CHAPTER 2
PSYCHROMETRICS

2-1. Introduction

Predominantly, environmental control means control of the aerial environment. The fluid of interest is moist air, and the study of moist air is psychrometrics. Part of psychrometrics deals with methods to determine moist air properties at known states and part deals with determining properties at an unknown state after a defined change from a known state – the study of psychrometric processes.

Standard applications of gas laws can be found in basic physics and thermodynamics texts. Boyle's law, Charles' law, Dalton's law, and the perfect gas law apply with sufficient accuracy to atmospheric air to be acceptable for most environmental control applications. Errors introduced by assuming air acts as a perfect gas are generally less than 1%.

$345 \cdot \frac{44}{289645}$

Dry air is defined as the state of air when all moisture and contaminants (pollutants, dust, etc.) have been removed; its composition is effectively constant. Carbon dioxide shows a seasonal and geographic variation and a long-term trend upward but today averages approximately 345 ppm (527 mg/kg). (Before the Industrial Revolution, the atmospheric carbon dioxide level is estimated to have been approximately 270 ppm.) The apparent molecular weight of standard dry air is 28.9645 based on a weighted average of all components. Its gas constant is 287.055 J/kgK. Dry air is heavier than water vapor and lighter than carbon dioxide. The gas constant of water vapor is 461.52 J/kgK and water's molecular weight is 18.01534.

Standard conditions are frequently chosen for psychrometric calculations. The Standard Atmosphere is a typical choice; the Standard Atmosphere is at 15 C temperature and 101.325 kPa pressure, which is sea level. Standard conditions for other elevations are in Table 2-1.

Table 2-1. Properties of the standard atmosphere at various elevations.

Elevation above Sea Level, m	Temperature, Celsius	Pressure, Pa
-500	18.2	107,478
0	15.0	101,325
500	11.8	95,461
1000	8.5	89,874
2000	2.0	79,495
3000	-4.5	70,108
4000	-11.0	61,640
5000	-17.5	54,020

(adapted from the ASHRAE Handbook of Fundamentals, 1989)

2-2. Psychrometric Properties

Moist air is a mixture of dry air and water vapor. Numerous properties describe the state of air and its degree of saturation with water vapor. In most cases, knowledge of two of the properties permits determination of the others.

2-2.1. Dry-Bulb Temperature. The reference for specifying ordinary air temperature is dry-bulb temperature – the temperature sensed by an ordinary thermometer at thermal equilibrium with air.

2-2.2. Water Vapor Saturation Partial Pressure. The greatest amount of moisture which can be held by dry air occurs at saturation, defined as the state of equilibrium between moist air and free water on a flat surface. The air and water must be at the same temperature – the temperature at which water would boil were it at a pressure equal to the water vapor saturation partial pressure. If water vapor partial pressure is less than the water vapor saturation partial pressure at the same temperature, the vapor is superheated.

Dry-bulb temperature determines the water vapor saturation partial pressure, p_{ws}. The water vapor saturation partial pressure can be determined (in Pa) from the following for temperatures, T, in Kelvin:

$$\ln(p_{ws}) = A_1 / T + A_2 + A_3T + A_4T^2 + A_5T^3 + A_6T^4 + A_7\ln(T). \quad (2\text{-}1)$$

In the dry-bulb temperature range from -100 to 0 C, water vapor saturation of air is over ice and the coefficients of Equation 2-1 have the following values:

A_1 = -5.6745359 E + 03
A_2 = 6.3925247 E + 00
A_3 = -9.677843 E - 03
A_4 = 0.6221570 E - 06
A_5 = 2.0747825 E - 09
A_6 = -0.9484024 E - 12
A_7 = 4.1635019 E + 00

Over water, in the temperature range from 0 to 200 C, coefficients to calculate water vapor saturation partial pressure are:

A_1 = -5.8002206 E + 03
A_2 = 1.3914993 E + 00
A_3 = -48.640239 E - 03
A_4 = 41.764768 E - 06
A_5 = -14.452093 E - 09
A_6 = 0.0
A_7 = 6.5459673 E + 00

A graph of water vapor saturation partial pressure based on Equation 2-1 is in Figure 2-1.

2-2.3. Relative Humidity. The actual partial pressure of water vapor in moist but unsaturated air, p_w, is related to the property of air called the relative humidity, ϕ, where

$$\phi = p_w / p_{ws} \qquad (2\text{-}2)$$

and where the partial pressure of the water vapor and its partial pressure at saturation are defined at identical temperatures and atmospheric pressures. Relative humidity is a measure of the degree to which air is saturated, for ϕ equals 0.0 for dry air and 1.0 when air is completely saturated.

Relative humidity also equals the mole fraction, x, of water vapor in a given air sample divided by the mole fraction were the air to be saturated at the same temperature and pressure,

$$\phi = x_w / x_{ws}. \qquad (2\text{-}3)$$

2-2.4. Humidity Ratio. A second measure of the water vapor content of air is the humidity ratio, W, which is the mass of water vapor evaporated into a unit mass of dry air, kg/kg. The ratio of molecular masses of water vapor and (averaged) air is 18.01534 / 28.9645 = 0.62198. Thus,

$W = \frac{m_w}{m_a} = \frac{n_w \cdot M_w}{n_a \cdot M_a}$

$$W = 0.62198 x_w / x_a. \qquad (2\text{-}4)$$

If air and water vapor are assumed to act as perfect gases,

$$p_a V = n_a RT, \qquad (2\text{-}5)$$

$$p_w V = n_w RT, \text{ and} \qquad (2\text{-}6)$$

$$pV = nRT, \qquad (2\text{-}7)$$

where p is atmospheric pressure ($p = p_a + p_w$) and n is the number of moles of moist air ($n = n_a + n_w$).

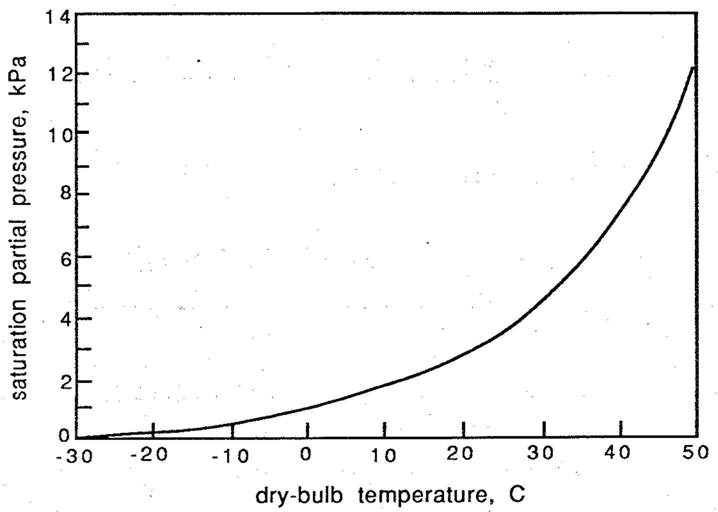


FIGURE 2-1. Water vapor saturation pressure, kPa, as a function of temperature, Celsius.

Thus,

$$x_a = p_a / p; \; x_w = p_w / p; \qquad (2\text{-}8)$$

and

$$W = 0.62198 \; \frac{P_w}{P_a}$$

$$P_w = \frac{P \cdot w}{0.62198 + w}$$

$$W = 0.62198p_w / (p - p_w);$$
$$W_s = 0.62198p_{ws} / (p - p_{ws}). \qquad (2\text{-}9)$$

If dry-bulb temperature, atmospheric pressure, and relative humidity are known, the humidity ratio can be calculated. The equations can also be used to calculate relative humidity if dry-bulb temperature, atmospheric pressure, and humidity ratio are known. This is frequently useful in environmental control calculations, as shall be seen.

Example 2-1

Problem: Moist air at standard atmospheric pressure is at 20 C dry-bulb temperature and 50% relative humidity. What is the humidity ratio of the air?

Solution: The humidity ratio is calculated from the partial pressure of the water vapor which can be obtained knowing the dry-bulb temperature and relative humidity.

From Equation 2-1 for a dry-bulb temperature of 293.15 K, the water vapor saturation partial pressure is

$$\begin{aligned} p_{ws} = {} & \exp(-5.8002206E + 03/293.15 + 1.3914993 \\ & - (48.640239E - 03)(293.15) + (41.764768E - 06)(293.15)^2 \\ & - (14.452093E - 09)(293.15)^3 + 6.5459673 \ln(293.15)) \\ = {} & \exp(7.757) = 2339 \text{ Pa}. \end{aligned}$$

By the definition of relative humidity, Equation 2-2, the actual partial pressure of the water vapor is

See

$$p_w = \phi p_{ws} = (0.50)(2339) = 1169 \text{ Pa} = 1.169 \text{ kPa}. \qquad (2\text{-}10)$$

ex2-2 The humidity ratio for an atmospheric pressure of 101.325 kPa is

for

$$W = 0.62198(1.169) / (101.325 - 1.169) = 0.00726 \text{ kg/kg}$$

Ws

2-2.5. Psychrometric Chart. Dry-bulb temperature and humidity ratio form the x and y axes of the psychrometric chart, a graph which can be used to determine many of an air sample's psychrometric properties if two of its properties are known. An outline of the psychrometric chart is in Figure 2-2.

Two standard psychrometric charts for sea level conditions are in Figures 2-3 and 2-4. (Charts for elevations above sea level are also available as engineering resources.) Dry-bulb temperature is the ordinate; humidity ratio is the abscissa. These two scales are divided evenly which makes scales for other psychrometric properties nonlinear. Copies of the chart are available from ASHRAE, the American Society of Heating, Refrigerating, and Air Conditioning Engineers.

The line of water vapor saturation defines the upper boundary of the psychrometric chart, and lines of constant relative humidity parallel the saturation line. (Note: The degree of saturation and water vapor partial pressure are not on the psychrometric chart and must be calculated if needed.)

Although emphasis in this text will be on using equations and a computer for psychrometric calculations, it is necessary also to be able to use the psychrometric chart. Consider again Example 2-1, air at sea level contains a dry-bulb temperature of 20 C and relative humidity of 50%. These conditions are found on Figure 2-3 – normal temperatures. When the intersection of the two given conditions is located on the chart, and a horizontal line is followed to the abscissa, a humidity ratio of approximately 0.0073 kg/kg is found.

Note that although dry-bulb temperature and humidity ratio form the x and y axes of the psychrometric chart, the independent variables used to graph the chart in the Mollier form are humidity ratio and enthalpy. One result of this is that lines of constant dry-bulb temperature are neither parallel to each other nor perpendicular to the x axis. Other forms of the psychrometric chart can be found which are graphed using other independent variables, but the Mollier form is the ASHRAE standard. Fewer thermodynamic approximations are required when the chart is drawn in this form.

2-2.6. Degree of Saturation. Relative humidity was defined as the ratio of partial vapor pressures and is a measure of the extent to which air is saturated with water vapor. The degree of saturation, μ, is a separate means to describe

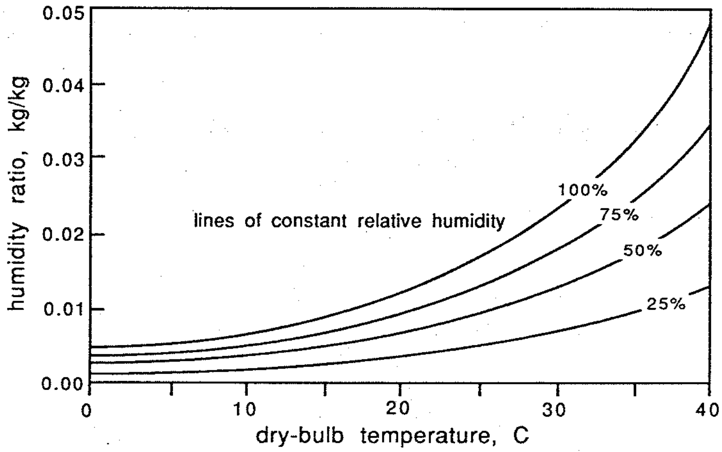
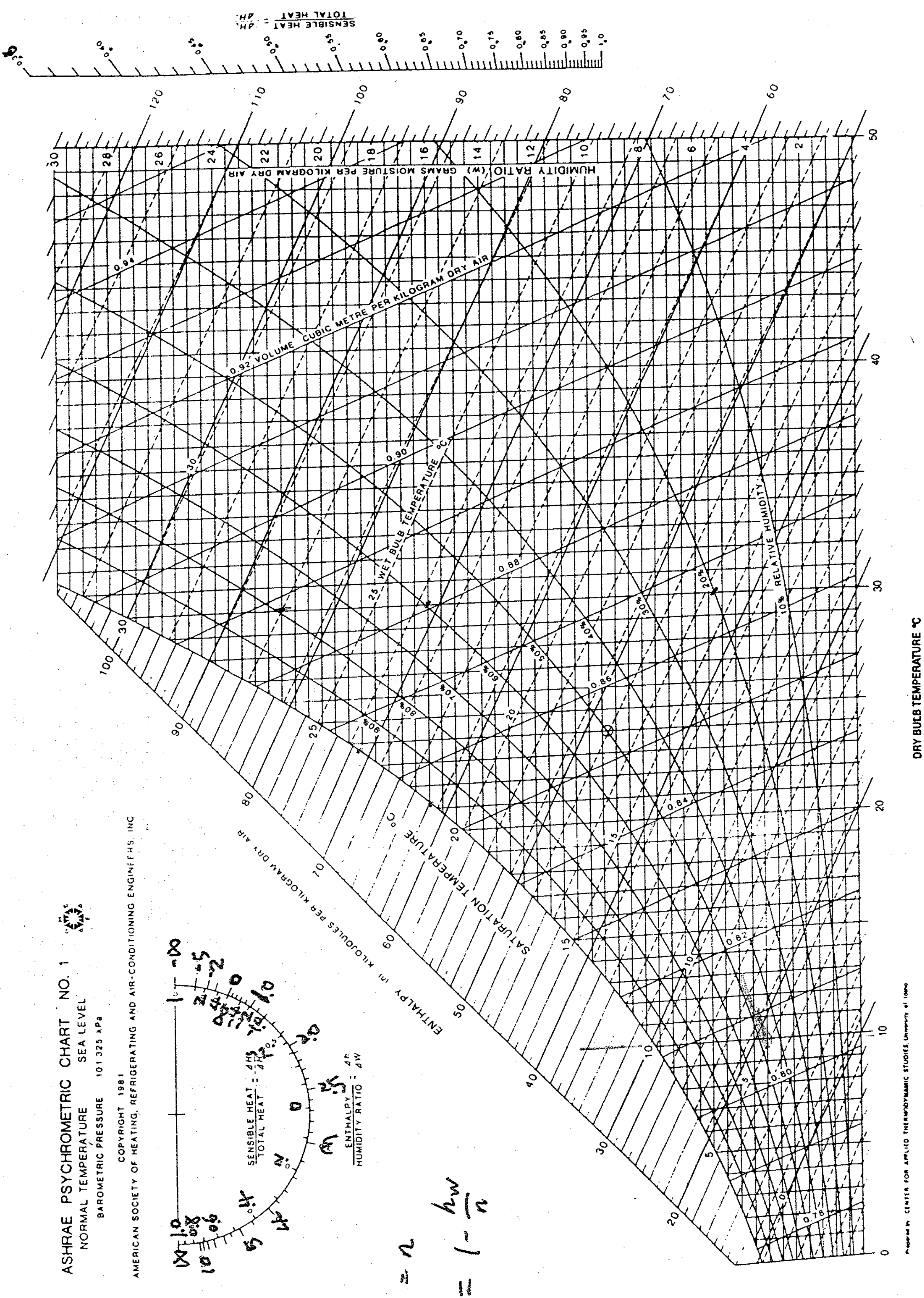


Figure 2-2. Basic psychrometric chart showing lines of constant relative humidity.



$+ \frac{m_w h_w}{m_w} =$ 外/[illegible] $= n$

$\frac{Q_s}{+ m_w h_w} =$ 内/[illegible] $= 1 - \frac{h_w}{n}$

Figure 2-3

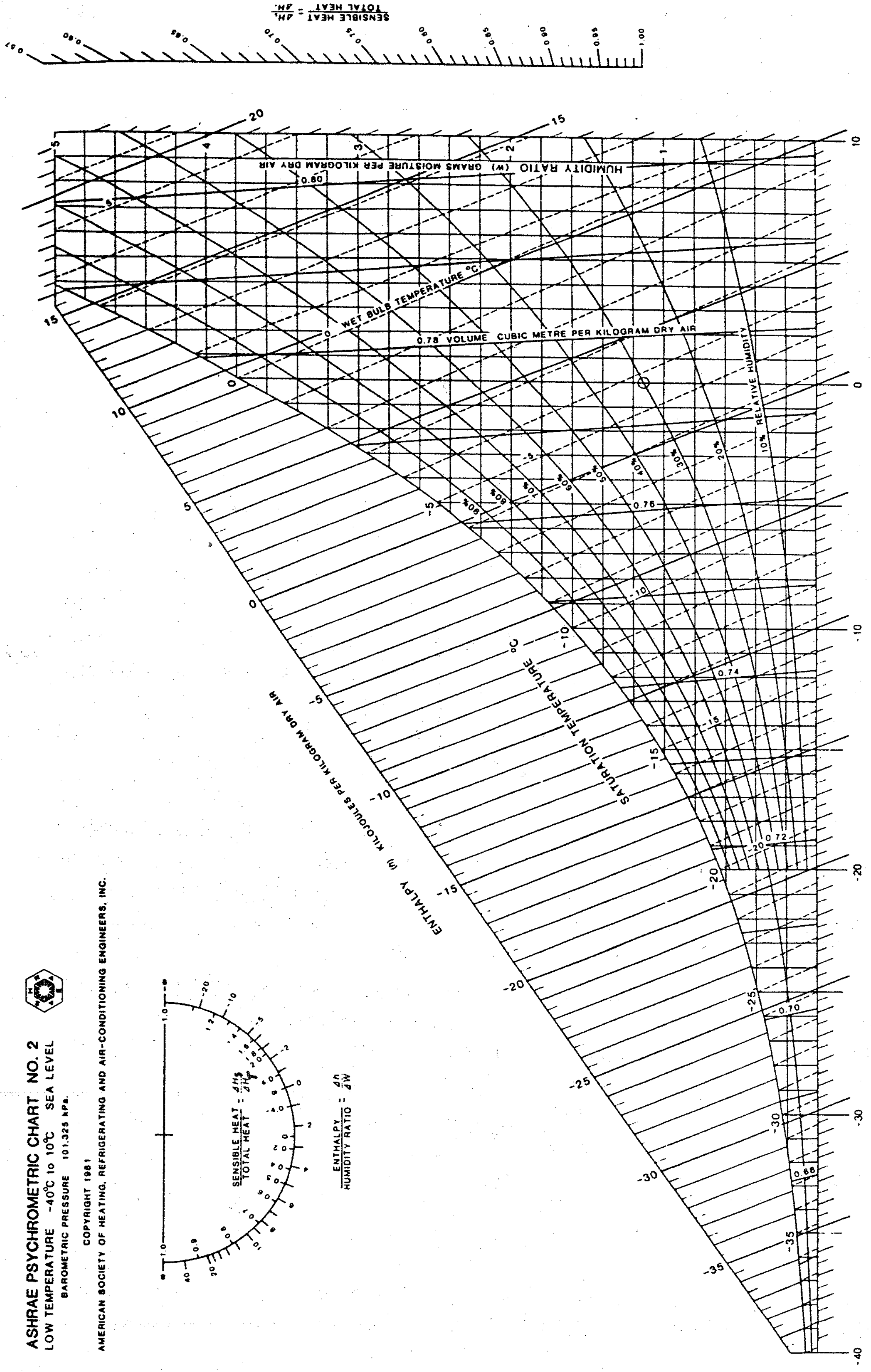

ASHRAE PSYCHROMETRIC CHART NO. 2
LOW TEMPERATURE -40°C to 10°C SEA LEVEL
BAROMETRIC PRESSURE 101.325 kPa
COPYRIGHT 1981
AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.
SENSIBLE HEAT / TOTAL HEAT = ΔHs / ΔHt
ENTHALPY / HUMIDITY RATIO = Δh / ΔW
HUMIDITY RATIO (W) GRAMS MOISTURE PER KILOGRAM DRY AIR
WET BULB TEMPERATURE °C
VOLUME CUBIC METRE PER KILOGRAM DRY AIR
RELATIVE HUMIDITY
SATURATION TEMPERATURE °C
ENTHALPY (h) KILOJOULES PER KILOGRAM DRY AIR
0.78
0.76
0.74
0.72
0.70
0.68
0.80
10%
20%
30%
40%
50%
60%
70%
80%
90%
10
0
-10
-20
-30
-40
5
4
3
2
1
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
0.57
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00

Figure 2-4

the extent of saturation. It is defined as

$$\mu = W / W_s \tag{2-11}$$

which is not the same as relative humidity. The two are related by

$$\phi = \mu / (1 - (1 - \mu)(p_{ws} / p)), \text{ and} \tag{2-12a}$$

$$\mu = \phi\,(1 - p_{ws} / p) / (1 - \phi p_{ws} / p). \tag{2-12b}$$

The degree of saturation and relative humidity are equivalent for dry air and saturated air, but they differ at intermediate moisture contents because of the nonlinear relationship between humidity ratio and water vapor partial pressure.

Example 2-2

Problem: To continue the example of air at 20 C and 50% relative humidity, determine the degree of saturation of the air.

Solution: The water vapor saturation partial pressure was calculated as 2.339 kPa and the actual water vapor partial pressure as 1.169 kPa. For the Standard Atmosphere, W was previously calculated as 0.00726 kg/kg. Equation 2-9 can be used again to find

$$W_s = 0.62198(2.339) / (101.325 - 2.339) = 0.01470 \text{ kg/kg},$$

and by Equation 2-11, the degree of saturation, 0.494, is slightly different from the relative humidity. To complete the circle, Equation 2-12a yields a relative humidity value of 0.5.

2-2.7. Specific Volume and Density. A physical property of moist air useful for environmental calculations is density, ρ, or its inverse, specific volume, v. Specific volume is based on a unit mass of dry air, thus,

$$v = V_a / M_a = V / (28.9645\, n_a) \tag{2-13}$$

The perfect gas relationship, with $p = p_a + p_w$, leads to

$$v = \frac{R_a T}{p_a} \Rightarrow v = R_a T / (p - p_w) = \frac{1}{p} R_a T \cdot \frac{1}{\left(1 - \frac{p_w}{p}\right)} = \frac{R_a T}{p} \cdot \frac{p}{p - p_w} = \frac{R_a T}{p} \tag{2-14}$$

$= \frac{R_a T}{p} \cdot ($

which, when combined with the definition of the humidity ratio, provides the following computational equation for specific volume of dry air, and through its inverse, density:

$=$

$$v_{\text{dry air}} = (1 / p) R_a T (1 + 1.6078\, W). \tag{2-15}$$

$\frac{R_a T}{p}(1+$

式 2-4, $W = 0.62198 \frac{K_w}{K_a}$

Note: In psychrometric equations, specific quantities are based on a unit mass of dry air, so, although units of v are in m^3/kg dry air, this is volume of moist air per unit mass of dry air. Dry air forms the basis of specific quantities because it is unchanged as the humidity changes during a psychrometric process. The value of specific volume used for environmental control calculations is typically based on moist air. Correcting the specific volume of dry air to the specific volume of moist air leads to

$V_{dry\ air}$ || $V_{moist\ air}$

dry air's gas constant = 287.055 J/kgK.

$v_{dry\,air} \cdot 1^{kg} = v \cdot (1+w)$

$$v = ((1 / p)R_aT(1 + 1.6078\ W)) / (1 + W). \tag{2-16}$$

$\frac{V}{M}$

The psychrometric chart includes specific volume of moist air as a parameter. Steep, diagonal lines from upper left to lower right define specific volume. Air density, ρ, is its reciprocal. Note: In Equations 2-15 and 2-16, atmospheric pressure is in pascals not kilopascals.

Example 2-3

Problem: For the previous example of 20 C and 50% relative humidity, the psychrometric chart shows a specific volume of approximately 0.84 m^3/kg. Determine the specific volume of the moist air using psychrometric equations instead.

Solution: Applying Equation 2-16 yields the following estimate of specific volume of the moist air:

$$v = \frac{(1/101{,}325)(287.055)(293.15)(1 + (1.6078)(0.00726))}{1 + 0.00726}$$
$$= 0.83\ m^3/kg.$$

2-2.8. Dew Point Temperature. When moist air is cooled sufficiently, water vapor condenses. Rain, snow, fog, and dew are formed this way. The temperature at which condensation occurs is the dew point temperature, t_d. When the state of air is below the saturation line on the psychrometric chart (as it is in normal situations), the dew point temperature is less than the dry-bulb temperature. That is, air in typical situations must be cooled at least a little before water begins to condense. The difference between dry-bulb and dew point temperatures is determined by the moisture content of the initial air sample relative to the moisture content at saturation at the same dry bulb temperature. Of course, at saturation the dew point and dry-bulb temperatures are the same.

When air is cooled, initially, there is no moisture content change. The relative humidity rises because cooler air has less moisture-holding capacity than does warmer air. However, the humidity ratio remains unchanged until air is cooled to the point of saturation, where water begins to condense out of the air if cooling is below the dew point temperature. If this reasoning is applied to the psychrometric chart, the dew point temperature is at the intersection of the saturation line and the line of constant humidity ratio (a horizontal line) which passes through the state defining the original condition of the air.

Because dew point temperature is a function of the partial pressure of water vapor in the air, it may be calculated from one of the following equations.

For conditions of frost between - 60 C and 0 C, the dew point in Celsius is

$$t_d = -60.45 + 7.0322\ln(p_w) + 0.3700(\ln(p_w))^2. \qquad (2\text{-}17)$$

For temperatures between 0 and 70 C

$$t_d = -35.957 - 1.8726\ln(p_w) + 1.1689(\ln(p_w))^2, \qquad (2\text{-}18)$$

where p_w has units of pascals. $P_w = \mathrm{Exp}\left(0.80101 + \sqrt{31.40302 + \frac{Td}{1.1689}}\right)$ --- 2-18a

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Example 2-4

Problem: Continuing with the example of air at 20 C and 50% relative humidity, the psychrometric chart shows the dew point temperature to be approximately 9 C. Check this value by calculation.

Solution: For a partial pressure of water vapor of 1169 Pa, as calculated in Example 2-1, the dew point can be found using Equation 2-18.

$$\begin{aligned} t_d &= -35.957 - 1.8726\ln(1169) + 1.1689(\ln(1169))^2 \\ &= 9.14\ \text{C}. \end{aligned}$$

2-2.9. Enthalpy. The enthalpy, h, of moist air is a property useful in quantifying psychrometric processes which involve thermal energy exchanges. Enthalpy is an extensive property, thus, the enthalpy of a mixture equals the sum of enthalpies of the parts – the dry air, h_a, and water vapor, h_w:

$$h = h_a + h_w. \qquad (2\text{-}19)$$

Enthalpy in psychrometrics is referenced to 0 C (in the SI system) and water is assumed to be liquid at that temperature. The specific heat of dry air is 1.006 kJ/kg-K and the specific heat of water vapor is 1.805 kJ/kg-K. The specific heat of dry air actually varies from 1.006 at 0 C to 1.009 at 50 C, but the change is so slight it usually is ignored.

Note: Psychrometric calculations in the IP system of units reference enthalpy to 0 F. Conversion of enthalpy values from one set of units to the other is not straightforward. When converting from one system of units to the other, the enthalpy difference between 0 C and 0 F must always be included in calculations of enthalpy. Calculations of enthalpy changes do not require this correction.

The heat of vaporization of water at 0 C is 2501 kJ/kg. Heat of vaporization, kJ/kg, is a function of temperature and can be described by

$$h_{fg} = 2501 - 2.42t \tag{2-20}$$

for dry-bulb temperatures, t, between 0 and 65 C. Because of its weak dependence on temperature, the heat of vaporization is often treated as a constant, 2501 kJ/kg.

Using the data as given, enthalpy of moist air in kJ/kg of dry air can be calculated if dry-bulb temperature and the humidity ratio are known.

$h = f(t, w)$

$$h = 1.006t + W(2501 + 1.805t). \tag{2-21}$$

also see P.31.

$t = f(h, w)$

It should be noted that in Equation 2-21, the combination 1.006 + 1.805W is frequently treated as the specific heat (kJ/kg-K) of moist air. However, in many practical applications, the value 1.006 kJ/kg-K is used for convenience to represent the specific heat of moist air. The error in this assumption is small. Note that in Equation 2-21, enthalpy is calculated assuming the water contained in the air evaporates at 0 C and is then heated, along with the air, to t. This is appropriate as enthalpy is a function of state, not path.

In Figures 2-3 and 2-4, lines of constant enthalpy are included and are the solid lines from the lower right to the upper left corner of the chart.

Example 2-5

Problem: Returning to the example of 20 C and 50% relative humidity, the chart in Figure 2-4 can be used to estimate an enthalpy content relative to 0 C of 39 kJ/kg of dry air. Check this value by calculation.

Solution: Equation 2-21 can be used to obtain a computed value:

$$\begin{aligned} h &= 1.006\,(20) + 0.00726\,(2501 + (1.805)\,(20)) \\ &= 38.5 \text{ kJ/kg.} \end{aligned}$$

2-2.10. Wet-Bulb Temperature. Another measure of the moisture content of air is the thermodynamic wet-bulb temperature. For any sample of moist air, a mental experiment could be performed which would isolate the air adiabatically from its surroundings, but permit contact with a water source on a flat surface (to eliminate surface tension effects) for water vapor exchange, with the limitation that thermal energy needed to evaporate water would come only from the air. Except for energy used for evaporation, no other thermal energy could be exchanged between the air and water.

If the air sample were not initially saturated, evaporation would occur with thermal energy from the air being the source of energy for evaporation. Water vapor would mix with the air and the humidity ratio would increase. The process would continue until the air became saturated. The air would have cooled, for sensible heat would have been transformed into latent heat. The cooling process would proceed until saturation. If the air were very dry initially, a great deal of cooling would occur. If the air were near saturation, little cooling would be possible. The limiting temperature, at which the air would become saturated, is the wet-bulb temperature.

The assumption of adiabatic conditions infers enthalpy is conserved in the evaporation process. Enthalpy (in the form of sensible heat) from the air used for evaporation returns to the air as latent heat. However, although enthalpy is conserved overall, the air gains enthalpy slightly in the process, and the water loses a like amount. The difference is the enthalpy content of the evaporated water prior to evaporation.

The wet-bulb temperature for given conditions of moist air can be determined from the psychrometric chart. Diagonal dashed lines from the lower right to upper left on the chart intersect the saturation line at the wet-bulb temperature corresponding to the initial conditions. There is a unique wet-bulb temperature for any given set of initial conditions although the reverse is not true. A given wet-bulb temperature applies to any of the combinations of conditions which lie along the wet-bulb line. Note that lines of constant wet-bulb temperature do not correspond to lines of constant enthalpy. The difference is the enthalpy content of water prior to evaporation. However, the two lines are nearly parallel, and on some psychrometric charts they are used interchangeably (sometimes with a correction factor introduced).

from 2-21

Wet-bulb temperature can be determined using equations, but the computational process is iterative. The process of adiabatic saturation of air is described by

$h_s^* = 1.006t^* + W_s^*(2501 + 1.805t^*)$

$h = 1.006t + W(2501 + 1.805t)$

$$h_s^* = h + h_w^*(W_s^* - W) \tag{2-22}$$

which is a statement of the enthalpy change of air as it saturates adiabatically. The humidity ratio starts at W and in the constant pressure process increases from W to W_s^* at saturation (the * superscript indicates conditions at the wet-bulb temperature) while enthalpy of the air increases slightly from h to h_s^*. Saturation is at the wet-bulb temperature, t*.

Enthalpy of water, h_w^*, is found from

$W_s^* = 0.62198\, P_{ws}^* / (P - P_{ws}^*)$

$W = 0.62198\, P_w / (P - P_w)$

$$h_w = 4.186t;\ h_w^* = 4.186t^*. \tag{2-23}$$

t in K ??

A procedure to determine wet-bulb temperature is to search for a temperature, t*, such that Equation 2-22 is satisfied. An ad hoc search procedure is to begin the search slightly above the air's dry-bulb temperature, and decrement the candidate temperature until the equation is satisfied to within an acceptable level of precision. Values for atmospheric pressure, initial dry-bulb temperature, initial enthalpy, and initial humidity ratio are required to begin the process. Accelerated search techniques sweeping in alternate directions with ever-decreasing step sizes, or using the bisection method, can reduce the time required for convergence, but searching in one direction with small decrements of temperature will lead to a solution as long as the initial direction of search is in the proper direction.

Example 2-6

If we return to the example of air at 20 C dry-bulb temperature and 50% relative humidity, the psychrometric chart in Figure 2-3 shows a wet-bulb temperature of approximately 13.5 C. A solution for wet-bulb temperature using a computerized procedure to solve Equation 2-22, program PLUS, is 13.8 C. Program PLUS uses computerized psychrometric functions and processes described later in this chapter.

2-3. Psychrometric Properties Examples

Throughout Section 2-2, moist air at 20 C and 50% relative humidity was examined for its other psychrometric parameters.

To provide benchmarks for practice in determining the parameters, Table 2-2 contains data for six different conditions. The data can be used with the psychrometric charts (where possible) and psychrometric equations to be sure both are understood. However, at this point it will not be possible to determine wet-bulb temperatures using the equations unless programmed on a computer. Case 1 is the example which has been followed through the descriptions of psychrometric parameters.

Data in Table 2-2 can help develop an intuitive understanding of psychrometrics. If relative humidity rises while air temperature and atmospheric pressure are constant (case #2 compared to #1), the humidity ratio, dew point temperature, wet-bulb temperature, and enthalpy increase. If air temperature decreases while atmospheric pressure and relative humidity remain the same (case #3 compared to #1), the humidity ratio, dew point temperature, wet-bulb temperature, and enthalpy decrease. These changes are obvious from examination of the psychrometric chart.

Conditions #1, #5, and #6 have identical dry-bulb temperatures and relative humidities. However, condition #1 represents sea level and conditions #5 and #6 represent increasing elevation. In spite of the atmospheric pressure decrease, dew point temperatures are the same. Why? Recall that dew point temperature is a function only of water vapor partial pressure, which is a function only of dry-bulb temperature and relative humidity. Atmospheric pressure does not affect the vapor pressure of water.

The humidity ratio increases as atmospheric pressure falls, while dry-bulb temperature and relative humidity remain constant. We have already learned that water vapor partial pressure does not change with atmospheric pressure. What does? Specific volume (or density) change causes the difference. At high elevations, there is less dry air in a unit volume but the same amount of water vapor if temperatures are identical. The result is more water vapor per unit mass of dry air.

Can the same explanation be used for the enthalpy increase as the pressure decreases? It can, but only in part because the ratio of humidity ratios (0.0120 / 0.0073, for example) does not equal the ratio of enthalpies (50.6 / 38.5). If exactly the same explanation were true, the ratios would be identical. Think about where the rest of the difference lies. Hint: The specific heat of dry air does not change as a function of altitude, but the humidity ratio does change if temperature and relative humidity remain constant.

Finally, it may not be intuitively obvious that wet-bulb temperature should decrease as atmospheric pressure decreases for the same dry-bulb temperature and relative humidity. However, it has been seen that when atmospheric pressure is reduced, the moisture carrying capacity of a unit mass of dry air

Table 2-2. Six example psychrometric combinations.

	Parameter	#1	#2	#3	#4	#5	#6
	atmospheric pressure, kPa	101.325	101.325	101.325	89.874	89.874	61.64
	dry-bulb temperature, C	20	20	-10	10	20	20
	relative humidity, %	50	80	50	20	50	50
f(P,T,rh)	humidity ratio, kg/kg	0.0073	0.0117	0.0008	0.0017	0.0082	0.0120
f(T,rh)	dew point temperature, C	9.1	16.3	-17.5	-10.9	9.1	9.1
f(P,T,rh)	wet-bulb temperature, C	13.8	17.7	-11.5	2.0	13.5	12.6
f(P,T,rh)	enthalpy, kJ/kg	38.5	49.8	-8.1	14.4	40.9	50.6
$f\left(\frac{P}{T}\right)$ ←	specific volume, m^3/kg	0.833	0.833	0.746	0.909	0.943	1.37

1175426 245.702 1169.117 Pa

increases because of the decrease of density. Air at low pressure can gain relatively more water vapor when brought from 50% relative humidity to saturation. When more water is evaporated, more thermal energy is needed for evaporation. Thermal energy must come from the air in an adiabatic saturation process and, as a consequence, the air is cooled further. More cooling reduces the moisture carrying capacity, and a balance is reached in case #6, 1.2 K below the wet-bulb temperature of case #1.

2-4. Measuring Psychrometric Properties

Instruments have been developed to measure several of the psychrometric properties. The most obvious is dry-bulb temperature which can be measured by simple thermometers, thermocouples, thermistors, resistance thermometers, and more recently, solid state devices for computerized measurements. In practical measurements, it is important to ensure the temperature sensor is not influenced significantly by thermal radiation such as solar heating.

Dew point temperatures can be measured by dew point hygrometers. These are integrated instruments which sense the presence of dew on a chilled mirror by measuring the intensity of light reflected from the mirror. When dew forms, light is scattered more than when the mirror is clear. The mirror is alternately cooled and warmed; dew alternately forms and evaporates. The temperature of the mirror is measured, and the centerpoint of the temperature cycling provides an estimate of the temperature at which dew forms – the dew point temperature.

Relative humidity can be measured several ways. The traditional means is to move air around a wick-covered, wetted thermometer at a speed of approximately 3 m/s and simultaneously around a dry thermometer. The thermometers can be aspirated using fans or relative air movement can be effected by whirling the pair, attached to a base and handle, through the air. In either way, the dry thermometer will reach approximate equilibrium with the dry-bulb temperature of the air, and the wetted thermometer will reach approximate equilibrium with the wet-bulb temperature. Evaporation of water within the wick reduces the wick temperature, and thereby the thermometer temperature, to approximately the thermodynamic wet-bulb temperature.

Accuracy of the wet-bulb estimate is improved if the wick is clean and the water pure and distilled. When the two thermometers reach equilibrium states, the readings can be used to determine relative humidity using a psychrometric chart or a distillation of the chart in the form of a slide rule or data table.

More recent methods to measure relative humidity rely on solid state devices and electronics. Several physical principles can be used. One is to measure the change of electrical properties of a matrix as water molecules diffuse into and out of the matrix in response to changes of the air's moisture content. Another is to measure the change of electrical properties of a suitable material as water molecules adhere to its surface. Depending on the specific device, either capacitance or inductance is the electrical property which is measured. Careful calibration of each sensor is required, and frequently these sensors cannot tolerate conditions at or near saturation where they may lose calibration permanently. At present the measurement of relative humidity in the dusty, very humid conditions of animal housing and greenhouses is still a problem without a universally satisfactory solution. New solid state humidity sensors are now coming onto the market which are less likely to exhibit problems near saturation. Older humidity measuring instruments, which relied on contraction and relaxation of a fiber (such as a human hair) as humidity changed, were notoriously unreliable for use in barns and greenhouses.

2-5. Psychrometric Processes

A psychrometric process can be defined as a change in the state of moist air caused by adding or removing, either individually or in combination, thermal energy or water vapor. When a barn is ventilated, animals in the barn add sensible heat and moisture to the air. Solar input to a greenhouse adds sensible heat and causes water to evaporate to form water vapor (directly and indirectly through transpiration). If the initial state of the air is known, and rates of heat and water vapor changes can be determined, the state of air within the conditioned space can be calculated from psychrometric processes. Alternately, if the beginning and end states are known, the sensible and latent heat additions (or removals) to achieve the end state can be determined.

2-5.1. Sensible Heating and Cooling. When only sensible heat is added or removed from air, the process follows a horizontal line on the psychrometric chart. The only exception is cooling to a temperature lower than the dew point which will be discussed later. As air is heated, the humidity ratio does not change and relative humidity falls. The reverse occurs upon cooling.

For steady flow conditions, heat which is exchanged, q, causes a temperature change as follows:

$$\Delta T = q / \left(\dot{M}_a c_{pa} \right\}$$ ~~or ΔT = q/Δh~~ (2-24)

${}_1q_2 = m_a(h_2 - h_1)$

where $\dot{M}_a$ is the mass flow rate of air involved in the process, and c_{pa} is the specific heat of the air at constant pressure.

Example 2-7

Problem: Determine the final state of moist air originally at 20 C and 50% relative humidity if 10 kJ are removed from 1.2 kg of the air.

Solution: The specific heat of air is approximately 1.006 kJ/kgK, thus, the temperature change using Equation 2-24 is

$$\Delta T = (-10\text{ kJ}) \Big/ \left[(1.2\text{ kg})(1.006\text{ kJ/kgK})\right] = -8.28\text{ K},$$

and the final temperature is 20 C - 8.28 K = 11.72 C. If the process is tracked on a psychrometric chart, it is as shown in Figure 2-5. The humidity ratio remains constant at 0.00726 kg/kg, and the relative humidity increases to approximately 85%.

An alternate means to follow the process on a psychrometric chart begins with the enthalpy change,

$$\begin{aligned}\Delta h &= q / \dot{M}_a \\ &= (-10\text{ kJ}) / (1.2\text{ kg}) = -8.33\text{ kJ/kg}.\end{aligned} \qquad (2\text{-}25)$$

The initial enthalpy is 38.5 kJ/kg and can be found from the chart at the initial conditions. The final enthalpy is 38.5 - 8.3 = 30.2 kJ/kg. The intersection of this new enthalpy value, and a line of constant humidity ratio drawn through the initial conditions of 20 C and 50% relative humidity, provide an estimate of the end point of the process – a dry-bulb temperature of slightly less than 12 C.

Example 2-8

Problem: Rework Example 2-7 using the psychrometric equations rather than the psychrometric chart.

Solution: The end state of Example 2-7 can also be determined using psychrometric equations, as would be done in a computer implementation of psychrometric processes. The first step is to calculate the end point temperature, 11.72 C, as was done in Example 2-7.

The humidity ratio is calculated from conditions at the beginning of the process. At a dry-bulb temperature of 20 C (293.15 K), the water vapor saturation partial pressure with the coefficients for temperatures above 0 C is calculated using Equation 2-1

在 $T_1 = 20°C$

求 $P_{ws_1} = 2339$ Pa

$\because rh = 0.5 \therefore P_w = 1169$

依 Ex2-7

$T_2 = 11.72$

求 $P_{ws_2} = 1377$

$\phi_2 = \frac{1169}{1377} = 0.849$

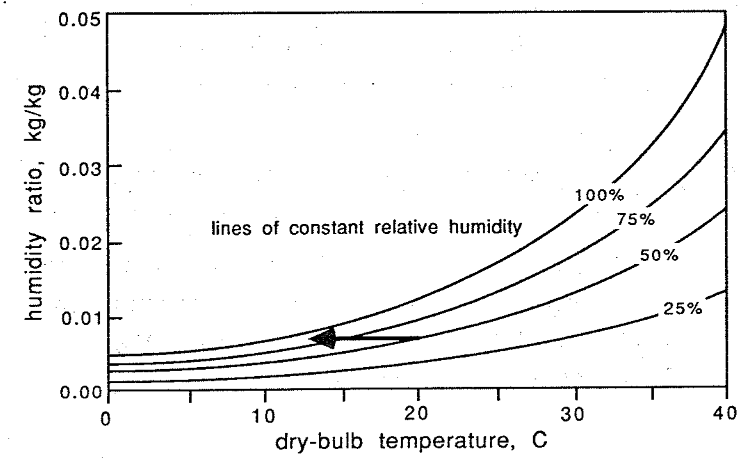


Figure 2-5. Sensible cooling, see Examples 2-7 and 2-8.

$$\ln(p_{ws}) = -5.8002206E+03/293.15 + 1.3914993 - 48.640239E-03\ (293.15) + 41.764768E06\ (293.15)^2 - 14.452093E-09\ (293.15)^3 + 6.5459673 \ln(293.15)$$

and $p_{ws} = 2339$ Pa.

The relative humidity is 50%, thus,

$$p_w = 0.50(2.339) = 1.169 \text{ kPa.}$$

Water vapor partial pressure remains constant during sensible cooling; at 11.72 C the partial pressure is still 1.169 kPa because the dew point temperature still has not been reached. (This can be checked in a computer program by calculating the dew point temperature once the water vapor partial pressure has been determined.)

The water vapor saturation partial pressure decreases, however, because of the lower dry-bulb temperature at the end of the process (284.87 K). Equation 2-1 can be used again with the new temperature to yield a water vapor saturation partial pressure of 1377 Pa. At this new state, the relative humidity, by its definition, is

$$\phi = 100(1.169 \text{ kPa} / 1.377 \text{ kPa}) = 84.9\%.$$

If other psychrometric parameters at the original or new state are desired, they can be calculated within the same computer program.

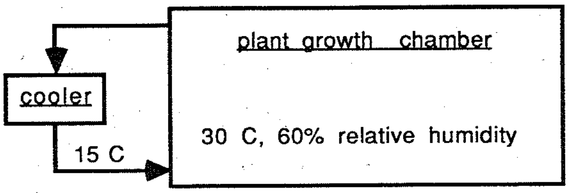
2-5.2. Cooling With Dehumidification. When air cools, the humidity ratio remains unchanged until the air is cooled to saturation. If air continues to cool after the dew point is reached, the process follows the saturation line and water is removed by condensation. If condensation occurs, the final state is at the intersection of the saturation line and the final dry-bulb temperature. The amount of water removed from the air equals the difference between the initial and final humidity ratios multiplied by the mass of dry air involved in the dehumidification.

Dehumidification can be traced on a psychrometric chart in two ways. If the final temperature is known – as it might be if air were passed through a refrigeration device and cooled to the temperature of the refrigeration coils – the process can be traced as shown in Figure 2-6. The initial point is known; the final point is at the intersection of the saturation line and the dry-bulb temperature to which the air is cooled.

The enthalpy change can be separated into its sensible and latent components. Psychrometric properties are functions of state not path. The dehumidification path from 1 to 2 in Figure 2-6 is equivalent to the path from 1 to 3 to 2. The path from 1 to 3 is only a process of water vapor removal (a latent heat removal which can be quantified by the enthalpy change from 1 to 3). The path from 3 to 2 is only temperature change, a sensible heat removal, quantified by the enthalpy change from 3 to 2.

Example 2-9

Problem: Air at 30 C and 60% relative humidity in a plant growth chamber is cycled past the cooling coils and is returned back to the chamber at a temperature of 15 C. Using the psychrometric chart, determine the psychrometric properties of the air after it is cooled, the sensible and latent heat removed, and the water vapor condensed per kg of dry air moved past the coils.



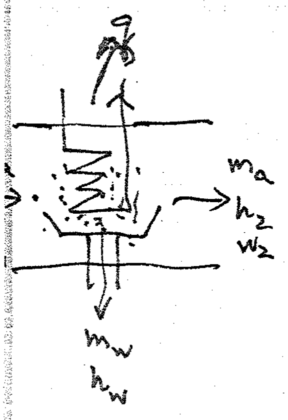
Solution: Point 1 on Figure 2-6 is at the intersection of the lines for 60% relative humidity and 30 C dry-bulb temperature. For this condition, dew point temperature is approximately 21.5 C; further cooling to 15 C must be accompanied by condensation. Point 2 is at 15 C on the saturation line. At point 2, air has the following properties:

t_1 (30°C) $\to P_{ws_1} \to P_{w_1} \to t_{d_1}$ (> t_2 才有冷凝)
$rh_1 \nearrow$; $P_{w_1} \searrow w_1$; $w_1, t_1 \to h_1$

t_2 (15°C) $\to P_{ws_2} = P_{w_2} \to w_2$; $w_2, t_2 \to h_2$

$w_3 = w_2$; $t_3 = t_1$ $\to h_3$

dry-bulb temperature: 15 C
dew point temperature: 15 C
wet-bulb temperature: 15 C
relative humidity: 100 %
humidity ratio: 0.010648 kg/kg
specific volume: 0.83 m^3/kg
enthalpy: 42.0 kJ/kg



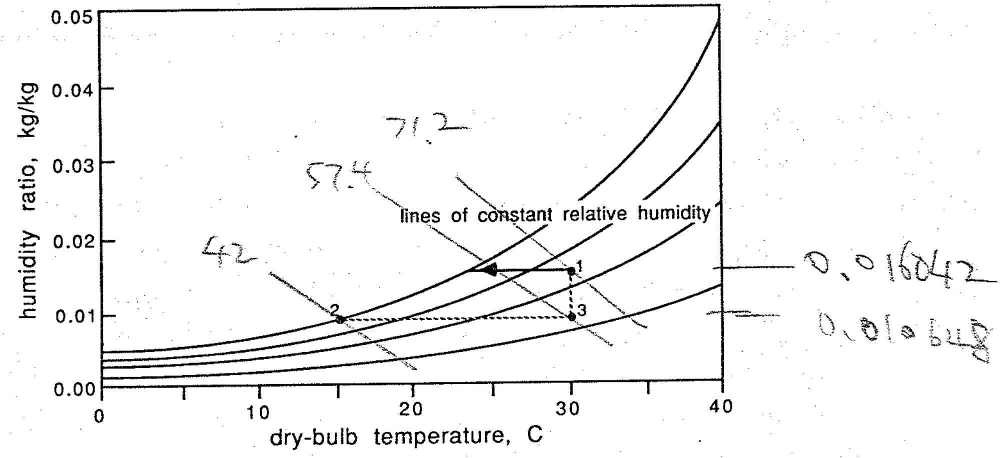


Figure 2-6. Cooling with dehumidification, see Examples 2-9 and 2-10.

$$\begin{cases} m_a h_1 - q = m_a h_2 + m_w h_w \end{cases} \rightarrow m_w = m_a(w_2 - w_3)$$

The removal of sensible and latent heat is represented by lines 3-2 and 1-3, respectively, on Figure 2-6. The enthalpy at point 2 has already been determined to be 42.0 kJ/kg. At points 1 and 3 the enthalpies are 71.2 and 57.4 kJ/kg, respectively. For every kg of air moved past the cooling coils, the sensible heat removal is

$$h_s = (1\ \text{kg})(57.4\ \text{kJ/kg} - 42.0\ \text{kJ/kg}) = 15.4\ \text{kJ},$$

and the latent heat removed is

$$h_l = (1\ \text{kg})(71.2\ \text{kJ/kg} - 57.4\ \text{kJ/kg}) = 13.8\ \text{kJ}.$$

The quantity of water removed can be determined from the humidity ratio change. The humidity ratios at points 1 and 2 are 0.016042 and 0.010648 kg/kg, respectively. The difference is 0.005394 kg for 1 kg of dry air.

$h_{fg} \approx (2501 - 2.42\,t)$ kJ/kg, °C

Water removal can also be determined from the enthalpy change if the heat of vaporization is known. From Equation 2-20, at 15 C the heat of vaporization is 2465 kJ/kg. When 13.8 kJ are removed, 13.8 kJ / 2465 kJ/kg = 0.0056 kg of water are condensed. The slight difference between the two estimates of the amount of condensed water arose from imprecision in reading the psychrometric chart. However, the degree of accuracy is normally adequate for environmental control applications. Note: We have assumed ideal conditions in the heat exchanger with all air cooled to 15 C and no short circuiting and mixing. Mixing will be addressed later.

Example 2-10

Problem: Repeat Example 2-9 using psychrometric equations in a way suitable for computer implementation.

Solution: A dehumidification process can be implemented readily on a computer if the final temperature is known. The final dry-bulb temperature, relative humidity, dew point, and wet-bulb temperatures are known a priori, although the psychrometric equations should also provide the correct answers. Again, we are assuming all the air is cooled to the same final temperature, and there is no short circuiting of part of the air with less condensation in that air.

A procedure suitable for computerized implementation is summarized in Table 2-3. Other sequences using the equations can also work. In some cases the sequence is unique – in others it is not. For example, specific volume can be calculated any time after the dry-bulb temperature and humidity ratio are known; further calculations do not depend on it. Dew point temperature can be calculated any time after water vapor partial pressure is known. However, water vapor saturation partial pressure must be calculated before humidity ratio can be determined, and enthalpy must be calculated before wet-bulb temperature. These are examples where proper sequences must be followed.

Table 2-3. Example computational sequence to determine psychrometric properties after a process of cooling and dehumidifying moist air.

Given:

1. The initial state was 30 C dry-bulb temperature and 60% relative humidity.
2. The final state is 15 C at saturation.

Procedure:

For the initial state of the air,

1. Determine the water vapor saturation partial pressure using Equation 2-1, the actual water vapor partial pressure using the definition of relative humidity, and the dew point of the original conditions using Equation 2-18.
2. Check to determine whether the final state is at a dry-bulb temperature below the dew point temperature of the original state. This is a check of whether there actually will be condensation. If there will be condensation, continue with the steps listed below.
3. Specify final relative humidity as 100% and dry-bulb temperature as 15 C (based on given conditions).

For the final state of the air,

4. Calculate water vapor saturation partial pressures using Equation 2-1.
5. Set the dew point temperature equal to the dry-bulb temperature.

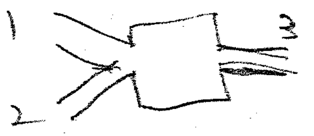
For both the beginning and final states of the air,

6. Calculate humidity ratios using Equation 2-9.
7. Calculate specific volumes using Equation 2-16.
8. Calculate enthalpies using Equation 2-21.
9. Calculate wet-bulb temperatures using Equation 2-22 and the iterative procedure as described. The wet-bulb temperature of the final state can be set immediately equal to the final dry-bulb temperature.
10. Calculate enthalpy of the state where dry-bulb temperature is still 30 C, but the humidity ratio is at its final value (point 3 on Figure 2-6).
11. Calculate enthalpy changes due to sensible and latent heat removal.
12. Calculate the amount of water removed. Use the difference of humidity ratios multiplied by the mass of air.

2-5.3. Adiabatic Mixing. Conditions frequently arise in environmental control where two streams of air are mixed adiabatically. An example is a calf nursery where air is recirculated to maintain a well-mixed condition in the nursery, and fresh air is added to the recirculated airstream with an equal mass flow rate of recirculated air being exhausted to the outdoors to maintain steady conditions. Recirculation tempers fresh air in cold weather to avoid drafts on the calves and provides more mixing than might be possible when only a small amount of fresh air is needed. Evenly distributing a small flow rate of air in a ventilated airspace with good air mixing is difficult (shown in detail in later chapters).

The process of adiabatic mixing is sketched in Figure 2-7. In the example shown in the sketch, warmer air (state 2) is mixed with colder air (state 1), and the warmer air contains more moisture than does the colder air. Intuitively, one might expect the resulting mixture (state 3) to be at a dry-bulb temperature intermediate to dry-bulb temperatures of states 1 and 2, and the same to be true for the humidity ratio of the mixture.

In many practical processes, mixing is essentially adiabatic and the following equations, where 3 is the mixed state, apply:



$$\dot{M}_{a1}h_1 + \dot{M}_{a2}h_2 = \dot{M}_{a3}h_3 \qquad (2\text{-}26)$$

$$\dot{M}_{a1}W_1 + \dot{M}_{a2}W_2 = \dot{M}_{a3}W_3 \qquad (2\text{-}27)$$

$$\dot{M}_{a1} + \dot{M}_{a2} = \dot{M}_{a3} \qquad (2\text{-}28)$$

Eliminating $\dot{M}_{a3}$ from Equations 2-26 and 2-27 yields the following relationships to determine the humidity ratio and enthalpy of state 3:

$$(W_2 - W_3)/(W_3 - W_1) = \dot{M}_{a1} / \dot{M}_{a2} \qquad (2\text{-}29)$$

$$(h_2 - h_3)/(h_3 - h_1) = \dot{M}_{a1} / \dot{M}_{a2} \qquad (2\text{-}30)$$

Equations 2-29 and 2-30 are linear, thus, state 3 must lie along a straight line connecting states 1 and 2 on the psychrometric chart. The location of point 3 on the line is determined by the ratio of the mass flow rates of the two airstreams, $\dot{M}_{a1} / \dot{M}_{a2}$.

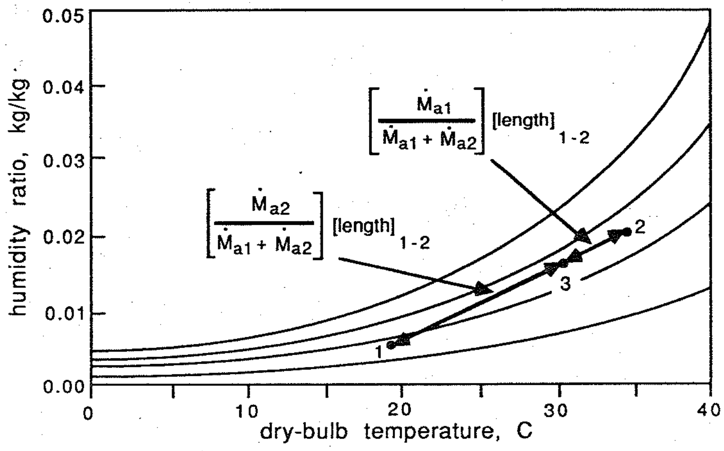
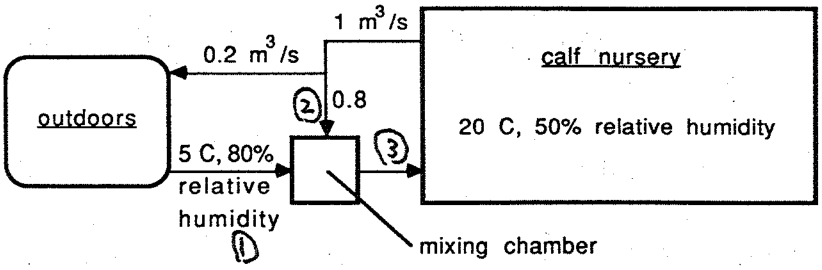


Figure 2-7. A process of adiabatic mixing.

Example 2-11

Problem: A ventilation system for a calf nursery draws 1 m³/s of air from the nursery, exhausts 0.2 m³/s of the air to the outside, and replaces the exhausted air with fresh air. Air in the nursery is at 20 C and 50% relative humidity, and outdoor air is at 5 C and 80% relative humidity. Determine properties of the mixed air when it is returned to the nursery.



Solution: The first step is to determine properties of the outdoor and nursery air. Volumetric airflow rate is denoted by V.

Note: The usual convention in stating such problems is to specify the volumetric airflow rate based on conditions at the inlet of the fan. In this example, fresh air is specified (or measured) at outdoor conditions, recirculated and exhausted air are specified at indoor conditions.

The psychrometric chart for normal temperatures can be used to obtain appropriate data as follows:

$\dot{V}_1 =$ ~~unknown,~~ 0.2 m³/sec $\qquad \dot{V}_2 = 0.8\ \mathrm{m^3/s}$, $\qquad T_{wb_2} = 13.8$

$T_{wb_1} = 3.6 \qquad W_1 = 0.00436$ kg/kg, $\qquad W_2 = 0.00735$ kg/kg, $\qquad T_{dp_2} = 9.1$

$T_{dp_1} = 1.9 \qquad h_1 = 16.0$ kJ/kg, $\qquad h_2 = 38.8$ kJ/kg, $\qquad \rho_2 = 1.2$

$\rho_1 = 1.27\ \mathrm{kg/m^3} \qquad v_1 = \frac{1}{1.27} = 0.787\ \mathrm{m^3/kg} \qquad v_2 = 0.8\underset{333\ldots}{}\ \mathrm{m^3/kg}$.

Volumetric flow rates are given, but psychrometric calculations are based on mass flow. Mass flow equals volumetric flow divided by specific volume, thus,

$\dot{M}_{a1} = (0.2\ \mathrm{m^3/s})/(\overset{0.787}{\cancel{0.83}}\ \mathrm{m^3/kg}) = \overset{0.254}{\cancel{0.24}}$ kg/s, and
$\dot{M}_{a2} = (0.8\ \mathrm{m^3/s})/(0.83\ \mathrm{m^3/kg}) = 0.96$ kg/s.

Equation 2-29 can be rearranged to solve for W_3 as follows:

eq 2-27 $\rightarrow$

$$W_3 = (\dot{M}_{a1}W_1 + \dot{M}_{a2}W_2)/(\dot{M}_{a1} + \dot{M}_{a2}). \qquad (2\text{-}31)$$

Equation 2-30 can be similarly rearranged:

eq 2-26 $\rightarrow$

$$h_3 \doteq (\dot{M}_{a1}h_1 + \dot{M}_{a2}h_2)/(\dot{M}_{a1} + \dot{M}_{a2}). \qquad (2\text{-}32)$$

Equations 2-31 and 2-32 can be solved to determine two of the properties of air at state 3.

$$W_3 = \frac{(0.24\ \text{kg/s})(0.00436\ \text{kg/kg}) + (0.96\ \text{kg/s})(0.00735\ \text{kg/kg})}{0.24\ \text{kg/s} + 0.96\ \text{kg/s}}$$

$$= 0.00675\ \text{kg/kg}.$$

$$h_3 = \frac{(0.24\ \text{kg/s})(16.0\ \text{kJ/kg}) + (0.96\ \text{kg/s})(38.8\ \text{kJ/kg})}{0.24\ \text{kg/s} + 0.96\ \text{kg/s}}$$

$$= 34.2\ \text{kJ/kg}.$$

With two properties of state 3 known, others can be determined from the psychrometric chart:

dry-bulb temperature = 17 C,
wet-bulb temperature = 12 C,
dew point temperature = 8 C,
relative humidity = 55%,
specific volume = 0.825 m^3/kg,
density = 1.212 kg/m^3,

$$\begin{tikzcd} h_3, W_3 \arrow[r] & t_3 \arrow[r] & P_{ws} \arrow[dr] & \\ W_3 \arrow[r] & P_w \arrow[rr] \arrow[dr] & & rh \\ & & t_d & \\ w, T \arrow[r] & v & & \end{tikzcd}$$

and the volumetric airflow rate after mixing is

$$\dot{V}_3 = 0.825\ \text{m}^3\text{/kg}(0.24\ \text{kg/s} + 0.96\ \text{kg/s}) = 0.99\ \text{m}^3\text{/s}.$$

Example 2-12

Problem: Repeat Example 2-11 using psychrometric equations in a way suitable for computer implementation.

Solution: In an adiabatic mixing process, humidity ratios and enthalpies of the two separate airstreams must first be determined, followed by humidity ratio and enthalpy of the mixed state, based on Equations 2-31 and 2-32.

A sequence to accomplish the task is listed in Table 2-4. Notes related to sequencing included in Example 2-10 also apply to this example.

Table 2-4. Example computational sequence to determine psychrometric properties after a process of adiabatic mixing of two airstreams.

Given:

1. State 1 represents air at 5 C and 80% relative humidity.
2. State 2 represents air at 20 C and 50% relative humidity.

Procedure:

For states 1 and 2,

3. Determine water vapor saturation partial pressures using Equation 2-1, actual water vapor partial pressures using the definition of relative humidity, humidity ratios from Equation 2-9, and enthalpies from Equation 2-21.
4. Determine the specific volume of the moist air at condition 2 using Equation 2-16.

For state 3,

5. Calculate the humidity ratio and enthalpy of the mixed state as described in Example 2-11.
6. Rearrange Equation 2-21 to solve for the dry-bulb temperature of the mixture.

$$t = (h - 2501W)/(1.006 + 1.805W). \qquad (2\text{-}33)$$

7. The next step is a check to catch the unlikely, but possible, situation of a mixed state above the saturation line. Both states 1 and 2 are near saturation, the straight line connecting them may pass above the saturation line.
8. Calculate the water vapor saturation partial pressure corresponding to the dry-bulb temperature determined in step 6. Use Equation 2-9 to calculate the humidity ratio at saturation at the calculated dry-bulb temperature of state 3. Check to determine whether the humidity ratio calculated in step 5 is less than that calculated in this step, and if so, continue.
9. Calculate the dew point temperature of state 3 using Equation 2-17 or 2-18.
10. Calculate the relative humidity at state 3 using Equation 2-2.
11. Calculate the specific volume at state 3 using Equation 2-15, corrected for humidity ratio.
12. Calculate the wet-bulb temperature of state 3 using Equation 2-22 and the iterative procedure as described.

2-5.4. Evaporative Cooling. Numerous applications of environment control in agriculture require more cooling than can be provided by ventilation alone. Temperature requirements for best animal production typically are within the range from 10 to 30 C. Day temperature requirements for greenhouse crops are seldom higher than 25 C. Whenever outdoor temperatures are warm, maintaining conditions within these ranges may become impossible unless artificial cooling is used.

Mechanical refrigeration is normally used to cool air within buildings for human habitation. However, people have been conditioned to expect a relatively narrow and carefully controlled range of comfort conditions. Such careful control has not been found necessary for animals and plants. This is fortunate because mechanical refrigeration would be expensive to install and energy-intensive to operate to meet the large cooling loads encountered in modern barns and greenhouse ranges.

An alternative means of cooling widely used in agriculture is evaporative cooling. It is most effective in dry climates, but uses have been found even in humid climates during the hottest part of the day when relative humidity may be significantly below saturation. Devices and design methods to provide evaporative cooling will be described in more detail later. For now it is enough to know evaporative cooling is achieved by placing outdoor air in contact with a wetted medium for a specific length of time to permit a process of adiabatic saturation to proceed nearly to completion.

Practical considerations preclude devices which permit air to attain the wet-bulb temperature completely. A measure of efficiency is involved. A well-designed evaporative cooler can be expected to achieve up to 80% of the "wet-bulb depression". For a given state of unsaturated air, the wet-bulb depression is defined as the difference between the dry-bulb and wet-bulb temperatures. For example, air at 35 C and 20% relative humidity has a wet-bulb temperature of 18.8 C. The difference between 35 C and 18.8 C is the wet-bulb depression, 16.2 C. An evaporative cooler which could achieve 80% cooling efficiency would cool the air by 0.80 (16.2 C) = 13 C. Air would exit the cooler at 35 C - 13 C = 22 C. Animals in a barn ventilated with fresh air at 35 C would probably be subjected to considerable heat stress, but would not be stressed at 22 C.

Obviously evaporative cooling is most effective in dry climates, but even in humid climates, such as the southeastern United States, relative humidity during midday may be only 50%. If air were at 35 C and 50% relative humidity, the wet-bulb temperature would be 26 C, and an 80% efficient cooler could provide ventilation air cooled to 28 C which is a significant improvement. Of course, careful economic and engineering analysis would be required to determine the usefulness of evaporative cooling in humid climates.

Example 2-13

Problem: When ambient conditions are 35 C and 25% relative humidity, determine the dry-bulb temperature to which ventilation air could be cooled if drawn through an evaporative cooler with an efficiency of 75%. Calculate how much water must be added to each cubic meter of air drawn through the cooler.

Solution: On the psychrometric chart, the wet-bulb temperature corresponding to the given conditions is 20 C. The wet-bulb depression is 35 C - 20 C = 15 C. A cooler operating at 75% efficiency will cool the air 0.75(15 C) = 11 C and reduce the dry-bulb temperature to 35 C - 11 C = 24 C.

At initial conditions, the specific volume is 0.88 m^3/kg and the humidity ratio is 0.00876 kg/kg. At a wet-bulb temperature of 20 C and dry-bulb temperature of 24 C on the psychrometric chart, the humidity ratio is 0.01320 kg/kg.

A cubic meter of air will contain 1.0 m^3/(0.88 m^3/kg) = 1.14 kg. The change of humidity ratio is 0.01320 kg/kg - 0.00876 kg/kg = 0.00444 kg/kg. Thus, the total water gained by each cubic meter of outdoor air will be (1.14 kg)(0.00444 kg/kg) = 0.005 kg, or approximately 0.005 L.

Example 2-14

Problem: Repeat Example 2-13 using psychrometric equations in a method suitable for computer implementation.

Solution: A suitable sequence is listed in Table 2-5. Because the process begins with the known dry-bulb temperature and relative humidity and proceeds along the constant wet-bulb line, checks are not needed to stop the calculation procedure if impossible conditions arise. Notes in previous examples regarding the calculation sequence apply.

Table 2-5. Example computational sequence to determine the final state of air after an evaporative cooling process and the amount of water required for evaporation into each cubic meter of air at the state before cooling.

Given:

1. The initial state is air at 35 C dry-bulb temperature and 25% relative humidity.
2. The efficiency of the evaporative cooling process is 75%.

Procedure:

For the initial state of the air,

3. Calculate the water vapor saturation partial pressure using Equation 2-1, the actual water vapor partial pressure using Equation 2-2, and the humidity ratio using Equation 2-9.
4. Calculate the enthalpy using Equation 2-21.
5. Calculate the wet-bulb temperature using Equation 2-22 and the iterative procedure as described.
6. This determines the initial state of the air. The evaporative cooling process can now be quantified by the wet-bulb depression, the actual cooling based on cooler efficiency, and the final dry-bulb temperature of air after passing through the evaporative cooler. The procedure in Example 2-13 may be used.
7. At wet-bulb temperature and saturation, calculate the humidity ratio using Equation 2-9. The difference between this value of humidity ratio, and the humidity ratio of air before evaporative cooling, is the maximum possible addition of water vapor to the air. This difference, multiplied by the evaporative cooler efficiency, is the actual water vapor added to the air.
8. Calculate the specific volume of the air prior to cooling using Equation 2-16.
9. Calculate water vapor added per unit volume of air at the initial state using the procedure in Example 2-13.

2-6. Integrated Psychrometric Processes

A real ventilation situation is likely to involve several psychrometric processes occurring simultaneously or sequentially. This section provides an example of a more complex process. Each component has been seen previously in concept or example.

Example 2-15

Problem: You are designing an evaporative cooling system to ventilate a controlled environment, totally enclosed, poultry house in a hot and dry climate. Summer design weather conditions for your location are 40 C dry-bulb temperature with a relative humidity of 20%. When the evaporative cooling system operates, you expect to have 75 m^3/s of outdoor air drawn through the evaporative pads and 15 m^3/s of outdoor air drawn through the poultry house by the mechanism of infiltration. Infiltration circumvents the evaporative cooling process. Each volumetric flow rate is determined based on outdoor air conditions.

The evaporative cooling pads will provide 75% efficiency if properly maintained. More water will flow through the cooling pads than will be needed for evaporation to avoid salt build-up within the pads as water evaporates. Excess water will flush salts from the pads. A (water flow/evaporation rate) ratio of 3.0 is desired.

The only significant heat gains in the poultry house are the sensible and latent heat gains from the birds. Because ventilation is so rapid (approximately one air change per minute) as a first approximation we may neglect heat gains or losses through the building shell. The birds are expected to produce 250 kW of total heat of which 40% is latent heat and the rest sensible heat. (Sources of animal heat production data and its partitioning between sensible and latent heats will be discussed in a later chapter.)

Air inside the building can be assumed well mixed (everywhere uniform). Standard atmospheric pressure is expected; the location is near sea level. For the analysis, complete the following three calculations:

1. Determine the psychrometric properties of air being drawn into the poultry house (infiltration plus cooled air mixed together before heat and humidity are added by the birds).
2. Determine the psychrometric properties and volumetric flow rate of air exhausted from the building (after sensible and latent heat are added by the birds).
3. Determine the rate (L/s) at which water must be supplied to the evaporative cooling pads by a water pump.

Solution: The ventilation process is sketched in Figure 2-8. Air at state 1 is at outdoor conditions, 40 C and 20% relative humidity. State 2 describes air which has been drawn through the evaporative cooler, and state 3 describes the mixture of cooled air and infiltration air. State 3 is the effective state of the ventilation air as it enters the poultry house. State 4 describes air expelled from the poultry house after gaining sensible and latent heat from the birds.

The change of state from 1 to 2 is evaporative cooling, from 1 and 2 to 3 is adiabatic mixing, and from 3 to 4 is a process of heating and humidifying.

Ventilation starts at state 1, and psychrometric properties at outdoor conditions may be obtained from either the psychrometric chart or equations.

At state 1:

(dry-bulb temperature = 40 C),
(relative humidity = 20%),
water vapor saturation partial pressure = 7.38 kPa,
water vapor partial pressure = 1.48 kPa,
humidity ratio = 0.009199 kg/kg,
specific volume = 0.893 m^3/kg,
enthalpy = 63.9 kJ/kg,
wet-bulb temperature = 22 C,
dew point temperature = 12.6 C.

The mass flow rate through the evaporative cooler is

v of state 2

$$\dot{M}_{al} = (75\ m^3/s)/(\cancel{0.893}\ m^3/kg) = 84\ kg/s,$$

and the mass flow rate entering the poultry house by infiltration is

$$\dot{M}'_{al} = (15\ m^3/s)/(0.893\ m^3/kg) = 17\ kg/s.$$

The next step is to determine the properties of air after it leaves the evaporative cooler (state 2). The wet-bulb temperature of state 1 is 22 C which is a wet-bulb depression of 40 C - 22 C = 18 K. Evaporative cooling is 75% efficient, thus, the actual cooling effect is 0.75(18 K) = 13.5 K. As a consequence, the dry-bulb

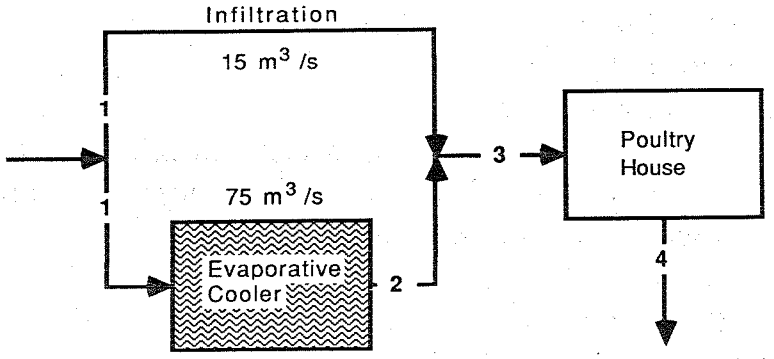


Figure 2-8. Ventilation with infiltration and evaporative cooling; see Example 2-15.

temperature of air leaving the evaporative cooler is 40 C - 13.5 K = 26.5 C, and the wet-bulb temperature is still 22 C. With two properties at state 2, the rest can be found from the psychrometric chart or psychrometric equations. The properties are:

(dry-bulb temperature = 26.5 C),
(wet-bulb temperature = 22 C),
water vapor saturation partial pressure = 3.46 kPa,
water vapor partial pressure = 2.35 kPa,
humidity ratio = 0.014783 kg/kg,
relative humidity = 67.9%,
enthalpy = 64.3 kJ/kg,
dew point temperature = 20.0 C,
specific volume = 0.855 m^3/kg.

The state of each airstream involved in the mixing process is now known. The state of the mixture can be determined. From Equation 2-31,

$$W_3 = \frac{((84\ \text{kg/s})(0.014783\ \text{kg/kg}) + (17\ \text{kg/s})(0.009199\ \text{kg/kg}))}{84\ \text{kg/s} + 17\ \text{kg/s}}$$
$$= 0.013843\ \text{kg/kg}.$$

From Equation 2-32,

$$h_3 = \frac{((84\ \text{kg/s})(64.3\ \text{kJ/kg}) + (17\ \text{kg/s})(63.9\ \text{kJ/kg}))}{84\ \text{kg/s} + 17\ \text{kg/s}}$$
$$= 64.2\ \text{kJ/kg}.$$

Other properties of state 3 may now be found and are:

(humidity ratio = 0. 013843 kg/kg),
(enthalpy = 64.2 kJ/kg),
dry-bulb temperature = 28.7 C,
wet-bulb temperature = 22 C,
dew point temperature = 18.9 C,
water vapor saturation partial pressure = 3.94 kPa,
water vapor partial pressure = 2.21 kPa,
relative humidity = 56%,
specific volume = 0.862 m^3/kg.

Note the wet-bulb temperature does not change in this mixing process. In general, a change would be expected, but in this example two airstreams each with a wet-bulb temperature of 22 C are mixed. One would not anticipate the wet-bulb temperature of the mixture to differ from that of the mixing streams. This observation provides a useful check to detect possible errors in using the psychrometric chart or psychrometric equations.

After adiabatic mixing, the next process is one of heating and humidifying. As previously stated, psychrometric properties at the end of a process are not functions of the path of the process. Heating and humidifying can be treated separately.

There are 101 kg/s of air at state 3 (and at state 4). To this air is added 150 kW (kJ/s) of sensible heat and 100 kW of latent heat. The dry-bulb temperature change of the heated air can be determined from

$$\Delta T = q_{sensible} / \left(\dot{M}_a c_p\right) \tag{2-34}$$

where the specific heat, c_p, is 1.006 kJ/kgK. Thus,

$$\Delta T = (150\ \mathrm{kJ/s})/((101\ \mathrm{kg/s})\underline{(1.006\ \mathrm{kJ/kgK})}) = 1.5\ \mathrm{K}.$$

The dry-bulb temperature of air within the poultry house is 28.7 C + 1.5 K or 30.2 C.

Heat of vaporization of water at 30.2 C, from Equation 2-20, is

$$h_{fg} = 2501 - (2.42)(30.2) = 2428\ \mathrm{kJ/kg},$$

$$\frac{\Delta W}{\Delta T} = -\frac{C_p}{h_{fg}}$$

for Adiabatic process

↓

psy chart 上絕熱線之斜率

and the humidity ratio change resulting from the birds' latent heat addition is

$$\begin{aligned} \Delta W &= q_{latent} / \left(\dot{M}_a h_{fg}\right) \\ &= (100\ \mathrm{kJ/s})/((101\ \mathrm{kg/s})\underline{(2428\ \mathrm{kJ/kg})}) = 0.000408\ \mathrm{kg/kg}. \end{aligned} \tag{2-35}$$

The humidity ratio of air within the poultry house equals the humidity ratio of air entering the house (state 3) plus the change or 0.013843 + 0.000408 = 0.014251 kg/kg. Two properties are now known, the others are:

(dry-bulb temperature = 30.2 C),
(humidity ratio = 0.014251),
water vapor saturation partial pressure = 4.30 kPa,
water vapor partial pressure = 2.27,
relative humidity = 53%,
dew point temperature = 19.4 C,
enthalpy = 66.8 kJ/kg,
wet-bulb temperature = 22.7 C,
specific volume = 0.870 m^3/kg.

The volumetric flow rate of air expelled from the poultry house is

$$\dot{V} = (101\ \mathrm{kg/s})\ (0.870\ \mathrm{m^3/kg}) = 87.9\ \mathrm{m^3/s}$$

which is slightly less than the total volumetric rate of outdoor air entering the building (75 m^3/s + 15 m^3/s = 90 m^3/s). The difference is due to changes of dry-bulb temperature and moisture content.

W_2 W_1 ΔW

The humidity ratio change of air passing through the evaporative cooler is 0.014783 kg/kg - 0.009199 kg/kg = 0.005584 kg/kg, based on data obtained in the analysis of the evaporative cooling process. Total airflow rate through the cooler is 84 kg/s, thus, water evaporates at a rate of

$$\dot{M}_{water} = (84 \text{ kg/s}) (0.005584 \text{ kg/kg}) = 0.47 \text{ kg/s}.$$

The pumping rate is to be triple the above rate, or approximately 1.41 kg/s (1.5 L/s). In an actual design, this pumping rate for the water pump would be specified at a pressure drop calculated separately for the plumbing system to be used.

Using the psychrometric chart. To this point, the solution has been presented with little detail of how psychrometric properties were determined after parameters of each process were calculated. The traditional means to trace processes and obtain values of properties has been the psychrometric chart. The processes of this example are traced on the psychrometric chart in Figure 2-9.

To use the chart, the first step is to locate state 1 – the outdoor air. The volumetric airflows of the two airstreams are given at state 1. The specific volume can be estimated and the respective mass flow rates determined.

State 2 is found 75% of the way (measured) from state 1 to the wet-bulb temperature of state 1.

State 3 is determined by the mixing process and lies along the line connecting states 1 and 2. The ratio $\dot{M}_{a1} / (\dot{M}_{a1} + \dot{M}_{a2})$ multiplied by the distance between states 1 and 2 is used to measure how far state 3 is from state 2. A ruler can be used, or dry-bulb temperature can be used as the scale. It is easy to measure in the wrong direction in this step. As drawn in Figure 2-9, state 3 is much nearer state 2 than state 1. This should be intuitively correct, for a greater mass of air at state 2 is involved in the mixing process. This intuitive check is useful to avoid inadvertent error.

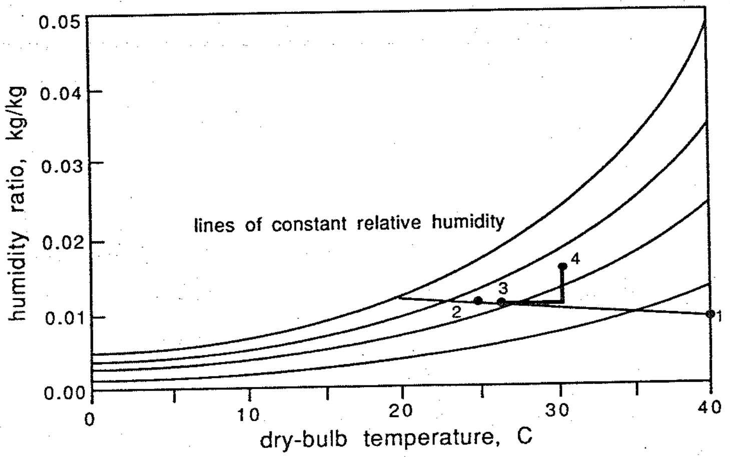


Figure 2-9. Evaporative cooling and reheating process, see Example 2-15.

Starting at state 3, the dry-bulb temperature and humidity ratio increases are calculated as done above and measured on the psychrometric chart to reach state 4.

Using the psychrometric equations. Example 2-15 could be readily implemented on a computer. Two computational sequences which would be required have been presented previously in this chapter. They may be integrated into the solution procedure described above. The sequence in Table 2-5 can be used to determine properties after the evaporative cooling process. Table 2-4 can be used to provide a suitable sequence to determine properties after mixing to reach state 3.

Dry-bulb temperature and humidity ratio for state 4 can be determined as done above. When they are known, other properties can be found using the sequence in Table 2-6.

Table 2-6. Example computational procedure to determine psychrometric properties when the dry-bulb temperature and humidity ratio are known.

Given: Dry-bulb temperature and humidity ratio.

Procedure:

1. Calculate the water vapor saturation partial pressure using Equation 2-1.
2. Calculate the water vapor partial pressure using Equation 2-9.
3. Calculate relative humidity using Equation 2-2.
4. Calculate specific volume using Equation 2-16.
5. Calculate dew point temperature using Equation 2-17 or 2-18.
6. Calculate enthalpy using Equation 2-21.
7. Calculate wet-bulb temperature using Equation 2-22 and the iterative procedure as described.

2-7. Cooling and Dehumidifying Revisited

Cooling and dehumidifying have previously been described as a process of first cooling to the dew point temperature, then following the saturation line to the

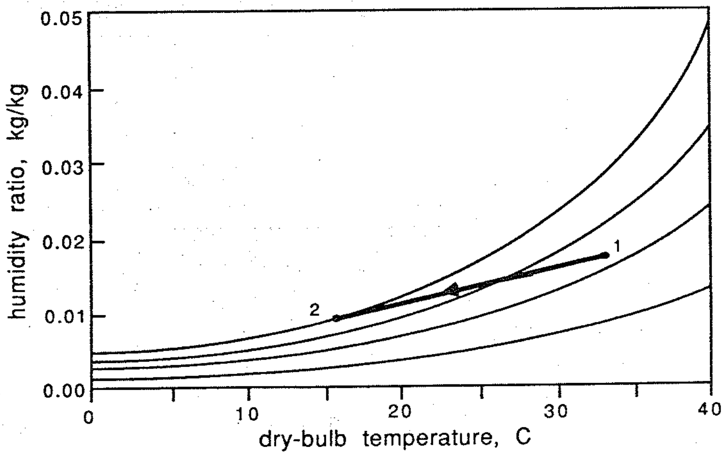


Figure 2-10. Simultaneous cooling and dehumidification, the straight-line law.

final dry-bulb temperature. While this may be correct in concept and suitable for many psychrometric calculations, it does not accurately describe the path followed by a mass of air on the average in contact with a surface below its dew point temperature.

A method to analyze combined heat and mass transfer (condensation) is the so-called "straight-line" law. This law states that when moist air loses heat and water vapor simultaneously to a surface below the air's dew point temperature, the process follows a straight line drawn between the original state of the air and saturation at the temperature of the surface. The process is sketched in

Table 2-7. Functions contained in computer file PSYFUNC.

Function	Action
PWR(x,y:real)	Raises a real number x to a real power y.
DEWPOINT(t,p:real)	Calculates dew point temperature (C) based on dry-bulb temperature, t (C), and water vapor pressure, p (kPa). Applies for dry-bulb temperatures between -60 to 70 C. See Equations 2-17 and 2-18.
PSAT(t:real)	Calculates partial pressure (kPa) of water vapor at saturation at dry-bulb temperature, t (C). Applies for dry-bulb temperatures between -40 and 120 C. See Equation 2-1.
ENTHALPY(t,w:real)	Calculates enthalpy of moist air (kg/kg) at dry-bulb temperature, t (C), and humidity ratio w, (kg/kg). See Equation 2-21.
SPEC_VOLUME (t,w,pa:real)	Calculates the specific volume (m^3/kg) of dry air at dry-bulb temperature, t (C), humidity ratio, w (kg/kg), and air pressure, pa (kPa). See Equation 2-15.
HUM_RATIO(p,pa:real)	Calculates the humidity ratio of moist air (kg/kg) at air pressure, pa (kPa), and water vapor partial pressure, p (kPa). See Equation 2-9.
WET_BULB(t,w,hh,pa:real)	Uses iterative procedure to determine wet-bulb temperature (C) when dry-bulb temperature, t (C), humidity ratio, w, (kg/kg), enthalpy, hh (kJ/kg) and air pressure, pa (kPa), are known. As written, determines wet-bulb temperature to nearest 0.01 C. See Equation 2-22.
REL_HUM(mu,pws,pa:real)	Calculates relative humidity (decimal) of moist air when degree of saturation, mu (dimensionless), water vapor saturation partial pressure, pws (kPa), and air pressure pa (kPa), are known. See Equation 2-12a.
DEG_SAT(rh,pws,pa:real)	Calculates the degree of saturation when the relative humidity, rh (decimal), water vapor saturation partial pressure, pws (kPa) and air pressure, pa (kPa), are known. See Equation 2-12b.

Figure 2-10. Such processes occur frequently in agricultural buildings, such as in air-air heat exchangers for energy conservation, and when condensation occurs on the inner surfaces of outside walls during cold weather. We will return to this subject after discussing heat transfer.

2-8. Computerized Psychrometric Functions

The file PSYFUNC contains psychrometric functions that can be used to develop psychrometric computer programs. See Table 2-7 for the functions contained in PSYFUNC.

2-9. Computerized Psychrometric Procedures

The file PSYPROC contains Pascal procedures that can be used in locally written programs to calculate psychrometric properties when two of the properties are known.

One other variable used in file PSYPROC is airp, the air pressure (kPa). The 12 variables (properties plus airp) should be declared as fields of a record in a program that uses PSYPROC and PSYFUNC. The 12 variables should be passed among the main program and its procedures as a variable of the type defined by the record. See Table 2-9 for an example where a suitable record type, and variable of the type, are defined and used to call the psychrometric procedures.

Numerous checks are incorporated into the procedures to screen out combinations of psychrometric property values which are not possible. The procedures and their uses are listed below. For each procedure, the listed psychrometric properties must be known before the procedure can be called. The procedure calculates values for the other properties. The entire file can be

Table 2-8. Properties required to use computer files PSYFUNC and PSYPROC.

Property	Name	Units
dry-bulb temperature	dbt1	C
relative humidity	rh 1	(decimal)
water vapor saturation partial pressure	ppsat1	kPa
water vapor partial pressure	pp1	kPa
humidity ratio	w1	kg/kg
dew point temperature	dpt1	C
enthalpy	h1	kJ/kg
wet-bulb temperature	wbt1	C
degree of saturation	mu 1	(decimal)
Two additional properties are calculated but cannot be included as known properties to begin the process of calculating the others.		
specific volume of dry air	spvol1	m^3/kg
density of moist air	dens1	kg/m^3

included in a locally written program by using the Include function of Turbo Pascal, or appropriate options available through other Pascal editors. Iterative search techniques are used in many of these procedures.

Procedure	Properties Which Must Be Known
DB_RH	dry-bulb temperature and relative humidity
DB_W	dry-bulb temperature and humidity ratio
DB_WB	dry-bulb and wet-bulb temperatures
DB_DP	dry-bulb and dew point temperatures
DB_H	dry-bulb temperature and enthalpy
RH_W	relative humidity and humidity ratio
RH_WB	relative humidity and wet-bulb temperature
RH_DP	relative humidity and dew point temperature
RH_H	relative humidity and enthalpy
W_WB	humidity ratio and wet-bulb temperature
W_H	humidity ratio and enthalpy
WB_DP	wet-bulb and dew point temperatures
WB_H	wet-bulb temperature and enthalpy
DP_H	dew point temperature and enthalpy

2-10. Example Using PSYPROC

Example 2-16

Problem: Develop a computer program to solve the ventilation problem described in Example 2-15 minus infiltration air. Write the program in Pascal. The program should be sufficiently user friendly and flexible to request the following input:

outdoor air temperature,
outdoor relative humidity,
atmospheric pressure,
airflow rate through the cooling pads (m^3/s),
cooling system efficiency,
latent heat production by the birds,
sensible heat production by the birds.

Output of the program should be indoor air temperature and relative humidity.

Solution: In Table 2-9 there is a listing of a simple program written for Turbo 3 (© Borland International) Pascal. Files PSYFUNC.PAS and PSYPROC.PAS are in the program through the use of Include files. A copy of a screen showing input and output of the program is included in the table. Note: The calculation procedure in the program is only one of many possible paths to the solution.

Table 2-9. Example Pascal (Turbo Pascal Version 3.0) program to solve the problem stated in Example 2-16.

```
program Example2_16;

CONST     cpair = 1006.0;

TYPE      psyprops = RECORD              {Properties required in psychrometric
                                          procedures in PSYPROC.PAS.  Records
                                          are easier to pass among procedures
                                          than are large groups of variables.}

                       airp,             {atmospheric pressure, kPa}
                       dbt,              {dry-bulb temperature}
                       rh,               {relative humidity}
                       ppsat,            {water vapor saturation pressure}
                       pp,               {water vapor pressure}
                       w,                {humidity ratio}
                       dpt,              {dew point temperature}
                       h,                {enthalpy}
                       wbt,              {wet bulb temperature}
                       mu,               {degree of saturation}
                       spvol,            {specific volume}
                       dens:             {air density}
                              real
                     END;

          probdata = RECORD              {data specific to the problem}

                       dbtout,           {outdoor dry-bulb temperature}
                       dbtin,            {indoor dry-bulb temperature}
                       rhout,            {outdoor relative humidity}
                       rhin,             {indoor relative humidity}
                       wout,             {outdoor humidity ratio}
                       win,              {indoor humidity ratio}
                       airp,             {atmospheric pressure, kPa}
                       volairflow,       {volumetric air flow rate}
                       massairflow,      {mass rate of air flow}
                       effic,            {evaporative cooling efficiency}
                       latentheat,       {addition of latent heat to the space}
                       sensibleheat:     {addition of sensible heat to the space}
                              real
                     END;


VAR       runagain:        boolean;
          airproperties:   psyprops;
          otherproperties: probdata;


{$IPSYFUNC.PAS}
{$IPSYPROC.PAS}

 PROCEDURE DrawBox(x1,y1,x2,y2:integer);

    VAR    i: integer;

    BEGIN

       gotoxy(x1,y1);
       write(chr(218));
       gotoxy(x2,y1);
       write(chr(191));
       gotoxy(x1,y2);
       write(chr(192));
       gotoxy(x2,y2);
       write(chr(217));

       FOR i := (x1+1) TO (x2-1) DO
          BEGIN
             gotoxy(i,y1);
             write(chr(196));
             gotoxy(i,y2);
             write(chr(196));
          END;
```

Table 2-9. Continued.

```
      FOR i := (y1+1) TO (y2-1) DO
         BEGIN
            gotoxy(x1,i);
            write(chr(179));
            gotoxy(x2,i);
            write(chr(179));
         END;

   END;  {PROCEDURE DrawBox}


FUNCTION DoAgain: Boolean;

   VAR  choice: char;

   BEGIN

      DrawBox(10,22,67,24);
      gotoxy(14,23);
      write('Enter <y> to run the program again, <n> if not: ');
      readln(choice);
      IF upcase(choice) = 'Y' THEN DoAgain := TRUE
      ELSE DoAgain := FALSE;

   END;  {FUNCTION DoAgain}
PROCEDURE Input(VAR airproperties:psyprops; VAR otherdata:probdata);

   {NOTE: no error trapping is included here, so program will bomb
          if other than numbers are entered}

   BEGIN


      WITH otherdata DO BEGIN

         gotoxy(10,1);
         textbackground(lightgray);
         textcolor(black);
         write(' SAMPLE PROGRAM TO SOLVE EXAMPLE 2-16, EVAPORATIVE COOLING ');
         textbackground(black);
         textcolor(lightgray);
         DrawBox(10,3,67,17);
         gotoxy(15,4);
         write('Please enter atmospheric pressure, kPa: ');
         readln(airproperties.airp);
         gotoxy(15,6);
         write('Please enter outdoor air temperature, C: ');
         readln(dbtout);
         gotoxy(15,8);
         write('Please enter outdoor relative humidity, %: ');
         readln(rhout);
         gotoxy(15,10);
         write('Please enter volumetric air flow rate, m3/s: ');
         readln(volairflow);
         gotoxy(15,12);
         write('Please enter cooling system efficiency, %: ');
         readln(effic);
         gotoxy(15,14);
         write('Please enter sensible heat production, W: ');
         readln(sensibleheat);
         gotoxy(15,16);
         write('Please enter latent heat production, W: ');
         readln(latentheat);

      END;  {WITH}

   END;  {PROCEDURE Input}


PROCEDURE Output(otherdata:probdata);

   BEGIN

      DrawBox(14,18,63,21);
      gotoxy(16,19);
      write('     Indoor air temperature is: ', otherdata.dbtin:7:1,' C');
      gotoxy(16,20);
```

Table 2-9. Continued.

```
   write('     Indoor relative humidity is: ', otherdata.rhin:5:1,' %');

END;  {PROCEDURE Output}

PROCEDURE Calculate(props:psyprops; VAR data:probdata);

   VAR   hfg: real;    {heat of vaporization of water}

   BEGIN

      WITH data DO BEGIN

         props.dbt := dbtout;
         props.rh := rhout/100.0;
         DB_RH(props);
         dbtin := dbtout - (effic/100.0)*(dbtout - props.wbt);
         massairflow := volairflow*props.dens;
         props.dbt := dbtin;
         DB_WB(props);
         dbtin := props.dbt + sensibleheat/(massairflow*cpair);
         hfg := 2501.0 - 2.42*dbtin;
         win := props.w + latentheat/(massairflow*hfg*1000.0);
         props.dbt := dbtin;
         props.w := win;
         DB_W(props);
         rhin := props.rh*100.0;

      END;  {WITH}

   END;  {PROCEDURE Calculate}


{*************************** MAIN PROGRAM ************************************}

BEGIN

   runagain := TRUE;
   window(1,1,80,25);

   WHILE runagain DO BEGIN
      clrscr;
      input(airproperties,otherproperties);
      calculate(airproperties,otherproperties);
      output(otherproperties);
      RunAgain := DoAgain;
   END;  {WHILE}

   clrscr;

END.
```

SAMPLE PROGRAM TO SOLVE EXAMPLE 2-16, EVAPORATIVE COOLING

```
Please enter atmospheric pressure, kPa: 101.325

Please enter outdoor air temperature, C: 40

Please enter outdoor relative humidity, %: 20

Please enter volumetric air flow rate, m3/s: 75

Please enter cooling system efficiency, %: 75

Please enter sensible heat production, W: 150000

Please enter latent heat production, W: 100000
```

```
Indoor air temperature is:     28.3 C
Indoor relative humidity is:   63.2 %
```

```
Enter <y> to run the program again, <n> if not:
```

2-11. Program PLUS

The program PLUS (Psychrometric Look-Up Substitute) is available as a substitute for the psychrometric chart and is an implementation of the psychrometric equations described in this chapter. It is provided as a tool for work related to future chapters rather than an auxiliary to this chapter. Contained within PLUS are the functions and procedures described in the previous sections of this chapter.

Program PLUS is self-contained and information windows are provided to assist users. It would be a useful exercise to go now to PLUS, become familiar with its operation, and check its results against some of the examples described above.

SYMBOLS

c_p	specific heat, J/kgK or kJ/kgK
h	enthalpy, J/kg or kJ/kg
M	mass, kg
$\dot{M}$	mass flow rate, kg/s
n	number of moles
p	pressure, Pa or kPa
q	thermal energy, joules
R	gas constant, J/kgK
t	temperature, C
T	absolute temperature, K
V	volume, m^3
v	specific volume, m^3/kg
$\dot{V}$	volumetric flow rate, m^3/s
W	humidity ratio, kg/kg
x	mole fraction
μ	degree of saturation
ρ	density, kg/m^3
ϕ	relative humidity

EXERCISES

1. Use the psychrometric charts to determine how much water vapor must be added to 5 kg of air at -15 C and 50% relative humidity, if it is to be conditioned to 25 C and 20% relative humidity.

2. Determine the final state of air resulting from an adiabatic mixing process where 20 kg of air at 10 C and 80% relative humidity is mixed with 4 kg of air at 30 C and 50% relative humidity. Sketch the process on a psychrometric chart.

3. Determine the final dry-bulb temperature of air at 35 C and 40% relative humidity which is cooled evaporatively at 80% efficiency.

4. Calculate, based on psychrometric equations, the humidity ratio, enthalpy, specific volume, and dew point temperature of air at 27.4 C dry-bulb temperature and 43% relative humidity when the atmospheric pressure is 92 kPa.

5. Develop a computer program to calculate relative humidity, humidity ratio, enthalpy, specific volume, and dew point temperature when dry-bulb and wet-bulb temperatures are known.

6. Develop a computer program to solve an adiabatic mixing problem such as described in Example 2-11. Retain sufficient flexibility in the input of the program so that dry-bulb temperatures, relative humidities, and volumetric flow rates of each airstream can be independently specified. That is, do not write the program specifically for the conditions of Example 2-11.

7. In a refrigeration unit, 2.8 m^3/s of air at 14 C dry-bulb temperature, 85% relative humidity, and standard atmospheric pressure enters the unit. The air is cooled by the refrigeration process to 4 C dry-bulb temperature, and there is no reheating. Using the psychrometric chart, sketch the process and determine the refrigerating capacity of the unit in kW, the rate of water removal from the air in kg/s, and the volumetric flow rate of air leaving the refrigerator.

8. A very well-insulated building (no heat loss or moisture diffusion through the structural cover) is being ventilated. The building is located at an elevation of 1750 m above sea level. Water vapor within the building is produced at a rate of 0.018 kg/s and sensible heat at a rate of 82 kW. If outdoor relative humidity remains constant at 80% and the indoor dry bulb temperature remains constant at 20 C, determine the outdoor temperature at which indoor relative humidity is minimized. Explore the outdoor air temperature range between - 25 to 15 C. Program PLUS may be useful in determining psychrometric properties quickly. Describe (in words) why there is a relative humidity minimum instead of a monotonic change as outdoor air temperature changes from - 25 to 15 C.

9. Consider the same building as in Problem 8 (very well insulated). If outdoor air relative humidity is 80% and outdoor air temperature is -10 C, determine the ventilation rate (to the nearest kg/s) at which the indoor relative humidity will be maximized. What will be the indoor temperature and relative humidity at that ventilation rate? Program PLUS may be helpful to find psychrometric properties for many conditions quickly. Explore the ventilation rate range between 5 and 20 kg/s. Describe (in words) why there is a relative humidity maximum instead of a monotonic change as the ventilation rate changes from 5 to 20 kg/s.

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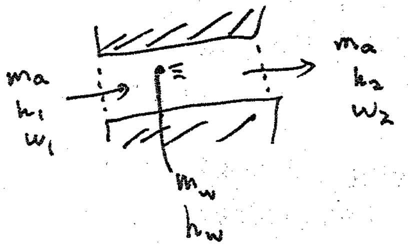
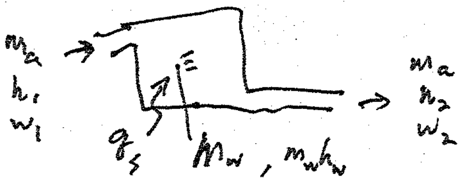
Adiabatic mixing of water injected into moist air



$$\begin{cases} m_a h_1 + m_w h_w = m_a h_2 \\ m_a w_1 + m_w = m_a w_2 \end{cases}$$

$$\Rightarrow \frac{h_2 - h_1}{w_2 - w_1} = \frac{\Delta h}{\Delta w} = h_w$$

Space heat Absorption & Moist Air Moisture Gains.



$$\begin{cases} m_a \cdot h_1 + q_s + m_w h_w = m_a h_2 \\ m_a \cdot w_1 + m_w = m_a w_2 \end{cases}$$

$$\Rightarrow \begin{cases} q_s + m_w h_w = m_a (h_2 - h_1) \\ m_w = m_a (w_2 - w_1) \end{cases}$$

$$\Rightarrow \frac{h_2 - h_1}{w_2 - w_1} = \frac{\Delta h}{\Delta w} = \underbrace{\frac{q_s + m_w h_w}{m_w}}_{\parallel\, m}$$

P12, 13.

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$$\frac{\text{Sensible heat}}{\text{Total}} \doteq \frac{\Delta H_s}{\Delta H_T} = \frac{q_s}{q_s + q_l} = \frac{q_s}{q_s + m_w \cdot h_w}$$

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$\rfloor$ — h_w.

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