

- K = enthalpy correction term to be added to enthalpy. See Table 6.
- h_a = enthalpy of dry air, Btu per pound.
- $h_{a,s}$ = $h_a - h_s$ = 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_f = enthalpy of liquid water, Btu per pound.
- h_g = enthalpy of saturated water vapor, Btu per pound.
- h_i = enthalpy of ice, Btu per pound.
- h_s = enthalpy of moist air at saturation per pound of dry air, Btu per pound of dry air.
- h_s^* = enthalpy of moist air at saturation at thermodynamic wet-bulb temperature t^* , Btu per pound of dry air.
- h_w = enthalpy of water vapor, Btu per pound.
- $h_{w,s}$ = enthalpy of condensed water (liquid or solid) at standard pressure, Btu per pound water.
- $h_{w,s}^*$ = enthalpy of water as added at the thermodynamic wet-bulb temperature t^* , Btu per pound of dry air.
- L = flow rate of liquid water, pounds per hour.
- m = molecular weight, pounds per mol.
- n_a = mols dry air.
- n_s = mols of water vapor at saturation.
- n_w = mols of water vapor.
- P = pressure, pounds per square foot absolute.
- P_a = atmospheric pressure, inches Hg.
- P_s = standard atmospheric pressure by definition 1,013,250 dynes per square centimeter, or approximately 29.921 in. Hg.
- $P_{s,w}$ = vapor pressure of water in saturated moist air, pounds per square inch or inches Hg, absolute. P_s differs from the saturation pressure of pure water because of the presence of the air.
- $P_{s,w}$ = saturation pressure of pure water at prevailing temperature, inches Hg.
- Q = energy added to the system between states 1 and 2, Btu.
- q = rate of energy addition to flow system between sections 1 and 2, Btu per minute.
- R = universal gas constant, 1544 foot-pounds per (Fahrenheit degree) (mol).
- R_a = gas constant for dry air.
- R_s = gas constant for water vapor.
- S = flow rate of solid water, pounds per hour.
- s = entropy, Btu per (pound) (Fahrenheit degree, absolute).
- s_a = entropy of moist air per pound of dry air, Btu per (pound) (Fahrenheit degree).
- s_a^* = correction to be added to entropy of moist air obtained from Table 2.
- s^* = additional correction to be added to entropy because of "mixing entropy" (obtained from Table 5). Correction to be added to value of s obtained from Table 2.
- s_a = entropy of dry air, Btu per (pound) (Fahrenheit degree, absolute).
- $s_{a,s}$ = 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_s = entropy of moist air at saturation per pound of dry air, Btu per (pound of dry air) (Fahrenheit degree, absolute).
- s_w = entropy of water vapor, Btu per (pound) (Fahrenheit degree, absolute).
- $s_{w,s}$ = specific entropy of condensed water (liquid or solid)

- at standard atmospheric pressure, Btu per (pound of water) (Fahrenheit degree, absolute).
- T = temperature, absolute, Fahrenheit.
- T_s = standard atmospheric temperature, by definition 518.4 F, absolute.
- t = temperature, Fahrenheit.
- t^* = thermodynamic wet-bulb temperature, Fahrenheit.
- U = internal energy of system, Btu.
- u = internal energy.
- V = volume, cubic feet.
- v_a = volume of moist air per pound of dry air, cubic feet per pound.
- v = correction to be added to volume of moist air per pound of dry air. See Table 6.
- v_a = specific volume of dry air, cubic feet per pound.
- $v_{a,s}$ = $v_a - v_s$, the difference between volume of moist air at saturation, per pound of dry air, and the volume of the dry air itself, cubic feet per pound of dry air.
- v_s = volume of moist air at saturation per pound of dry air, cubic feet per pound of dry air.
- W = rate of work output of the system between sections 1 and 2, Btu per minute.
- W = humidity ratio of moist air, pounds of water per pound of dry air.
- W_s = humidity ratio, at saturation, weight of water vapor per pound of dry air, pound per pound.
- W_s^* = humidity ratio corresponding to thermodynamic wet-bulb temperature t^* , pounds of water per pound of dry air.
- w = mass of gas, pounds.
- Z = elevation above any datum, feet.

Subscripts with symbols have following meanings: 1, 2, 3 indicate section of flow; a = air, v = water vapor, ss = pure saturated water vapor, w = water, ws = liquid water, ws = solid water, s = saturation, m = mixture; * indicates that the value is at thermodynamic wet-bulb temperature.

REFERENCES

- J. A. Goff and S. Gratch: The humidity ratio of moist air at saturation (University of Pennsylvania Thermodynamic Research Laboratory Special Report, March 1948).
- J. A. Goff: Standardization of thermodynamic properties of moist air (ASHVE TRANSACTIONS, Vol. 55, 1949, p. 459).
- J. H. Arnold: The theory of the psychrometer (Physics, Vol. 4, 1933).
- O. A. Hougen and K. M. Watson: Chemical Process Principles (John Wiley and Sons, New York).
- Tables of Thermal Properties of Gases (National Bureau of Standards Circular 564, November 1955).
- J. H. Keenan and F. G. Keyes: Thermodynamic Properties of Steam (John Wiley and Sons, New York, 1936).
- J. A. Goff and S. Gratch: Thermodynamic properties of moist air (ASHVE TRANSACTIONS, Vol. 51, 1945, p. 125).
- Smithsonian Meteorological Tables (Smithsonian Institution, 1951).
- J. A. Goff and S. Gratch: Low pressure properties of water in the range -160 to 212 F (ASHVE TRANSACTIONS, Vol. 52, 1946, p. 95).
- R. Mollier: Ein neues diagramm für dampfluftgemische (ZVDI, Vol. 67, September 8, 1923, p. 809).
- R. Mollier: Das i-x diagramm für dampfluftgemische (ZVDI, Vol. 73, July 20, 1929, p. 1009).
- Walter S. Diehl, Standard Atmosphere—Tables and Data, National Advisory Committee for Aeronautics Technical Report No. 218, 1925.
- W. G. Bombacher: Altitude-Pressure Tables Based on United States Standard Atmosphere, National Advisory Committee for Aeronautics Technical Report No. 538, 1935.

CHAPTER 4

FLUID FLOW

Theory of Fluid Flow, Pressure Loss in Circular Pipes, Pressure Loss in Non-Circular Pipes, Flow of Compressible Fluids, Ideal Flow Through Nozzle or Orifice, Flow Measurement, Head Meters, Location of Head Meters and Pressure Taps, Pitot Tube, Variable Area Flow Meters

THE flow of fluids which is part of the branch of engineering science known as fluid mechanics will be discussed here insofar as it applies to the work of engineers in the fields of heating, ventilating, and air conditioning. Probably air is the most frequently handled fluid, but other gases and liquids are often involved. Compressible fluids (gases) and incompressible fluids (liquids) vary somewhat in behavior, though in cases where pressure and density changes are small, the gases may be treated as incompressible fluids.

THEORY OF FLUID FLOW

The following energy equation for one dimensional steady flow processes will serve as a basis for the theory of the flow of fluids. This equation is presented in several ways in various texts, but a suitable form is

$$\frac{V_1^2}{2g} + J u_1 + p_1 v_1 + J q + \frac{g}{g_c} z_1 = \frac{V_2^2}{2g} + J u_2 + p_2 v_2 + W + \frac{g}{g_c} z_2 \quad (1)$$

where

- V = velocity, feet per second.
- g = gravitational acceleration, feet per (second) (second).
- g_c = gravitational conversion factor = 32.174 (pounds mass per pound force) $\times$ ft per (second) (second).
- J = mechanical equivalent of heat = 778 foot pounds per Btu.
- u = internal energy, Btu per pound of fluid.
- p = pressure per square foot, pounds.
- v = specific volume, cubic feet per pound.
- W = mechanical work done by the fluid, foot pounds per pound of fluid.
- q = heat transferred to the fluid, Btu per pound of fluid flowing.
- z = elevation above some arbitrary datum, feet.

Subscript 1 refers to the entrance, subscript 2 to the exit.

Introducing the enthalpy h , which by definition is $u + \frac{pv}{J}$, expressed in Btu per pound of fluid, Equation 1 becomes

$$\frac{V_1^2}{2g} + J h_1 + J q + \frac{g}{g_c} z_1 = \frac{V_2^2}{2g} + J h_2 + W + \frac{g}{g_c} z_2 \quad (2)$$

The equivalent differential form for energy Equation 1 is

$$\frac{1}{2g} dV^2 + J du + d(pv) + \frac{g}{g_c} dz - J dq + dW = 0 \quad (3)$$

Replacing v by its equal $g/\rho g_c$ (where ρ is density in pounds weight per cubic foot) and rearranging, Equation 3 becomes

$$\frac{1}{2g} dV^2 + \frac{1}{\rho} dp + dz + \frac{g}{g_c} [J du + p dv - J dq + dW] = 0 \quad (4)$$

In the case of flow through a pipe, no outside work is performed so that $dW = 0$. Furthermore,

$$J du + p dv = JT ds = J dq + JT ds' \quad (5)$$

where

ds = total change in entropy.

ds' = change in entropy due to internal irreversibility from turbulence and friction.

Accordingly, Equation 4 may be written

$$\frac{1}{2g} dV^2 + \frac{dp}{\rho} + dz + \frac{g}{g_c} JT ds' = 0^* \quad (6)$$

In cases where there is no internal irreversibility, $ds' = 0$, and Equation 6 may be integrated to give

$$\frac{V^2}{2g} + \frac{p}{\rho_m} + z = \frac{V_s^2}{2g} + \frac{p_s}{\rho_m} + z_s \quad (7)$$

where

ρ_m = proper mean density.

This is commonly called the Bernoulli equation, named after

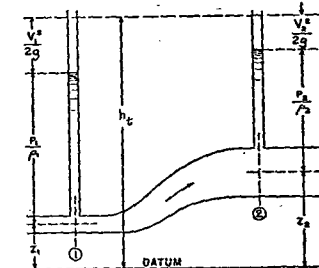


Fig. 1.... Relation of Various Factors in Bernoulli Equation

* In the analysis of subsequent portions of this chapter the distinction between s and s' will be omitted. Aside from the dimensional consistency the factor, g/g_c , is not in general significant in fluid flow analysis.