UNIVERSITY OF FLORIDA
IFAS EXTENSION

CIR1097

# Psychrometrics and Postharvest Operations [1]

Michael T. Talbot and Direlle Baird[2]

The Florida commercial vegetable industry is large and diverse and the value of vegetable production in the state of Florida is over 1.5 billion dollars annually. Most of these vegetable crops are produced for the fresh market and require proper postharvest control to maintain quality and reduce spoilage. The ambient environment to which the freshly harvested vegetables are exposed has a very significant effect on the postharvest life of these perishable commodities.

Psychrometrics deals with thermodynamic properties of moist air and the use of these properties to analyze conditions and processes involving moist air [1, 7] (numbers in brackets refer to cited references). Commonly used psychrometric variables are temperature, relative humidity, dew point temperature, and wet bulb temperature. While these may be familiar, they are often not well understood [2, 3, 4, 5, 81. A better understanding of psychrometrics will allow vegetable producers, packinghouse operators, and commercial cooler operators to improve postharvest cooling and storage conditions for fresh vegetables. This publication presents the relationship of psychrometric variables, considers their effect on perishable commodities, and reviews how they can be measured. This publication further suggests how the psychrometric variables can be used and more importantly how they should be used by managers.

## Psychrometric Variables

Atmospheric air contains many gaseous components as well as water vapor. Dry air is a mixture of nitrogen (78%), oxygen (21%), and argon, carbon dioxide, and other minor constituents (1%). Moist air is a two-component mixture of dry air and water vapor. The amount of water vapor in moist air varies from zero (dry air) to a maximum (saturation) which depends on temperature and pressure. Even though water vapor represents only 0.4 to 1.5% of the weight of the air, water vapor plays a very significant role in the effect of air conditions on the postharvest life of perishable commodities.

The physical and thermodynamic properties of moist air (psychrometric variables) are related by a number of physical laws. These properties of moist air can be expressed in terms of many different variables. Psychrometric properties important to postharvest horticulture include dry bulb temperature, wet bulb temperature, dew point temperature, relative

1. This document is CIR1097, one of a series of the Agricultural and Biological Engineering Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Original publication date May, 1993. Reviewed July, 2002. Visit the EDIS Web Site at http://edis.ifas.ufl.edu.
2. Michael T. Talbot, Associate Professor, <Department>Department of Agricultural and Biological Engineering</Department> and Direlle Baird, Professor, Department of Agricultural and Biological Engineering, Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, 32611.

humidity, humidity ratio, enthalpy, and specific volume.

The *dry bulb temperature* (db) is the actual air temperature measured with a common thermometer or thermocouple. The *wet bulb temperature* (wb) is measured with a common thermometer or thermocouple with the bulb or junction covered with a water-moistened wick and in a moving stream of ambient air. Evaporation from the wick attains a steady state, in which sensible heat from the surroundings provides heat of vaporization. Air flow past the bulb must be high enough to prevent significant change in the ambient air temperature. Evaporation of water cools the bulb. The drier the surrounding air, the greater the rate of evaporation and the lower the wet bulb temperature. The wet bulb temperature is the lowest temperature to which an air mixture can be cooled solely by the addition of water with absolutely no heat removed.

The process of cooling an air mixture with the addition of water and with no removal of heat is called "evaporative cooling". If air is cooled without changing its moisture content, it will lose capacity to hold moisture. If cooled enough, it will become saturated and if cooled further, will lose water in the form of dew or frost. The temperature that causes condensation to form is called the *dew point temperature* (dp) if it is above 0°C (32°F) or the frost point temperature if it is below 0°C (32°F).

*Relative Humidity* (RH) is the best known and perhaps the most used (and misused) term for expressing the water vapor condition of moist air. RH is defined as the ratio of the water vapor pressure in the air to the saturation vapor pressure at the same temperature, and is normally expressed as a percent.

The *humidity ratio (or mixing ratio or absolute humidity* ,) is the ratio of the weight of water vapor in a moist air sample to the weight of dry air contained in the sample. It is usually expressed in terms of kg water per kg dry air (lb water per lb of dry air). This property is very useful since it allows two conditions to be compared in terms of the moisture gradient between the conditions. Water vapor will move from a condition with a higher moisture level to a condition with a lower moisture level.

The *enthalpy* is the heat energy content of an air- water vapor mixture. The energy is both sensible (indicated by dry bulb temperature) and latent heat of vaporization (energy content of the water vapor). This variable is important for engineering calculations such as estimating the tons of refrigeration required to cool perishable produce. Enthalpy will not be emphasized since the purpose of this publication is to discuss the use of psychrometric variables to analyze environmental conditions and then determination of required action to optimize the conditions.

The *specific volume* of a moist air mixture is defined as the volume of the mixture per unit weight of dry air and is expressed in terms of $m^3$ per kg dry air ($ft^3$ per lb dry air). It is also more important for engineering calculations rather than analysis of environmental conditions.

## Psychrometric Chart

The psychrometric chart is a graphical representation that describes the relationships between these variables ( Figure 1 ). Although complicated in appearance, this chart can be used to establish a state point and is easily mastered. The charts in pads like graph paper can be obtained from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [1] and several refrigeration equipment manufacturers.

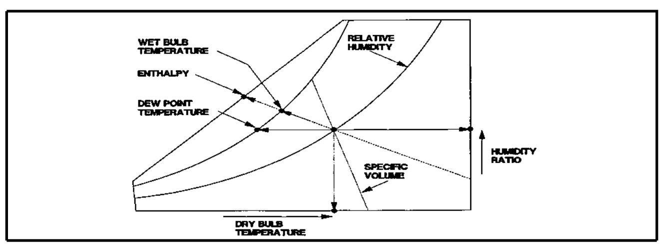


**Figure 1 .**

The dry bulb temperature is the horizontal axis of the chart. The vertical axis located on the right side of the chart is the humidity ratio. Two of the variables must be known to establish a state point from which other variables can be readily obtained as shown in Figure 1 and Figure 2 .

The maximum amount of water vapor that air can hold at a specific temperature is given by the left most, upward-curved line in Figure 1. It is noted that

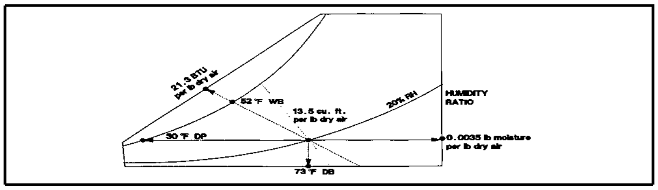


**Figure 2 .**

air holds increasingly more water vapor at increasing temperatures. As a rule of thumb, the maximum amount of water that the air can hold doubles for every ll°C (20°F) increase in temperature. This line in Figure 1 is also called the 100% RH line. A corresponding 50% RH line is approximated by the points which represent the humidity ratio when the air contains one-half of its maximum water vapor content. The other relative humidity lines are formed in a similar manner.

The relative humidity without some other psychrometric variable does not determine a specific moist air condition on the chart and is not very meaningful. As will be shown, 80 percent relative humidity at 0°C (32°F) is a much different air condition than 80 percent relative humidity at 20°C (68°F).

Another commonly used psychrometric variable is wet bulb temperature. On the chart (Figure 1) this is represented by lines that slope diagonally upward from right to left. In practice, wet bulb lines are used to determine the exact point on the psychrometric chart which represents the air conditions in a given location as measured by a psychrometer which will be described below. The intersection of the diagonal wet bulb temperature line (equal to the temperature of a wet bulb thermometer) and the vertical dry bulb temperature line defines the temperature and humidity conditions of air.

The dew point temperature for a given state point is found by the intersection of a horizontal line drawn through the state point and the 100% RH or saturation line (Figure 1).

Vapor pressure is not shown on all psychrometric charts, but is an important concept in handling perishables. At a given barometric pressure [4], a direct correlation exists between humidity ratio and vapor pressure regardless of temperature. Vapor pressure is often used as an expression of humidity levels, particularly in terms of the difference between vapor pressures at two points (vapor pressure deficit). Water vapor will flow from a point of higher pressure to a point of lower pressure just like water flow created by pumps during irrigation or air flow created by fans during forced-air cooling. The vapor pressure deficit determines the rate of evaporation and therefore the transpiration from horticultural products, which is of great importance when handling fresh commodities.

Figure 2 illustrates the properties of air that can be determined when the dry bulb and wet bulb temperature are known (73°F db and 52°F wb), which for this case are 20% RH, 30°F dp, 0.0035 lb water per lb of dry air humidity ratio, 21.3 Btu/lb dry air enthalpy and 13.5 ft $^3$ per lb dry air specific volume.

Figure 3 and Figure 4 are psychrometric charts in English and metric units, respectively, which will help to illustrate the meaning of various terms.

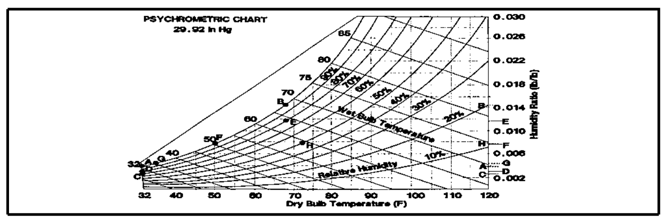


**Figure 3 .**

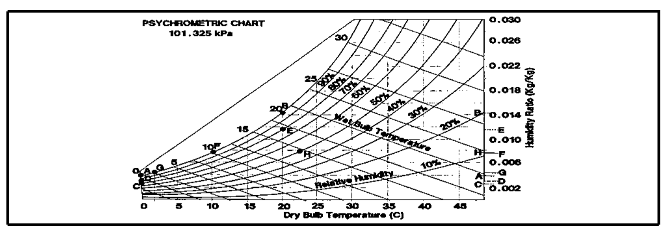


**Figure 4 .**

Psychrometric charts and calculators are based on a specific atmospheric pressure, usually a typical sea level condition. Precise calculations of psychrometric variables will require adjustment for barometric pressures different from those listed on a particular chart. The ASHRAE Handbook [1] provides more information. Most field measurements will not require adjustment for pressure.

## Effect of Psychrometric Variables On Perishable Commodities

### Temperature

Air temperature is the most important variable because it tends to control the flesh temperature of perishable commodities. All perishables have an optimum range of storage temperatures [8, 9]. Above the optimum, they respire at unacceptably high rates and are more susceptible to ethylene and disease damage. In fact, horticultural commodities respire at rates which double, triple, or even quadruple for every 10°C (18°F) increase in temperature [9]. Temperatures below the optimum will result in freezing or chilling damage. Accurate control of temperature during precooling and storage is vitally important in maintaining maximum shelf-life and quality.

### Humidity Ratio/Vapor Pressure

The rate of moisture loss from a perishable is primarily controlled by the difference in vapor pressure between the air in the intercellular spaces of plant material and the air surrounding it. As indicated above vapor pressure increases as the air moisture content (humidity ratio) increases. The air in fresh plant material is nearly saturated or, in other words, is close to 100% RH. Therefore, the humidity ratio of this air is determined solely by the temperature of the plant material. From the psychrometric chart it is apparent that low temperatures result in low humidity ratios and high temperatures cause high humidity ratios.

Consider several examples of how the drying of perishables is influenced by vapor pressure (humidity ratio) differences. If sweet corn were precooled to 0°C (32°F) [Point A, Figure 3 and Figure 4 ] and placed in a refrigerated room with saturated air at 0°C (32°F) [also Point A, Figures 3 and 4], the sweet corn would not lose moisture because the humidity ratio and temperature of the air in the sweet corn and the surrounding air are the same. However, if the sweet corn were at 20°C (68°F) [Point B, Figures 3 and 4] because it was not precooled before being placed in the same refrigerated room, the air in the sweet corn would have a high vapor pressure (high temperature and humidity ratio) compared to the refrigerated air, causing the sweet corn to dry. If the sweet corn were precooled to 0°C (32°F) [again Point A, Figures 3 and 4] but the refrigerated air were at 70 % RH [Point C, Figures 3 and 4], drying would also occur because the refrigerated air is at a lower humidity ratio than the saturated air in the sweet corn. However, the rate of moisture loss is much greater when the sweet corn is not precooled than when the sweet corn is at the storage temperature but the storage room air is not saturated. For this example, the difference in humidity ratio between the air in the sweet corn and the storage air is over nine times more when the sweet corn is not precooled than when it is cooled and put in unsaturated storage air.

Drying of perishables in refrigerated storage is reduced by decreasing the difference in humidity ratio (vapor pressure) between air in the perishable commodity and air surrounding it. Total moisture loss is reduced by reducing the time of exposure to this difference in humidity ratio by cooling the product close to the surrounding air temperature as rapidly as possible and by maintaining the condition of the surrounding air as close to saturation as possible. Both the temperature of the commodity and humidity ratio in the surrounding air must be controlled. It is important that these variables be known (measured) so proper control actions can be implemented by managers.

### Relative Humidity

Relative humidity is a commonly used term for describing the humidity of the air but is not particularly meaningful without knowing the dry bulb temperature of the air. These two variables allow the determination of humidity ratio which is a better index of the potential for desiccation. For example as noted above, the humidity ratio of air at 80% RH and 0°C (32°) [Point D, Figure 3 and Figure 4 ] is much less than the humidity ratio of air at 80% RH at 20°C (68°F) [Point E, Figures 3 and 4]. In the example above, if the sweet corn were cooled to 10°C (50°F) [Point F, Figures 3 and 4] and the refrigerated air was at 0°C (32°F) and 100% RH [again Point A, Figures 3 and 4] , drying would also occur because the refrigerated air is at a lower humidity ratio than the saturated air in the sweet corn. Therefore 100% RH alone does not mean there is no moisture loss potential. To further illustrate that use of relative humidity alone can create confusion, consider a cold storage running at 2°C (35°F) and 100% RH [Point G, Figures 3 and 4] exposed to an outside air condition of 23°C (72°F) and 50% RH [Point H, Figures 3 and 4]. Considering % RH only, there is an apparent 2 to 1 moisture gradient from the storage room atmosphere outward toward the ambient conditions, while considering the humidity ratio, the actual moisture gradient is 2 to 1 from the ambient conditions inward toward the storage room atmosphere. Use of the psychrometric chart ascertains the direction of potential water vapor migration.

### Dew Point Temperature

Condensation of liquid water on perishables and on container surfaces can be a factor in causing disease problems and degradation of container strength. If a commodity is cooled to a temperature below the dew point temperature of the outside air and brought out of the cold room, condensation will form. This can occur when the product is exposed to ambient conditions between the precooler and the cold storage and the cold storage and refrigerated trucks.

Condensation on the perishables, containers, and walls of the storage room can also occur in storage if air temperatures fluctuate too greatly. Another form of condensation occurs in the storage room as the air in the room is circulated over the evaporator cooling coils of the refrigeration system. The temperature of the cooling coil is usually lower than the return air and the air is cooled below the dew point temperature; moisture condenses and is removed from the cold storage (drain pan). Unless moisture is added by a humidification system, the moisture condensed on the coils will be replaced by moisture from the product in storage. To reduce the moisture loss due to condensation on the cooling coils, the temperature difference between the return air and the coil must be reduced. This can be accomplished by using sufficiently large coil surface area. This will increase the cooling system cost but is the best way to maintain high humidity levels.

## Measurement of PsychrometricVariables

All psychrometric properties of air can be determined by measuring two psychrometric variables (three, if barometric pressure is considered). For example, if wet and dry bulb temperatures are measured, then relative humidity, humidity ratio (vapor pressure), dew point, and so on, can be determined with the aid of a psychrometric chart. While many variables can be measured to determine the psychrometric state of air, the most commonly measured are dry bulb temperature, wet bulb temperature, dew point temperature, and relative humidity.

### Wet Bulb Temperature

The use of a wet bulb thermometer in conjunction with a dry bulb thermometer is a very common method of determining the state point on the psychrometric chart. Such an instrument, called a psychrometer, consists of a pair of matched temperature sensors, one of which is maintained in a wetted condition. The wet bulb thermometer is basically an ordinary glass thermometer (although electronic temperature sensing elements can also be used) with a wetted, cotton wick secured around the reservoir. Air is forced over the wick causing it to cool to the wet bulb temperature. The wet and dry bulb temperatures together determine the state point of the air on the psychrometric chart allowing all other variables to be determined.

A psychrometer is a valuable instrument for evaluating the conditions inside a cold storage room. Several types of psychrometers are available from a number of agricultural and general supply catalogs. A sling psychrometer consists of the dry and wet bulb thermometers and a handle for rotating the psychrometer in order to provide the necessary air flow for adequate evaporation. Prices range from $50 to $200. A portable psychrometer replaces the handle with a battery powered fan and is available in the price range of $125 to $200.

An accurate wet bulb temperature reading is dependent on: (1) sensitivity and accuracy of the thermometer, (2) maintaining an adequate air speed past the wick, (3) shielding the thermometer from radiation, (4) use of distilled or deionized water to wet the wick, and (5) use of a cotton wick.

The thermometer sensitivity required to determine an accurate humidity varies according to the temperature range of the air. At low temperatures more sensitivity is needed than at high temperatures. For example, at 65°C (149°F) a 0.5°C (0.9°F) error in wet bulb temperature reading results in a 2.6 percent error in relative humidity determination but at 0°C (32°F) a 0.5°C (0.9°F) error in wet bulb temperature reading results in a 10.5 percent error in relative humidity measurements [8]. In most cases, absolute calibration of the wet and dry bulb thermometer is not as important as ensuring they produce the same reading at a given temperature. For example, if both thermometers read 0.5°C (0.9°F) low this will result in less than a 1.3 percent error in relative humidity at dry bulb temperatures between 65°C (149°F) and 0°C (32°F) when the difference between dry and wet bulb temperature readings is 5°C (9°F) [8]. Before wetting the wick of the wet bulb thermometer, both thermometers should be operated long enough to determine if there is any difference between their readings. If there is a difference and the thermometers must be used, one is assumed correct and the reading of the other adjusted accordingly when determining relative humidity.

The rate of evaporation from the wick is a function of air velocity past it. A minimum air velocity of about 3 m per sec (500 ft per min) is required for accurate readings. An air velocity much below this will result in an erroneously high wet bulb reading. Wet bulb devices that do not provide a guaranteed air flow, such as those that sit on a desk, cannot be relied on to give an accurate reading.

As with the dry bulb thermometer, sources of radiant heat such as motors, lights, and so on, will affect the wet bulb thermometer. The reading must be taken in an area protected from these sources of radiation or thermometers must be shielded from radiant energy.

A buildup of salts from impure water or contaminants in the air will affect the rate of water evaporation from the wick and result in erroneous data. Distilled or deionized water should be used to moisten the wick and the wick should be replaced if there is any sign of contamination. Care should be taken to ensure that the wick material has not been treated with chemicals such as sizing compounds that would affect the water evaporation rate.

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

## Relative Humidity

Direct relative humidity measurement usually employs an electric sensing element or a mechanical system. Electric hygrometers operate using substances whose electrical properties change as a function of their moisture content. As the humidity of the air surrounding the sensor increases, its moisture increases proportionally affecting the sensor's electrical properties. These devices are more expensive than wet and dry bulb psychrometers, but their accuracy is not as severely affected by incorrect operation. An accuracy of less than 2 percent of the actual humidity is often obtainable. Sensors will lose their calibration if allowed to become contaminated and some lose calibration if water condenses on them. Most sensors have a limited life. Relative humidity instruments are not recommended for use in the harsh conditions found in commercial packinghouses. Mechanical hygrometers usually employ human hairs as a relative humidity sensing element. Hair changes in length in proportion to the humidity of the air. The hair element responds slowly to changes in relative humidity and is not dependable at very high relative humidities.These devices are acceptable as an indicator of a general range of humidity but are not especially dependable for accurate relative humidity measurement.

## Dew Point Indicators

Two types of dew point sensors are in common use today: a saturated salt system and a condensation dew point method. The saturated salt system will operate at dew points between -12° to 37°C (10° to 100°F) with an accuracy of less than 1°C (2°F). The system is lower in cost than the condensation system, is not significantly affected by contaminating ions, and has a response time of about

4 minutes. The condensation type is very accurate over a wide range of dew point temperatures (less than 0.5°C (0.9°F) from -73° to 100°C (-100° to 212°F). A condensation dew point hygrometer can be expensive.

There are a variety of other methods for measuring psychrometric variables [2]. Some are extremely accurate and have some characteristics which make them suited to particular sampling conditions. However, most are not commercially available and are used primarily as laboratory instruments.

## Summary

The use of the psychrometric chart and the relationship of psychrometric variables and their effect on perishable commodities were presented. This article further suggests how the psychrometric variables can be measured and used -- more importantly how they should be used by vegetable producers, packinghouse operators, and commercial cooler managers. A better understanding of psychrometrics will allow vegetable growers, packinghouse operators, and commercial cooler operators to improve postharvest cooling and storage conditions for fresh vegetables. A $500 investment in a simple, reliable, and accurate hand-held thermocouple thermometer and portable psychrometer and use of a psychrometric chart will allow the determination of all the psychrometric variables needed to properly control the ambient environment within precoolers and cold storage rooms. Proper use of these tools will allow the managers to correct problems (such as high temperatures and low moisture levels) and maintain the quality and reduce the spoilage of their valuable perishable commodities.

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