

of the thermometer. Arnold¹ has developed a theory which makes possible the calculation of the thermodynamic wet-bulb temperature from observed data through the use of suitable corrections to be applied to the readings of the wet-bulb thermometer. However, it is frequent practice to take the observed equilibrium readings of a wetted-wick thermometer as being essentially equal to the thermodynamic wet-bulb temperature, if the air velocity past the wick is about 1000 fpm and if the wick is exposed to radiation exchange with surroundings at temperatures differing from the dry-bulb temperature by no more than about 20 F deg.

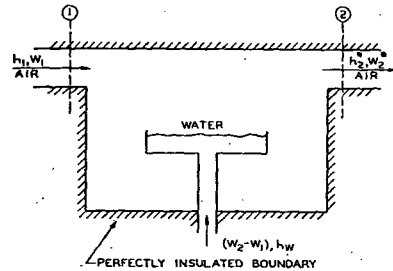


Fig. 3 Illustration of Adiabatic Saturation

USEFUL PERFECT-GAS RELATIONSHIPS

In early thermodynamics, with particular reference to the properties of gases, pure and mixed, scientists expressed relationships between the properties of gases in formulations which they called *laws*. Today, with evidence from highly precise measurements and with greatly improved scientific knowledge of the details involved, these early so-called *laws* have been found to be approximations. Many useful engineering results, however, can be accomplished with the aid of judicious approximations, if the accuracy and limitations involved can be established. Calculations making use of so-called *perfect gas* relationships fall into this category.

Thermodynamically considered, a perfect gas can be defined as one for which the pressure, volume, and temperature are related by the following *equation of state*:

$$PV = w \frac{R}{m} T \quad (9)$$

where

P = pressure, pounds per square foot, absolute.

V = volume occupied, cubic feet.

w = mass of gas, pounds.

R = constant (which is the same for all perfect gases) = 1544 foot pounds per (mol) (Fahrenheit degree, absolute).

m = molecular weight, pounds per mol.

T = temperature, Fahrenheit, absolute.

From the above relationship follow:

(1) Boyle's Law,

$$P_1 V_1 = P_2 V_2 \text{ when } T_1 = T_2, \text{ and } \quad (10)$$

(2) Charles' or Gay-Lussac's Law,

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \text{ when } P_1 = P_2 \quad (11)$$

where subscripts 1 and 2 refer to two different states of the gas.

Historically, the above laws were derived from experimental observations by the men for whom they are named.

Common diatomic and triatomic gases, such as are dealt with in air conditioning, follow perfect-gas relationships fairly well at pressures less than a few atmospheres and temperatures which are far enough removed from the saturation temperature. A quantitative measure of departure from perfect-gas behavior may be had in magnitudes of the *compressibility factor*, F_c , defined as

$$F_c = \frac{P(V/w)}{(R/m)T} \quad (12)$$

For a perfect gas, F_c is unity. Magnitudes of F_c are given in many treatises on thermodynamics.⁴

The adopted definition of *partial pressure* means that the pressure of a gas mixture is exactly the sum of the partial pressures of the constituents. This is a present-day formulation of a concept first given by Dalton, who indicated that each gas in a mixture occupies the total volume of the mixture just as though the other gases were not present. If this concept of direct addition of constituent properties to obtain mixture properties were generally applicable, then the gas-mixture properties on a per-mol basis such as enthalpy, entropy, specific heat, and internal energy, all could be determined by simple summations of mol fractions times the property in question for each constituent of the mixture. In reality this simple relationship is not true, but it is approximated closely at low or moderate pressures where the gases approach perfect-gas behavior.

Mechanistically considered, a perfect gas may be described as having perfectly elastic point-mass molecules with no molecular attraction or repulsion forces either between the molecules or involving the container walls. Real gases approach these attributes more closely as the pressure diminishes and the molecules move about more freely without collision.

The following gaseous-state equations are in common use (the symbols used are defined after Equation 26):

Equation of State:

$$\text{for air} \quad P_a V_a = w_a R_a T_a \quad (13)$$

$$\text{for water vapor} \quad P_v V_v = w_v R_v T_v \quad (14)$$

$$\text{for mixture} \quad P_m V_m = w_m R_m T_m \quad (15)$$

where

$$\frac{V_a}{w_a} = v_a; \quad \frac{V_v}{w_v} = v_v; \quad \frac{V_m}{w_m} = v_m \quad (16)$$

$$w_m = w_a + w_v \quad (17)$$

R_a = gas constant for dry air

= 53.3 ft lb per (lb) (F deg abs).

R_v = gas constant for water vapor

= 85.6 ft lb per (lb) (F deg abs).

$$R_m = \left(\frac{w_a}{w_a + w_v} \right) R_a + \left(\frac{w_v}{w_a + w_v} \right) R_v \quad (18)$$

¹ Denotes precise application to perfect gases only.

Thermodynamics

Relative humidity:

$$\phi = \frac{P_v}{P_{vs}} = \frac{w_v}{w_{vs}} \quad (19)$$

Humidity ratio:

$$W = \frac{18.016 P_v}{28.966 P_a} = 0.622 \frac{P_v}{P - P_v} \quad (20)$$

where 18.016 and 28.966 are the molecular weights of water and air respectively.

$$P = P_a + P_v \quad (21)$$

$$P_a = \frac{n_a}{n_a + n_v} P; \quad P_v = \frac{n_v}{n_a + n_v} P \quad (22)$$

$$n_a = \frac{w_a}{28.966}; \quad n_v = \frac{w_v}{18.016} \quad (23)$$

In the thermodynamic properties which follow, it is convenient and conventional to express all mixture properties as *per unit mass of dry air* in the mixture of air and water vapor.

Specific heat:

$$c_{pm} = c_{pa} + W c_{pv} \quad (24)$$

where

$$c_{pa} = 0.24 \text{ and } c_{pv} = 0.44 \text{ Btu/(lb) (F deg)} \text{ in the ordinary temperature range.}$$

Enthalpy:

$$h_m = h_a + W h_v \quad (25)$$

Entropy:

$$s_m = s_a + W s_v \quad (26)$$

where

s_a and s_v are evaluated at the respective partial pressures in the mixture.

Symbols for Equations 13-26 are given below.

Subscripts: a denotes dry air

v denotes water vapor

m denotes air-vapor mixture

vs denotes saturated pure water vapor

P = pressure, pounds per square foot, absolute.

V = volume, cubic feet.

v = specific volume, cubic feet per pound.

w = mass, pounds.

R = gas constant per unit mass, foot-pounds per (pound) (Fahrenheit degree, absolute).

T = temperature, Fahrenheit, absolute.

ϕ = relative humidity, decimal.

W = humidity ratio, pounds vapor per pound dry air.

n = moles.

c_p = specific heat, Btu per (pound) (Fahrenheit degree).

h = enthalpy, Btu per pound; note especially that h_m is Btu per pound of dry air in the mixture.

s = entropy, Btu per (pound) (Fahrenheit degree absolute); note especially that s_m is in Btu per (pound of dry air in the mixture) (Fahrenheit degree absolute).

The mixture enthalpy h_m , Equation 25, can be empirically

¹ Denotes precise application to perfect gases only.

expressed, within about 0.1 percent accuracy over the range 32 to 100 F at 1 atmosphere pressure by the equation

$$h_m = (0.2402 + 0.44W)t + 1061W \quad (27)$$

where

t = dry-bulb temperature, Fahrenheit.

Equation 27 states that:

$$h_m = 0.2402 t, \text{ and} \quad (28)$$

$$h_m = 1061 + 0.44 t \quad (29)$$

TABULATED THERMODYNAMIC PROPERTIES OF MOIST AIR AND OF WATER AT SATURATION FOR ACCURATE CALCULATIONS

Engineering designs and analyses often require accuracies which cannot be achieved with perfect-gas assumptions. This need is expeditiously met by using properties in tabular form. Properties of steam⁴ and many gases⁴ have been tabulated.

The latest and most precise formulation of the thermodynamic properties of moist air is found in the work of Goff and Gratch.⁷ Much of the work basic to this material was performed as an ASHAE cooperative research activity in the Towne Scientific School of the University of Pennsylvania.

Table 2 gives complete data for moist air at a pressure of 1 standard atmosphere and temperatures from minus 160 F to plus 200 F. In Table 2 there are 15 columns of values, each column being headed by a symbol; in the following subparagraphs brief explanations of these columns are given.

$t(F)$ = Fahrenheit temperature defined in terms of absolute temperature T by the relation,

$$T = t + 459.67 \quad (30)$$

W_s = humidity ratio at saturation. Saturation is the condition at which the vapor phase (moist air) may exist in equilibrium with a condensed phase (liquid or solid) at the given temperature and pressure (standard atmospheric pressure in the case of Table 2). At given values of temperature and pressure, the humidity ratio W can have any value from zero to W_s .

v_a = specific volume of dry air, cubic feet per pound.

v_{as} = $v_a - v_{as}$, the difference between the volume of moist air at saturation, per pound of dry air, and the specific volume of the dry air itself, cubic feet per pound of dry air.

v_s = specific volume of moist air at saturation per pound of dry air, cubic feet per pound of dry air.

h_a = specific enthalpy of dry air, Btu per pound of dry air. The specific enthalpy of dry air has been assigned the value zero at 0 F, standard atmospheric pressure. The energy unit Btu is related to the foot-pound by definition, as follows: 1 Btu = 778.3 ft-lb.

h_{as} = $h_a - h_{as}$, the difference between the enthalpy of moist air at saturation, per pound of dry air, and the specific enthalpy of the dry air itself, Btu per pound of dry air.

h_v = enthalpy of moist air at saturation per pound of dry air, Btu per pound of dry air.

s_a = specific entropy of dry air, Btu per (pound) (Fahrenheit degree absolute). It will be noticed that the specific entropy of dry air has been assigned the value zero at 0 F and standard atmospheric pressure.

s_{as} = $s_a - s_{as}$, the difference between the entropy of moist air at saturation, per pound of dry air, and the specific entropy of the dry air itself, Btu per (pound of dry air) (Fahrenheit degree absolute).

s_v = entropy of moist air at saturation per pound of dry air, Btu per (pound of dry air) (Fahrenheit degree, absolute).

h_w = specific enthalpy of condensed water (liquid or solid) in equilibrium with saturated air at standard atmospheric pressure, Btu per pound of water. The specific enthalpy of

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