Psychrometric Chart Celebrates 100th Anniversary

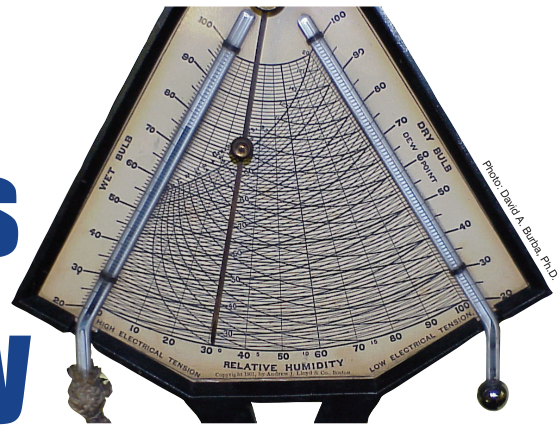

Photo: David A. Burba, Ph.D.

Hygrodeik wet and dry-bulb hygrometer.
Vanderbilt University Garland Collection.

By Donald P. Gatley, P.E., Fellow/Life Member ASHRAE

What is psychrometrics? One Web site calls it the dreaded "P-word!" Psychrometrics is a subscience of physics dealing with the properties and processes of moist air. Moist air is defined as a mixture of two gases: dry air and water vapor (the gas phase of H_2O).[1] Some broaden the definition of psychrometrics to cover mixtures of the gas of one substance (any dry gas component) and the condensable vapor of a second substance. Psychrometrics is not confined to the world of air conditioning. It is used in the fields of agricultural and aeronautical engineering, food engineering, drying of crops, grains, and pharmaceuticals, dehydration, dehumidification, humidification, moisture control, meteorology, and weather reporting.

A Simple Tool

"At first glance a psychrometric chart appears ominous with its myriad of tiny lines crisscrossing in every direction. Actually, once understood, this apparent complexity is readily dismissed and the psych chart can become a relatively simple and invaluable design tool." (Circa 1950) — Julian R. Fellows, emeritus professor of mechanical engineering, University of Illinois.

This article looks at the state-of-the art of psychrometrics prior to 1904 when Willis H. Carrier produced the first chart and then traces the developments from 1904 to 2004.

The Psychrometric Chart

So what is a psychrometric chart and why would anyone want to use it? The psychrometric chart is a convenient and useful tool for (1) determining moist air psychrometric properties, and (2) visualizing the changes of properties in a sequence of psychrometric processes; e.g., (a) as the outside and return air mixes, (b) proceeds through heating and cooling coils, (c) the supply fan, (d) supply duct, and on to (e) the conditioned space.

Prior to the advent of personal computer psychrometric software, the psychrometric chart also was used extensively as an extremely useful graphical tool for solving and diagnosing and then visualizing psychrometric processes. Younger air-conditioning designers may have difficulty visualizing the tasks of the designer in pre-1960 when handheld calculators and PCs did not exist. Most calculations were performed manually or with a slide rule, or perish the thought, with a table of logarithms. Some engineers were lucky when a group of 10 shared a noisy Frieden™ calculator. Designing systems and solving problems using the "psych" chart was a time-saving blessing—not a chore.

By 1990 approximately 75% of practitioners used the psychrometric chart

About the Author

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Measurable Psychrometric Properties

Description	Symbol	SI Unit	I-P Unit
Dry-Bulb Temp.	t_{DB}	°C	°F
Wet-Bulb Temp.	t_{WB}	°C	°F
Dew-Point Temp.	t_{DP}	°C	°F
Relative Humidity	*RH*	%	%
Barometric Pressure	P_{BAR}	Pa	in. H_G or psia

Calculable Psychrometric Properties

Description	Symbol	SI Unit	I-P Unit
Specific Enthalpy	*h*	kJ/kg_{DA}	Btu/lb_{DA}
Specific Volume	*v*	m^3/kg_{DA}	ft^3/lb_{DA}
Humidity Ratio	*w*	kg_{wv}/kg_{DA}	lb_{wv}/lb_{DA}
Water Vapor Pressure	p_{wv}	Pa	in. H_G or psia

Table 1: Nine of the most common psychrometric properties.

James Apjohn	**J.F. Daniell**	**Charles LeRoy**
Ludwig Achim von Arnim	**Francesco Eschinardi**	**John Leslie**
Richard Assman	**James Pollard Espy**	**Charles F. Marvin**
Ernest Ferdinand August	**Gabriel Daniel Fahrenheit**	**Edme Mariotte**
Amedeo Avogadro	**William Ferrel**	**Sir Isaac Newton**
Carl Wilhelm Böckman Jr.	**Joseph Louis Gay-Lussac**	**Blaise Pascal**
Robert Boyle	**James Glaisher**	**Joseph Priestly**
Auguste Bravais	**James Hutton**	**Henri Victor Regnault**
Anders Celsius	**James Ivory**	**Horace Bénédict de Saussure**
Jacques Alexander Cèsar Charles	**Julius Juhlin**	**C.W. Scheele**
John Dalton	**Antoine Laurent de Lavoisier**	**Evangèlista Torricelli**

Table 2: Partial listing of psychrometric pioneers prior to 1900.

as a tool in solving psychrometric problems and the rest used computer software. In the first decade of the 21st century most practitioners rely on psychrometric software based on ideal-gas algorithms (with 99% or greater accuracy). As a secondary function most software programs generate a psychrometric chart showing the state points and the psychrometric process lines connecting the state points. The displayed state point properties either will be original data entries or the results of accurate calculations, not the result of graphical plotting.

The demise of printed psychrometric charts will probably be similar to the demise of the slide rule (replaced by the handheld calculator), and the log-log and other special plotting papers (replaced by plotting capabilities of spreadsheet software). It is only a matter of time before the once-familiar pads of psychrometric charts from ASHRAE and air-conditioning and dehumidification manufacturers will no longer be available. Put a collection away for your grandchildren (someday they may have the value of baseball cards of the 40s and 50s).

What Preceded Carrier's 1904 Psychrometric Chart?

Table 1 lists nine of the most used psychrometric properties. Thanks mainly to the field of meteorology, these properties were already in use in the 1850 to 1900 era because of a host of individuals listed in *Table 2*.

Prior to 1900, tables of empirical psychrometric property values were used by meteorologists. In 1847 Glaisher's Hygrometrical Tables were the first reliable tables listing water-vapor pressure; barometric pressure; stationary wet-bulb, dry-bulb, and dew-point temperature; relative humidity, water-vapor density (in grains and pounds per cubic foot), and the additional quantity of H_2O required for complete saturation. Part of Glaisher's data was empirical and based on two years of observations of these properties at Greenwich, England. Glaisher may not have been aware that stationary wet-bulb temperature varied widely because it was dependent not only on two other properties but also the velocity of natural (and quite variable) air currents across the (stationary) wet-wick-covered-thermometer bulb.

In 1886 the American meteorologist William Ferrel developed an improved empirical formula for computing water vapor pressure from dry-bulb and sling-psychrometer-wet-bulb temperature and barometric pressure. Starting in 1886 the U.S. Weather Bureau used Ferrel's formula, his tables, and the sling (whirled) psychrometer to achieve greater accuracy compared with Glaisher's tables and stationary wet-bulb temperature. Improved tables were prepared for the bureau in 1900 by Professor Marvin. Willis Carrier probably had a copy of "Marvin's Psychrometric Tables for Obtaining the Vapor Pressure, Relative Humidity, and Temperature of the Dew Point (from readings of the Wet- and Dry-Bulb Thermometers)," U.S. Department of Commerce Weather Bureau Publication No. 236.

The only psychrometric-like charts prior to Carrier's 1904 chart were cross plots of the Glaisher or Ferrel empirical tabular data. A picture of a stationary wet-bulb–dry-bulb instrument called a Hygrodeik (patented in 1865) appears on the title page.

Willis H. Carrier
President ASRE 1927
President ASHVE 1931

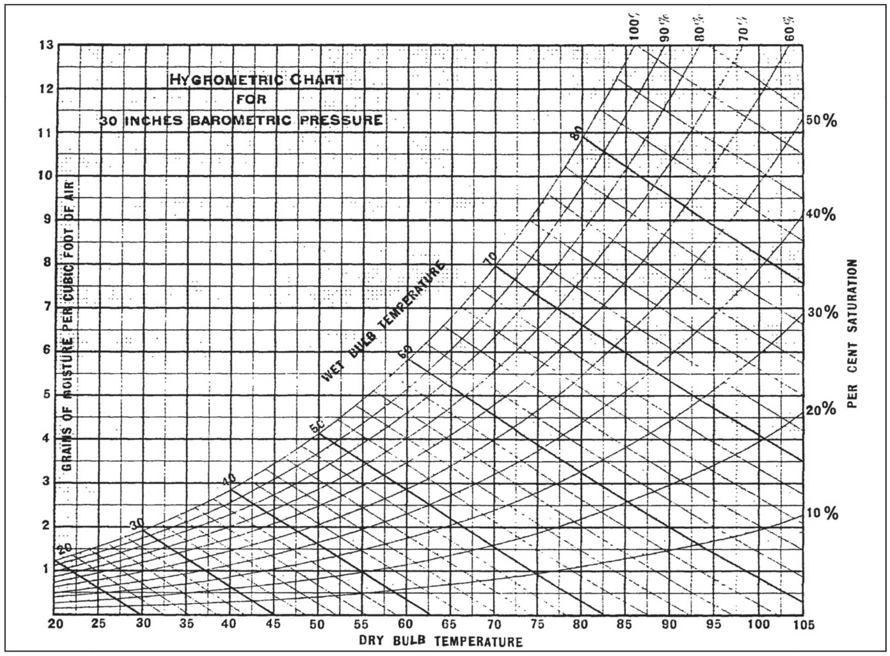

Figure 1: Willis H. Carrier hygrometric chart, circa 1904–1906.

A chart mounted between the two thermometers included wet-bulb, dry-bulb, and dew-point temperature, relative humidity, and the moisture content in units of grains per cubic foot (Note that 7,000 grains = 1 lb). In addition the chart designated the region to the left of the 60% RH line as high electric tension and to the right as low electric tension.

State-of-the-Art in 1901

For starters, the term air conditioning did not exist until 1906 when it was coined by Stuart Cramer, a Charlotte, N.C., textile engineer.

The physical and chemical laws governing many of the phenomena applicable to the atmosphere and the variable quantity of water vapor associated with the dry air gases of the atmosphere were only partially understood. The ideal gas constant, Joule's equivalent between heat and work, the molar mass of air, the molar mass of H_2O, the specific heat of dry air, and the specific heat of water vapor were not as accurate as they are today.

Some of the psychrometric tabular data were based on examinations of recorded weather data over a period of several years. Surprisingly, thanks to dedicated meteorologists like Glacier and Ferrel, the data turned out to be fairly accurate, although it only covered a limited temperature range.

1904 Carrier Psychrometric Chart

By 1903 Carrier had completed the world's first scientifically based air-conditioning system specifically designed to control humidity. This required estimates of space heat and moisture gain and psychrometric properties of moist air. In 1904, to simplify the task of air-conditioning design, he graphed the data from Marvin's tables. This resulted in the basic psychrometric chart shape as we know it today. *Figure 1* is a similar chart to a 1906 Buffalo Air Washer and Humidifier catalog. Carrier called it a hygrometric chart, and discussion in the catalog indicated that it was drawn in 1905. L. Logan Lewis, a coworker, indicated that the 1905 chart was similar to a much larger blueprint version of the chart made in 1904.[2] Carrier's early charts used water vapor density (grains_WV/ft^3) as the ordinate. Water vapor density is directly proportional to water vapor pressure, which may have simplified the task of creating the first chart.

Carrier's choice of plotting coordinates made this chart nearly ideal for the analysis and plotting of air-conditioning applications. Dry-bulb temperature lines were vertical with a uniform scale along the abscissa. The horizontal lines of the chart represent moisture content expressed in the common units of the era, grains of moisture per cubic foot of air. The moisture content scale is uniform along the left ordinate of the chart. Also shown are percent saturation (now called relative humidity) curves from 10% to 100% and psychrometer wet-bulb lines in 5°F increments.

Psychrometric Chart from 1904 to 1911

Between 1908 and 1911, the ordinate was changed to what is now called humidity ratio (lb_{WV}/lb_{DA} or $grains_{WV}/lb_{DA}$), which was more useful. Humidity ratio is also called moisture content and some European practitioners call this value *humidity x*. To add confusion, this term is sometimes called specific humidity or absolute humidity despite the fact that the World Meteorological Organization, ASHRAE and most dictionaries define these terms differently than humidity ratio. Carrier called this property specific humidity, but this was before scientists redefined the term.

The change to humidity ratio (as the chart ordinate) added these features: (a) psychrometric process lines representing

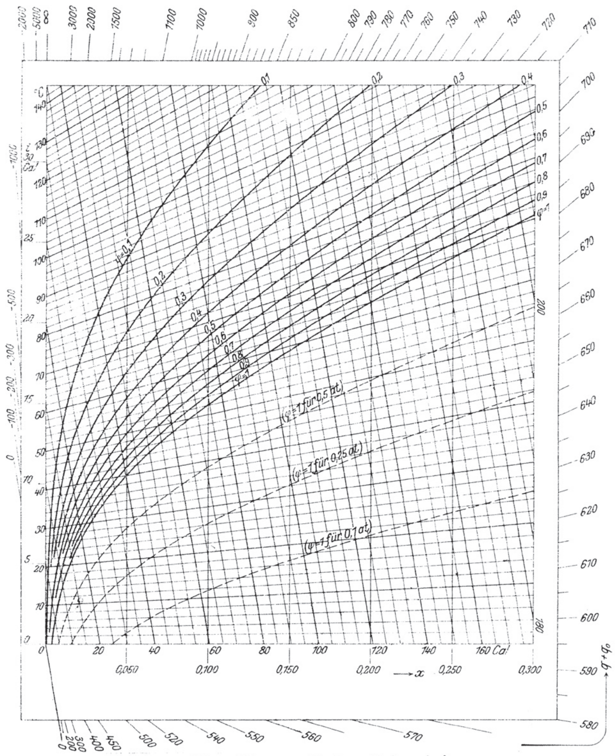

Abb. 1. Diagramm für Dampfluftgemische.

Figure 2: Mollier chart (circa 1923) was one of the early psychrometric charts.

sensible heating or sensible cooling are horizontal lines at constant moisture content (these lines were slightly curved and nearly horizontal with the former water vapor density ordinate); and (b) the process lines representing humidification only (latent heating) or dehumidification only (latent cooling) are vertical lines at constant dry-bulb temperature. These features work well with space heat gain and heat loss “load” calculations, which are separated into sensible and latent components.

As he pursued psychrometrics, Carrier observed that the empirically determined wet-bulb temperature in Marvin’s tables agreed substantially with his calculated temperature of adiabatic saturation, (now more commonly called thermodynamic wet-bulb temperature, which is frequently shortened to wet-bulb temperature). Thermodynamic wet-bulb temperature as contrasted with sling psychrometer wet-bulb temperature is a thermodynamic property that is a mathematical function of other psychrometric properties.

Carrier probably originated the concept of the adiabatic saturation chamber, which in simple terms is a very long (think infinite) perfectly insulated watertight air duct with a layer of liquid water in the bottom of the level air duct. Entering air with a relative humidity (RH) less than 100% traverses the length of the duct exposed to the surface of water and leaves the duct at 100% RH (the leaving air is saturated with water vapor), and as a consequence, the leaving dry-bulb temperature, thermodynamic wet-bulb, and dew-point temperature have the same value.

One other condition is that the temperature of the water in the duct is at the wet-bulb temperature of the leaving air. The apparatus is perfectly insulated and, thus, there is no heat gain or heat loss to or from the air passing through the duct or the water in the duct and, hence, the name adiabatic (Greek for without transfer of heat to or from the surroundings).

If air is passed through the duct for a long period of time, it will be necessary to replenish the water that has evaporated into the passing air.

Discerning Types Of Charts

For those who want to know if a particular chart uses a dry-bulb temperature major coordinate or a skewed specific enthalpy major coordinate, the easiest test is to observe two vertical dry-bulb temperature lines that are separated by 30° or 40°.

If the lines diverge slightly as they extend upwards, then the major coordinate is specific enthalpy.

If all dry-bulb temperature lines are precisely parallel, the major coordinate is dry-bulb temperature.

With software, all calculations are performed using psychrometric algorithms, and the resultant state points are plotted on a displayed chart. Many software-generated charts use vertical dry-bulb temperature lines to improve the speed and to avoid slightly jagged lines. No advantage or disadvantage exists for one software display over another because the display is no longer a calculation tool but just a very good way to visualize the psychrometric processes or cycles.

Carrier also observed in tests that the wet-bulb temperature of the air remained constant from the entry to the exit of the adiabatic saturator as more water vapor entered the air passing along the length of the saturator.

Mass and energy balances reveal that the sensible cooling of the air is equal to the latent heat gain of the air, which is the product of the mass of water evaporated and the latent heat of evaporation at the wet-bulb temperature. Carrier, using low pressure steam (water vapor) property tables and knowing barometric pressure, the adiabatic saturator entering dry-bulb temperature, and thermodynamic wet-bulb temperature could then calculate all other entering psychrometric properties.

Willis Carrier and his associates continued their psychrometric research for the remainder of his life (1876-1950). In 1911 Carrier shared his early research and developments with the rest of the world in his landmark 49-page ASME paper No. 1340: Rational Psychrometric Formulae.

Chart from 1911 to 2004

In the 100 years since the first Willis Carrier chart, the science of psychrometrics has progressed from its infancy to a very mature science. Many changes have been made to the chart to improve its usefulness, accuracy and the accuracy of process plots on the chart.

Through all of these changes, the chart has retained its basic and familiar form—a testimony to the foresight of its creator.

ASHVE initially adopted the Carrier chart until 1926 when it changed to the Bulkely log scale psychrometric chart. In 1938, ASHVE returned to the Carrier-style chart.

A subtle change to increase the accuracy of process plots and calculations is the use of a skewed specific enthalpy[3] scale to replace the dry-bulb temperature plotting coordinate. This resulted in perfectly straight wet-bulb temperature and enthalpy lines which formerly had a very slight curvature. The dry-bulb temperature lines are perfectly straight, but diverge slightly from one another as the moisture content increases. In 1963 the new ASHRAE psychrometric charts changed to the humidity ratio—skewed enthalpy coordinates.[4]

This wraps up the history of the first psychrometric chart. To view 20 other historical charts including the 1908 Grosvenor chart, the 1923 Mollier chart, and the other early psychrometric charts, see Note 1, *Understanding Psychrometrics*. These early charts range from those significantly stretched in one or both directions, to those using log scales and even include two triangular shaped charts.

The author has yet to see a circular chart, but on second thought, the 1862 chart on the title page used 60° of a circle with the RH lines radiating from the center at 6° for every 10% change in RH.

Notes

1. Gatley, Donald P. 2002. *Understanding Psychrometrics*. 292 p. Atlanta: ASHRAE.
2. Wile, D.D. 1960. "Psychrometric charts." *ASHRAE Journal* p. 61. March.
3. The use of a skewed plotting coordinate or grid was conceived by Richard Mollier in 1923 in "Ein neues Diagramm für Dampfluftgemische," in which he introduced the "*h x*" moist air chart (*h* is Mollier's symbol for enthalpy; *x* his symbol for humidity ratio). Some engineers, scientists and meteorologists of Northern and Eastern European Countries use the Mollier *h x* Enthalpy – Humidity Ratio chart. This Mollier moist air chart differs from the ASHRAE chart as follows: humidity ratio is the abscissa (vertical grid with horizontal scale) and enthalpy is the skewed grid with vertical scale. The accuracy of the two charts is identical. An ASHRAE chart can be "seen" as a Mollier *h x* chart by rotating it 90° counterclockwise, and observing the image in a mirror.
4. Palmatier, E.P. 1963. "Construction of the normal temperature ASHRAE psychrometric chart." *ASHRAE Transactions* 69:7–12.