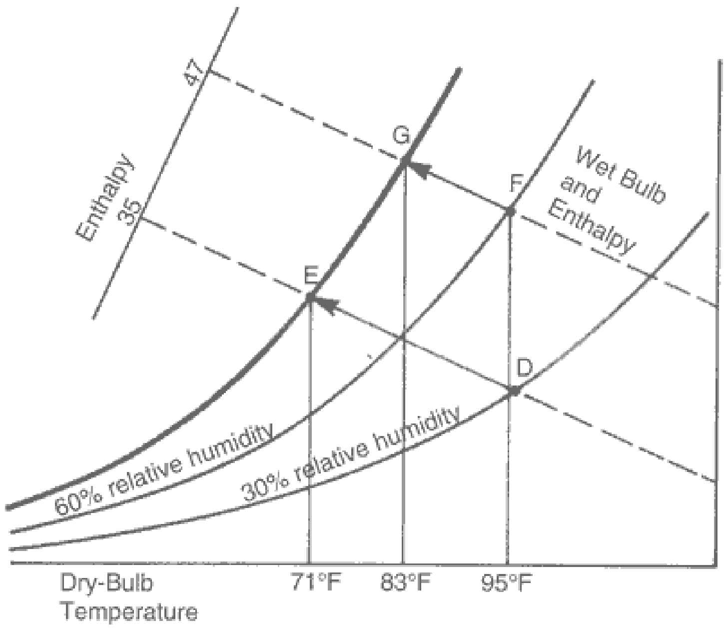
Plot the following two cases on psychrometric chart and interpret your observations.

Case#1: Air at 95°F dry-bulb temperature and 30 % relative humidity is passed through a water spray washer and leaves at 100% RH.

Case#2: Air at 95°F dry-bulb temperature and 60 % relative humidity is passed through a water spray washer and leaves at 100% RH.

Solution:

Refer the figure below:



Case#1: represented by points D and E. This can be categorized as "Hot and Dry Air".

Case #2: represented by points F and G. This can be categorized as "Hot and Humid Air".

Infer the following:

For case#1 the temperature drops by 24°F from 95°F to 71°F and for case#2, the temperature drops by 12°F from 95°F to 83°F.

The enthalpy of air for case#1 is 47 Btu per lb of dry air and for case#2 it is 35 Btu/lb of dry air.

Observations: Greater evaporative cooling capacity occurs for the dry air as with case#1. The hot dry air (points D to E with a 24°F temperature drop) has more capacity for evaporative cooling than hot humid air (points F to G with only a 12°F temperature decrease).

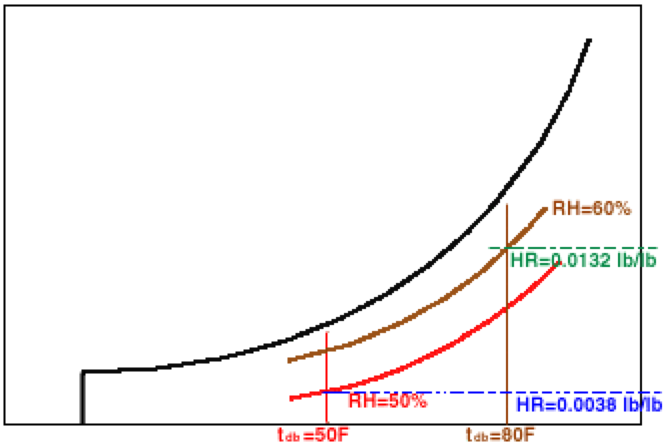
Evaporative cooling uses heat contained in the air to evaporate water. Air temperature (dry-bulb) drops while water content (humidity) rises to the saturation point. Evaporation is often used in hot weather to cool ventilation air.

When the spray water temperature is the same as the WB temperature of the entering air, the evaporative cooling process is a constant WB process. The process moves upward along the line of constant enthalpy or constant web-bulb temperature, for example, from point D to point E.

Example Problem # 7:

How much moisture is added to 20 lb of air going from 50° F, 50% RH to 80° F, 60% RH?

Solution:



HR (50 F, 50% RH) = 0.0038 lbm/lb da

HR (80 F, 60% RH) = 0.0132 lbm/lb da

Water added = 20 lb * (0.0132 - 0.0038) lb/lb = 0.188 lb-m

Example Problem # 8:

The air in a swine nursery building has a dry bulb temperature of 80° F and is at 70 percent relative humidity. How warm do the walls have to be to prevent condensation?

***Solution*:**

In this example, we need to know the dew point temperature. Locate the intersection of the 80°F dry bulb temperature line and the 70 percent relative humidity line. Proceed horizontally to the left until the dew point temperature scale is intersected. This gives the dew point temperature as 69°F. The wall temperatures must be warmer than this to prevent condensation.

Example Problem # 9:

A swine producer is considering installing evaporative cooling in a breeding herd building. What is the lowest temperature that can theoretically be obtained from the air coming off the cooling pads if the outside air has a 90°F dry bulb temperature and 35 percent relative humidity?

Solution:

Locate the intersection of the 90°F dry bulb temperature line and the 35 percent relative humidity line (which is not shown on the chart, but is mid-way between the 30 and 40 percent lines). Since evaporative cooling is the same process that determines wet bulb temperature, follow the wet bulb temperature line upward and to the left until the wet bulb temperature scale is intersected. The lowest possible temperature for these conditions would be the wet bulb temperature of 69°F. However, due to the inefficiency of evaporative coolers, the temperature of the air coming off the cooling pads will be 3 to 5 degrees F above the wet bulb temperature. This producer can probably expect to obtain air at about 73°F from the evaporative cooler under these conditions. This air would also have a relative humidity of approximately 85%.

Example Problem # 10:

Find the other properties of air at 73°F dry bulb temperature and 20% RH

Solution:

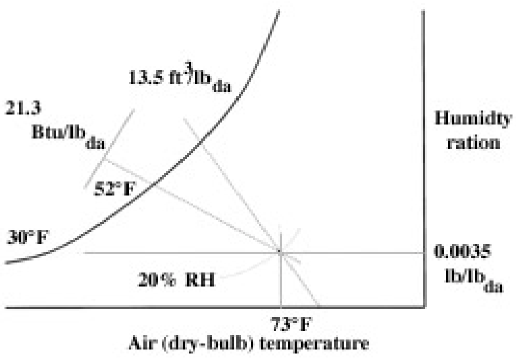


Figure above illustrates properties of air.

- Wet-bulb temperature is 52°F;
- Enthalpy is 21.3 Btu/lb;
- Humidity ratio is 0.0035 lb/lb;
- Dewpoint temperature is 30°F and
- Specific volume is 13.5 ft^3 /lb.

Example Problem # 11:

7500 CFM of chilled air at 57°F DB and 56°F WB mixed with 2500 CFM of outside air at 96°F DB and 78°F WB. Find the properties of mixture.

Solution

1) Locate points for re-circulated and outside air on the chart.

2) Connect with a straight line.

3) Read specific volumes of air at each point

4) Convert CFM of air to pounds of air and find total weight of mixture

Weight of Mixture: $\frac{7500}{13.22} = 567.3$ lbs / min

$\frac{2500}{14.37} = 173.9$ lbs / min

$= 741.2$ lbs / min

5) Dry Bulb of Mixture: $\frac{567.2}{741.2} \times 57 = 43.6$ deg F

$\frac{173.9}{741.2} \times 96 = 22.5$ deg F

$= 66.1$ deg F

Intersect 66.1° F dry bulb line with line between two points P_1 and P_2.

Read WB = 62.1°F, h = 27.83 Btu/lb of dry air, humidity ratio = 77.1 grains of moisture per lb of dry air.

Approximate solution does not convert CFM to pounds per minute

$\frac{7500}{10000} \times 57 = 42.75$ deg F

$\frac{2500}{10000} \times 96 = 24.00$ deg F

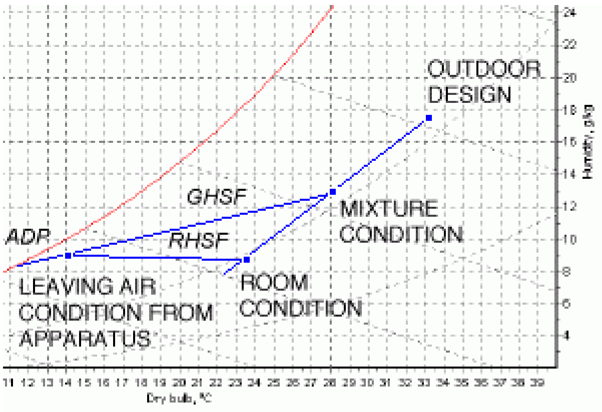
$= 66.75$ deg F

At intersection of this line with line between two points,

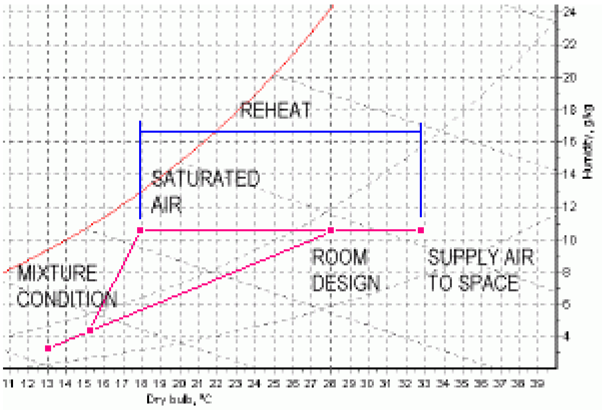
Read WB = 62.5°F, h = 28.1 Btu/lb of dry air, humidity ratio = 78.0 grains of moisture per lb of dry air.

Example Problem # 12:

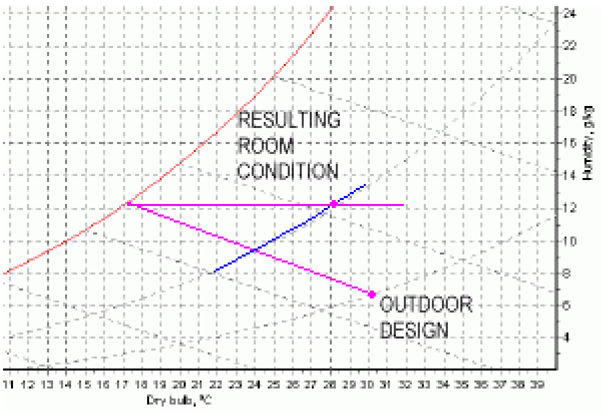
Interpret the sketches below and explain how this is achieved?



Sketch - 1



Sketch - 2



Sketch - 3

Solution

Sketch – 1 represents Cooling and Dehumidification. This is done on the cooling coil of the apparatus. The cooling coil may be direct expansion type where refrigerant evaporates or it could be chilled water-cooling coil where the chilled water produced by a chiller is circulated through the coil.

Sketch – 2 represents Heating and humidification. This could be achieved by means of a spray type humidifier and hot water or steam coils, or electric heaters.

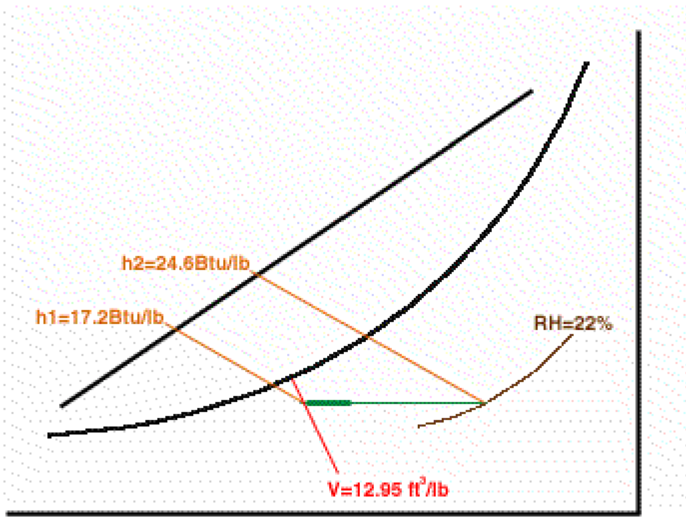
Sketch – 3 represents Evaporative Cooling. This can be achieved by means of an air washer / swine evaporative cooler.

Example Problem # 13:

How much heat must be added to 100 ft^3 of moist air with a dry bulb temperature of 50°F and a relative humidity of 60% to raise the temperature of the air 30°F? What will be the relative humidity of the air once this heat is added?

Solution:

Heat added is the enthalpy differential = 24.6 – 17.2 = 7.4 Btu/lb

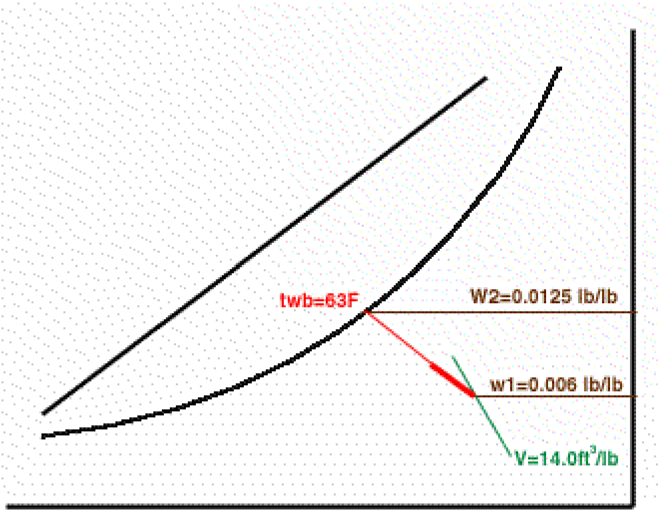


Example Problem # 14:

How much water would be required to saturate the air in the room if the initial conditions are t_{db} = 50°F and RH = 20%?

Solution

The water required shall be = 0.0125 – 0.006 = 0.0065 lb/ lb of dry air

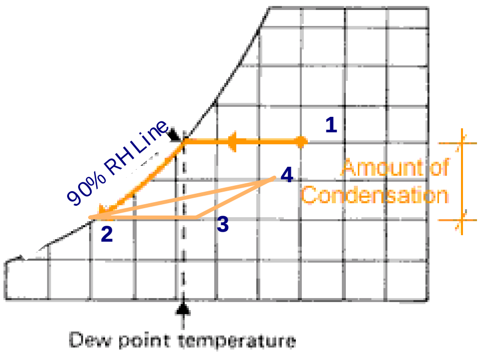


Example Problem # 15:

A system is designed with a coil that cools and dehumidifies air from 80° F db and 67° F wb to 51.5° F db and 90 % RH for supply to the space. The space is to be maintained at 75° F db and 50 % RH.

There are off-design periods when the cooling loads change and the SHF is estimated to be 0.6. The flow rate of the air remains constant. (a) Assume the cooling coil operates as given above at all times, and determine the amount of reheat required and the state of the air supplied to the space for the off-design periods. (b) Compare the space-cooling load for the two different conditions. Assume standard sea level pressure.

Solution:



The given design conditions are shown in figure above… (Not to scale).

For the first part of the question "A system is designed with a coil that cools and dehumidifies air from 80° F db and 67° F wb to 51.5° F db and 90 % RH for supply to the space. The space is to be maintained at 75° F db and 50 % RH."

The process 1-2 is for the cooling coil: (Note that the path for the cooling coil process depends on coil design and temperature of cooling medium. However for thermodynamic analysis only the end points are relevant and straight line from points 1 and 2 is sufficient)

The process 2-4 is for the space. (Note that extending this line to the north to hit the sensible heat factor line shall provide the space SHF reading)

The space SHF is about 0.71 for the design condition. (obtained by extending line 2-4 to cut the SHF line, refer ASHRAE psychrometric charts showing SHF scale)

STATE	TEMPERATURE (DB / WB, deg F)	R H (%)	Enthalpy (h) (Btu / lb)	Specific Volume (v) (Cu ft / lb)
1	80 / 67	51	31.5	13.85
2	51.5 / 49.9	90	20.3	13.0
3	61 / 54	64	22.6	13.3
4	75 / 62.5	50	28.2	13.7

When the SHF is 0.6 indicating that the space sensible heat is reduced, Process 3-4 for the off-design period is laid out from state 4 for a SHF of 0.6. Then the reheat process is 2-3 (sensible heating). Read space temperatures as 61°F db and 64 % RH determined by the intersection of processes 2-3 and 3-4.

(a) The amount of reheat per unit mass of dry air is

$$Q_{23} = C_{pt} (t_3 – t_2)$$

$$Q_{23} = 0.244 (61 – 51.5) = 2.32 \text{ Btu/ lb}$$

(b) The design-cooling load is

$$Q_{24} = (h_4 – h_2)$$

$$Q_{24} = (28.2 – 20.3) = 7.9 \text{ Btu/lb}$$

(c) The cooling load for off design period

$$Q_{34} = (h_4 – h_3)$$

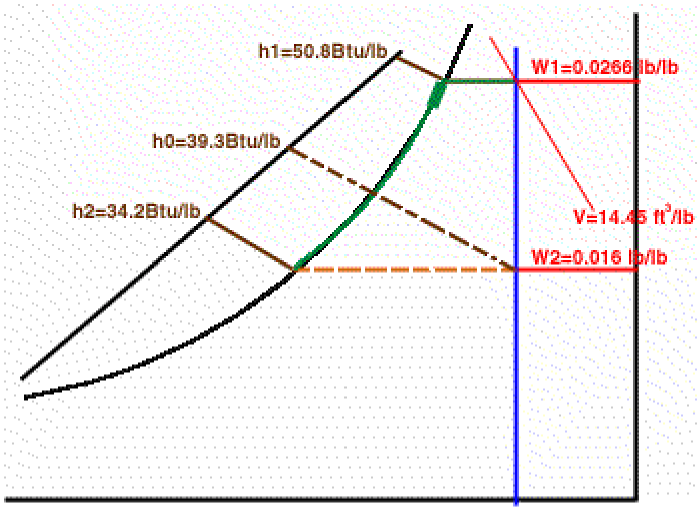
$$Q_{24} = (28.2 – 22.6) = 5.6 \text{ Btu/lb}$$

The cooling load for the off-design period is about 29 % less than the design-cooling load.

Example Problem # 16:

How much heat must be removed to cool “X” amount of air at 90°F dry-bulb and 85°F dewpoint to 70°F dry-bulb and 100% RH? How much moisture is removed from the air? What is the Sensible heat factor in this process?

Solution:



Sensible heat removed	= 39.3 – 34.2	= 5.1 Btu/lb
Latent heat removed	= 50.8 – 39.3	= 11.5 Btu/lb
Total heat removed	= 50.8 – 34.2	= 16.6 Btu/lb
Sensible heat factor	= 5.1/16.6	= 0.307
Moisture removed	= 0.0266 – 0.016	= 0.0106 lb /lb

Example Problem # 17:

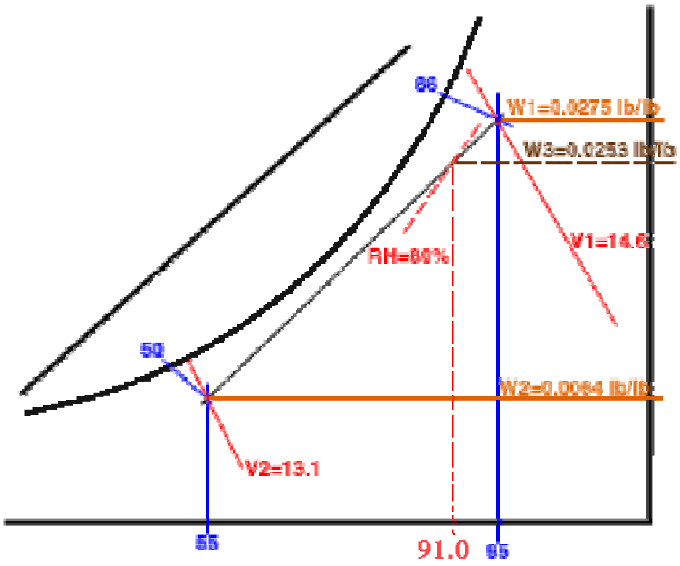
Outside air at 95°F dry-bulb and 88°F wet-bulb is mixed with conditioned air at 55°F dry-bulb and 50°F wet-bulb. If the mixing ratio of outside air to the conditioned air is 10:1, what is the dry-bulb temperature and relative humidity of the resulting mixture?

Solution:

Plot the two state points on the psychrometric chart.

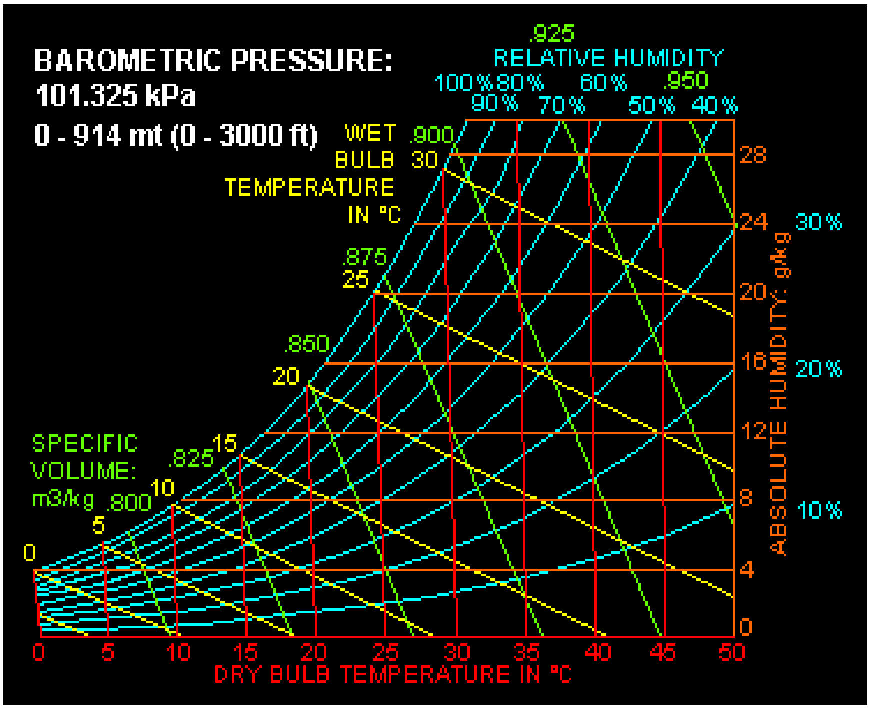
Join the two state points and divide the line in 10:1 ratio as shown in the figure

Read dry bulb temperature as 91°F and RH as 80% on the resultant state point.



*Psychrometric Examples **(in SI UNITS)***

The psychrometric chart in SI metric units is shown below:

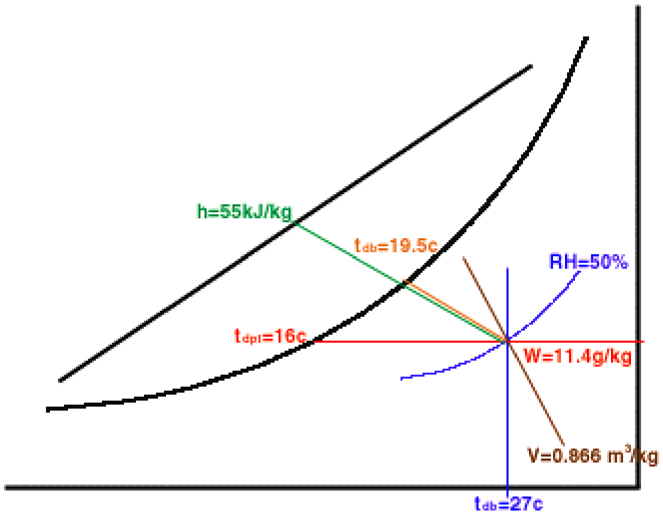


Example Problem # 18:

Use a psychrometric chart to determine the following air-water properties:

Given: t_{db} = 27° C; RH = 50%; and the atmospheric pressure is 101.3 kPa (standard barometric pressure at sea level)

Solution:



Dewpoint temperature, t_{dpt}	= 16°C
Wet-bulb temperature, t_{wb}	= 19.5°C
Humidity Ratio, W	= 11.4 g/kg of dry air
Specific Volume, v	= 0.866 m^3/kg
Enthalpy, h	= 55 kJ/kg

Example Problem # 19:

a) A dry-bulb thermometer reads 25°C and a wet-bulb thermometer reads 18°C. What is the relative humidity?

The vertical 25°C dry bulb (db) line and the diagonal 18°C wet-bulb (wb) line intersect at point (state point), which falls on the 50% relative humidity (rh) line.

b) What is the dew point temperature of the air in problem a)?

If the air is cooled without changing its moisture content, it will follow a horizontal line until it reaches 14°C. At that temperature, it has 100% relative humidity. Any further cooling will cause water to condense out of the air (dew forms). The dew-point (dp) temperature is 14°C.

c) What is the humidity ratio?

Find the humidity ratio of the air by reading horizontally across to the vertical axis on the right side of the psychrometric chart. The humidity ration (hr) is 0.01 kg/kg.

d) If the air is passed through a 100% efficient evaporative cooler, what will be its temperature after it leaves the cooler?

Evaporative cooling (and spray humidification), follow the diagonal wet-bulb lines. As air passes through the cooler, it will move from state point along the 18°C wet bulb line until it reaches 100% relative humidity (saturation). At this humidity it is saturated; will not accept more water vapor, and will cool no further. It will leave the cooler at a temperature of 18°C, its wet-bulb temperature.

e) When air represented by state point (db= 25°C, wb=18°C) enters a storage room with a temperature of 0°C and a relative humidity of 95%, will it add moisture to the storage room or dry it out?

The air has a dew point temperature of 14°C (from b). When this air is cooled to just less than 14°C it will begin to lose water and will continue to do so until it reaches the storage room temperature. In fact, air will lose about 0.006 kg/kg of dry air as it cools down to 0°C. Thus, air at state point will add moisture to the room.

f) If air leaves a wet-coil evaporator at 0°C and 100% relative humidity and is heated 2°C by the circulation fan before it reaches a stored product, what is the relative humidity of the air to which the product is exposed?

Sensible heating processes follow horizontal lines on the psychrometeric chart. Air will leave the coil at point say B represented by 0°C and 100% and move horizontally to the right on the chart until it reaches 2°C. At that point, the relative humidity will be about 87%.

Air Conditioning Processes (moisture control)

Before commencing on the design phase, it is important to look at the ambient conditions you are going to be designing for and assess the required indoor thermal comfort conditions throughout the year.

Outdoor air creates the baseline for indoor humidity levels, besides numerous indoor activities such as occupancy (people exhale moisture and perspire), cooking, cleaning, etc. add moisture to air. We typically apply the psychometric process to design the desired indoor conditions. As we have seen in the first part of this tutorial, the process of conditioning /changing the temperature of air shall alter the indoor relative humidity.

In the air conditioning process the moisture content of the air may be reduced by the use of a cooling coil or added by the use of a humidifier. Most refrigerant-type or chilled water air – conditioning systems, by design, remove moisture from the air during the cooling cycle through condensation at the evaporator coil. This moisture is removed from the interior using a condensate drainage network. In certain applications, dehumidifiers may be necessary if indoor relative humidity levels get too high.

Lets check out other practical applications of psychrometric analysis in equipment duty estimation or performance evaluation:

1 Performance Evaluation of Cooling Coil

Plotting a process on the psychrometric chart allows you to calculate the total duty, sensible duty and humidification rate. Once you have calculated the heat load and done the psychrometrics, you will need to select air-conditioning plant equipments. The most fundamental of these is the cooling/heating coil.

The most common psychrometric analysis made by HVAC contractors involves measuring the dry and wet bulb temperatures of *air entering* and *leaving the cooling coil*. If these temperatures are measured along with the CFM airflow rate, the performance or cooling capacity of a unit can be verified.

Procedure:

Step # 1: Measure entering air-dry bulb and wet bulb temperature of the coil in degrees F and locate this state point 1 on the psychrometric chart.

Step # 2: Measure the leaving air-dry bulb and wet bulb temperature of the coil in degrees F and locate this state point 2 on the psychrometric chart.

Step # 3: Read the corresponding enthalpy values (h_1) & (h_2) against the state point 1 and 2.

Step # 4: Measure the volume of air passing through the coil in CFM across the coil through an Anemometer.

Step # 5: The total energy output or cooling capacity of the coil in BTU/hr can than be worked out by multiplying 4.5 times the CFM value times the enthalpy difference of the two air state points i.e.

$$Q = 4.5 \times CFM \times (h_1 - h_2)$$

Notes:

1. The air mixture calculations are performed on mass basis rather than volume basis. Air mixing problems must be solved on a mass basis because the volume will change but the mass will not. This usually requires changing a volumetric flow to a mass airflow.

2. The empirical relation value 4.5 is derived from the converting the volume (CFM) to the mass flow (lb/hr) by multiplying it with density 0.75 lb/cuft @ 70°F x 60 min/hr.

3. The Sensible heat could be determined by multiplying 1.08 x CFM x $(t_1 - t_2)$. The empirical value 1.08 is derived from (0.24 (specific heat) * 0.75 lb/cuft @ 70°F * 60 min/hr)

4. The airflow rate could be measured through a device known as “Anemometer”. Anemometer measures the air velocity across the face of the coil in fpm (or m/s). The air velocity measured multiplied with the face area in sqft (or m^2) of coil gives the airflow rate in CFM (or in m^3/s).

Contractors often have to perform this calculation to prove that their equipment is working properly and to certify that the equipment is of right duty.

---

2 Performance Evaluation for Drying Applications

Since the moisture holding capacity of air increases with increasing temperature, heat may be added to aid in moisture removal in ventilation air for instance in grain drying applications. In home, moisture can either be added or removed from the air to change the relative humidity. In each case, air provides the link between the controls and the mechanical equipment, and air properties influence the results of the processes.

In forced aeration drying systems the performance evaluation is straightforward. First, calculate the humidity ratio lb water per lb of dry air (or kg water/kg dry air) and enthalpy in Btus per lb of dry air (or J/kg dry air) of the exhaust air at specified temperature and relative. Then calculate the humidity ratio and enthalpy of the inlet air conditions. The difference between inlet and exhaust for each of these quantities, multiplied by the mass flow of air (in kg dry air per unit time) gives the moisture removal and energy removal rates:

$$\Delta Moisture = Airflow\left(H_{exhaust} - H_{inlet}\right)$$

and

$$\Delta Enthalpy = Airflow\left(h_{exhaust} - h_{inlet}\right)$$

Where (units expressed in SI)

$\Delta Moisture$ = Moisture removal via convection (kg H_2O / day)

$Airflow$ = Mass flow of dry air (kg air / day)

H = humidity ratio (kg H_2O / kg dry air)

$\Delta Enthalpy$ = Energy removal via convection (kJ / day)

h = enthalpy of air - vapor mixture (kJ / kg dry air)

In composting applications, the known or readily measured parameters usually include atmospheric pressure, relative humidity, and dry bulb temperature. The humidity ratio and enthalpy can be derived either directly from psychrometric charts or calculated from the governing equations.

Theoretical Psychrometrics (for Academics)

The psychrometric chart is a very convenient way to determine the air water relationships. Several sets of equations are used to express the air mixture relationships. These equations are somewhat lengthy polynomials, which are available in ASHRAE Standards books. The computer software programs use these arithmetic expressions.

This is however more an academic area and is not of great importance to end-users. Brief is provided herewith and those interested in further reading can refer to book on thermodynamic and ASHARE and ASAE standards (D 271.2)

The psychrometric equations define the thermodynamic properties of moist air under specified conditions of temperature and relative humidity. Two governing laws, which are important in understanding the relationships between psychrometric properties, are *Dalton's Law* and *the Ideal Gas Law*

1 Dalton's Law

Sum of the partial pressure of each gas in a mixture of gases equals the total pressure exerted by the entire mixture. Each gas behaves as if the other gas were not present.

Moist air $P = P_{water\ vapor} + P_{air}$

$P_{air} = P_{nitrogen} + P_{oxygen}$

Or

P = Pa + Pw

Where:

P = Total barometric pressure of the moist air

= Pressure exerted by the atmosphere (standard atmospheric pressure)

= 14.696 psi [101.33 kPa]

P_w = Partial pressure of the water vapor

P_a = Partial pressure of the air

2 Ideal Gas Law

Moist air is a mixture of perfect gases and it obeys the ideal gas laws up to 3 atm.

P*V = n*R*T

P_a*V = n_a*R*T

P_w*V = n_w*R*T

Where:

P = Absolute pressure, psf [Pa]

V = Gas volume, ft^3 [m^3]

n = Number of pound-moles

= Weight of gas divided by its molecular weight = M/mole wt

$n_a = M_a$ / 28.9645 for air

$n_w = M_w$ / 18.01534

R = Universal gas constant = 1545.32 ft-lb / (lb-mole-°R) [8314 J/kgK-mole]

T = Absolute temperature, °R

Terminology and Definitions

1) Humidity Ratio (W):

Humidity ratio (W) of a given moist air sample is defined as the ratio of the mass of water vapor to the mass of dry air contained in the sample:

W = Mw / Ma where,

Mw = mass of water vapor of the sample of air

Ma = mass of dry air contained in the sample.

$W = M_w / M_a$

For ideal gas

$= (P_w V/R_w T)/ (P_a V/R_a T)$

$= 0.622\ P_w/P_a$

$= 0.622*P_w/(P_{atm}-P_w)$

P_w = actual water vapor pressure

Humidity ratio is expressed as lb of water vapor per lb of dry air. Older references used grains of vapor per pound of dry air (7000 grains equal 1 lb)

2) Specific Humidity (q):

Specific humidity is the ratio of the mass of water vapor to the total mass of the moist air sample:

q = Mw / (Mw + Ma) where,

Mw = mass of water vapor of the sample of air.

Ma = mass of dry air contained in the sample.

3) Absolute Humidity (dv):

Absolute humidity (alternatively, water vapor density) dv is the ratio of the mass of water vapor to the total volume of the sample of air:

dv = Mw / V where,

Mw = mass of water vapor of the sample of air

V = total volume of sample air

4) Density (ρ):

The density of a moist air mixture is the ratio of the total mass to the total volume.

ρ = (Ma + Mw) / V = (1 / v) (1 + W) where,

Mw = mass of water vapor of the sample of air

Ma = mass of dry air contained in the sample

V = total volume of sample air

v = the moist air specific volume, ft^3 / lb (dry air)

W = Humidity Ratio

5) Relative Humidity (ϕ):

The humidity of air in any condition can be expressed relative to the amount of moisture the air could support at that temperature, i.e., as a percentage of the saturation humidity. This is the relative humidity

RH = (AH/SH) x 100 (%), where

RH = Relative humidity

AH = Absolute humidity

SH = Saturation humidity

Or

Relative humidity, RH, is defined as the ratio of the mole fraction of water vapor in a moist sample of air to the mole fraction in an saturated sample at the same temperature and pressure. Relative humidity is expressed as a percentage.

$RH\% = 100*p_w/p_{ws}$

where:

p_w = actual water vapor pressure

p_{ws} = vapor pressure of saturated air

6) Degree of Saturation (u):

Degree of saturation, u is the ratio of the actual density of water vapor in the air to the density of saturated water vapor at the same dry-bulb temperature.

$u = W/W_s = (P_w/P_{ws})*[(P-P_{ws})/(P-P_w)]$

where:

W = actual humidity ratio

W_s = humidity ratio at saturation

7) Specific volume (v):

The specific volume (v) is a mixture per pound of dry air (inverse of density)

v = V / Ma where,

V = total volume of the mixture

Ma = total mass of dry air

Empirical relation……….

$v = V/M_a = V/(28.9645*n_a) = (nRT/P)/(28.9645*n_a)$

Since $RT/V = P_a/n_a$, then $P_a = P*n_a/n$, and:

$v = RT/(P_a*28.9645 = RT(1 + 1.6978*W)/(28.9645*P)$

Where;

n= Number of pound-moles

= Weight of gas divided by its molecular weight

$n_a = M_w / 28.9645$ for air

Mw = mass of water vapor of the sample of air.

R = Universal gas constant = 1545.32 ft-lb / (lb-mole-^oR) [8314 J/kgK-mole]

T = Absolute temperature, ^oR

P = Absolute pressure, psf [Pa]

8) Dry-bulb temperature, (t db):

Temperature as read from a common thermometer

9) Wet-bulb temperature, (t wb):

Temperature indicated by thermometer covered with a wicking material saturated with liquid once the system has reached equilibrium. Wet bulb temperature decreases as rate of evaporation of water from the wick increases.

10) Wet-bulb temperature depression:

Wet bulb depression is a difference between the dry-bulb and wet-bulb temperatures. The temperature is depressed by evaporative cooling of the wet bulb. The greater the difference between the amounts of water in the air and the saturation water capacity the more rapid the evaporation and thus the greater the temperature depression. The greater the wet bulb depression, the lower is the RH.

11) Dew-point temperature (t_{dp})

Dew point is the temperature of moist air saturated at the same pressure p, with the same humidity ratio W as that of the given sample of moist air. It is defined as the solution $t_{dp}(p,W)$ of the equation.

$Ws\ (p,\ t_{dp}) = W$

If you slowly reduce the temperature of moist air while holding p and W constant, then the temperature at which the saturation is reached t_{dp}. The terms derives from the phenomenon of the formation of dew-drops, which are formed when the air at a high temperature and absolute humidity cools down so far that it can no longer hold the moisture as vapor and has to relinquish the excess moisture for that temperature.

12) Enthalpy:

Enthalpy is the heat energy content of an air-water mixture. The enthalpy of a mixture of perfect gases equals the sum of the individual partial enthalpies of the components. Therefore, the enthalpy of moist air can be:

$h = c_p*t_{db} + W*h_w$

$h = 0.240*t_{db} + W*(1061 + 0.444*t_{db})$

Where:

cp = specific heat of dry air, 0.240 Btu/lb-°F

t db = dry bulb temperature, °F

W = humidity ratio of air, lb of water/lb dry air

hw = enthalpy of water vapor, Btu/lb

1061 = latent heat of vaporization, Btu/lb

0.444 - specific heat of water vapor, Btu/lb-°F

For air conditioning work, enthalpy is expressed in Btu per pound of dry air (J/kg). Measurement of enthalpy is a relative thing, that is, the actual heat content is dependent on the datum or zero point chosen. The usual datum for dry air is 0°F and for water 32°F.

13) Heat, Q (small q denotes rate of heat transfer):

Heat is a form of energy transferred from a warmer body to a colder body because of their temperature differences (sensible heat) or energy that is released or absorbed during a phase change (latent heat).

- 1 Btu = quantity of heat needed to raise 1 lb of water from 59.5°F to 60.5°F (i.e. 1°F) under 1 atmospheric pressure
- 1 Btu = 778.16 ft-lbs = 1055 J (1 joule = 1 N-m) = 252.2 cal
- 1 cal = amount of heat required to raise 1 g of water from 14.5°C to 15.5°C (i.e. 1°C)
- 1 cal = 4.184 joules (J)

14) Specific Heat or Specific Heat Capacity (c):

Quantity of heat needed to increase a unit weight of a material by one degree. Units are Btu/lb°F [J/kgK]

15) Sensible Heat (Qs):

Heat energy absorbed or released when a body changes temperature form one point to another.

$Q_s = M \times c \times (t_1 - t_2)$

where:

M = weight or mass

c = specific heat

16) Sensible Heat (Q_l):

Quantity of heat absorbed or released when a material changes phases without a change in temperature.

- Latent Heat of Fusion: Heat required for a solid-liquid phase change. For ice to melt or water to freeze, 144 Btu/lb [335 kJ/kg] must be supplied or removed.
- Latent Heat of Vaporization: Heat required for changing liquid to vapor. The latent heat of vaporization is a function of temperature as shown in the following table. A common value used for designing animal ventilating systems is 1044 Btu/lb of water.

Temperature, F	Temperature, C	Latent heat, Btu/lb	Latent heat, kJ/kg
32	0.0	1075	2500
40	4.4	1071	2491
60	15.6	1059	2463
87	30.6	1044	2428
100	37.8	1037	2412
140	60.0	1014	2359
180	82.2	990	2302
212	100.0	970	2256

17) Heat of Condensation:

Heat of condensation is heat given up by a gas as it returns to the liquid phase. The heat of condensation per unit weight equals the heat of vaporization.

18) Vapor Pressure, (P):

Vapor pressure is the independent pressure exerted by the water vapor in the air. The vapor pressure is proportional to the humidity ratio. The natural tendency for pressures to equalize will cause moisture to migrate from an area of high vapor pressure to an area of low vapor pressure. The saturation vapor pressure varies with temperature.

Saturation vapor pressure P_{sat} is the maximum possible vapor pressure for air at some temperature (ignoring the possibility of super saturation).

At any one time the actual vapor pressure P_w could be anything between 0 and P_{sat}.

Relative humidity is P_w / P_{sat}. At 100% RH, P_w = P_{sat}

Water Vapor Saturation Pressure, (P_{ws})

Temperature, F	Temperature, C	Pws, psia	Pws, Pa
-20	-28.9	0.0062	43
-10	-23.3	0.0108	74
0	-17.8	-0.0185	128
10	-12.2	0.0309	213
20	-6.7	0.0505	348
32	0.0	0.0885	610
40	4.4	0.1217	839
60	15.6	0.2563	1767
80	26.7	0.5069	3495
100	37.8	0.9492	6545
120	48.9	1.6924	11670
140	60.0	2.8886	19917

Psychrometric Software's

Psychrometric Analysis Software can take the drudgery out of performing psychrometric calculations. Software can greatly aid in the analysis and handling of psychrometric data. With a conventional psych chart, designer must use a straight edge and pencil to plot lines and read data. The whole affair is very imprecise as the width of a pencil lead can cause significant error. In addition, most psych charts are printed for sea level barometric pressure. If a project is located at different elevation, a standard psych chart cannot be reliably used. Barometric pressure affects the density of air and hence, the thermodynamic properties of air. High altitude psychrometric analysis requires a special psych chart or lengthy manual calculations.

Good software must contain….

There is actually a wide range of psychrometric software available. Some of it does nothing more than list all the properties of air when two conditions are inputted to achieve a state point. Nice, but not that useful.

The next level of analysis involves the ability to perform mixed air psychrometrics, where two state points are defined along with corresponding air flow (CFM) values. An ideal application for this type of analysis is the mixing of return air with outside air in the determination of entering cooling coil air conditions. These types of psychrometric software tend to be non-graphical and print the tabular reports.

Conclusive Recap

1) The versatility of the psychrometric chart lies in the fact that by knowing just two properties of moist air, the other properties can be determined. The dry bulb temperature and wet bulb temperature is most simple to measure.

2) At a given barometric pressure, temperature is the key factor regarding how much moisture can be retained. One pound of water = 7,000 grains

3) The air mixture calculations are performed on mass basis rather than volume basis because the volume will change but the mass will not.

4) Relative humidity is a relative measure, because the moisture-holding capacity of air increases as air is warmed. *Air at 60 percent relative humidity contains 60 percent of the water it could possibly hold (at that temperature). It could pick up 40 percent more water to reach saturation.*

5) At the same relative humidity, warm air holds more moisture than cold air. *For instance, 80 percent relative humidity at 32°F has much lower humidity ratio than air with 80 percent relative humidity at 68°F.*

6) At a given temperature and pressure, air can support only one maximum amount of moisture and no more. *This is referred to as the saturation humidity (SH).*

7) Air can gain heat with *"either an increase in temperature or increase in moisture content"*.

8) Air holds more water vapor at increasing temperatures. *As a rule of thumb, the maximum amount of water that the air can hold doubles for every 20°F increase in temperature.*

9) At cold temperatures, air can hold very little water as indicated by the steeply sloping saturation line. *This is the reason that winter months have so much precipitation.*

10) If a mass of air is cooled without changing its moisture content, it loses capacity to hold moisture. If cooled enough, it becomes saturated (has 100 percent relative humidity) and if cooled further, begins to lose water. That's the reason *cold weather promotes dry air because low temperatures cause whatever moisture in the air to fall out as dew, frost, rain, sleet, or snow.* The main point to remember is that a point cannot be located to the left of the saturation line on the psych chart. Attempting to take air into this region causes precipitation, and thus air can never go beyond the saturation line.

11) Wet-bulb temperature represents the amount of moisture the air can evaporate.

12) Wet bulb temperature decreases as rate of evaporation of water from the wick increases.

13) The measure wet bulb temperature is not a thermodynamic property i.e. not solely a function of state of air to which the thermometer is exposed. Measured wet bulb temperature is affected by heat and mass transfer rates.

14) Dry bulb temperature can be measured by RTD, thermocouple or in-glass thermometer. Wet bulb temperature could be measured by ordinary thermometer whose bulb is soaked with wick at air velocity of around 500 fpm.

15) Dew point measurements could be taken from chilled mirror hygrometers.

16) RH can be measured directly by capacitive sensors, electrical, polymer film or hair hygrometers.

17) When the air is fully saturated RH = 100%.

18) RH tells us how close we are to saturation but does tell us how much moisture is in the air. If we have a third of the amount of vapor needed for saturation; RH = 33%.

19) RH reaches 100% (saturation); at that point we have cooled the air to its dew point temperature.

20) When air is fully saturated, dry-bulb, wet-bulb, and dewpoint temperatures are all equal.

21) Maximum amount of water vapor air can hold (saturation vapor pressure) increases with temperature.

22) The greater the wet bulb or dew point depression), the lower the RH. The wet bulb depression is $(t_{db} - t_{wb})$.

23) The temperature at which condensation begins to form is called the dew point temperature. High dew point means the water content of air is high.

24) Most everyone has witnessed bathroom mirrors 'fogging' during a hot shower or iced-drink glasses 'sweating' on the outside. The cool surfaces are simply condensing moisture out of humid air.

25) The terms sensible heat and latent heat are used to distinguish how air has gained heat.

- Sensible heat can be thought of as "dry" heat since a sensible heat gain involves gaining heat with no increase in the moisture content of the air.
- On the other hand, latent heat can be thought of as "wet" heat since a purely latent heat gain results from adding moisture to the air with no increase in the air temperature.

26) Located at 78°F db and 50% RH is an ‘ Alignment Circle’. This is used in conjunction with the sensible heat factor to plot the various air conditioning process lines for instance in estimating the coil dewpoint temperatures.

27) Standard psychrometric charts are based on a sea-level condition. Precise calculations of psychrometric variables require an adjustment for barometric pressures different from those listed on a standard chart. Consult the ASHRAE handbook for more information on this.

28) Humidity ratio is not affected by a temperature change unless it drops below the saturation temperature. Humidity ratio is useful in calculating the amount of moisture involved in a process, such as the amount removed by ventilating a stable or the amount added by an evaporative cooler used in a greenhouse

29) Note that cooler air (located along lower, left region of chart) will not hold as much moisture (as seen on the y-axis' humidity ratio) as warm air (located along right side of chart). *A rule of thumb, during winter conditions, is that a 10°F rise in air temperature can decrease relative humidity 20 percent.* When air is cooled, relative humidity increases.

30) Moist Air Properties Units

- Dry bulb temperature (°F or °C)
- Wet bulb temperature (°F or °C)
- Dew point temperature (°F or °C)
- Relative humidity (%)
- Humidity ratio (lb H_20/lb dry air, or kg H_20/kg dry air)
- Enthalpy (BTU/lb dry air, or kJ/kg dry air)
- Density (lb/ft^3, or kg/m^3)

Course Summary

A psychrometric chart graphically describes the relationship of seven air properties under variety of conditions and illustrates how these properties change as the heat and moisture content of the air changes.

The psychrometric chart graphically represents the interrelation of air temperature and moisture content. This aspect of psychrometrics is very important when it comes to analyzing indoor conditions as temperatures and humidity levels within our environments are very dynamic.

In air-conditioning applications the knowledge of psychrometrics is essential to design the system for optimal thermal comfort. Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment. The air conditioning engineer uses the psychometric chart to analyze how the state of moist air alters as an air conditioning process takes place.

The engineers in industry fields it useful to design the process systems, ventilation of livestock building, moisture control applications and variety of drying applications such as drying of grains, leaves, ceramic, art objects etc. etc.

A solid understanding of psychrometrics can prevent costly mistakes in the design and operation of commercial, residential, industrial cooling, dehumidification, drying and humidification systems.

A lot of energy is used in air-conditioning, and with an understanding of psychrometrics you can estimate energy flows, evaluate performance and plan energy conservation.

Related Reading

Understanding Psychrometrics, ISBN 1-931862-14-1, published by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), provides a practical desk reference book for air conditioning designers, process engineers and meteorologists and a learning module for students and those new in the field.