Reduction of Data for Piston Gage Pressure Measurements

J. L. Cross

Pressure measurements made with piston gages are affected by gravity, temperature, pressure, and several other variables. For accurate determinations of pressure the calculations must take these variables into account. A general equation is developed and simplified procedures for calculating pressure are illustrated.

1. Introduction

The dead weight piston gage is one of the few instruments that can be used to measure pressure in terms of the fundamental units, force, and area. Piston gages are known by several names such as "dead weight gage," "dead weight tester," "gage tester," and "pressure balance." The name, "piston manometer," is used in Germany, and, since it aptly describes the instrument, might very well be used more extensively in this country. In principle, it is a piston inserted into a close fitting cylinder. Weights loaded on one end of the piston are supported by fluid pressure applied to the other end. Construction of piston gages varies as to method of loading, methods of rotating or oscillating the piston to reduce friction, and design of the piston and cylinder. Three designs of cylinders are commonly used; the simple cylinder with atmospheric pressure on the outside; the re-entrant cylinder with the test pressure applied to the outside as well as the inside; and the controlled clearance cylinder with an external jacket in which hydraulic pressure can be applied so as to vary the clearance between the piston and cylinder at the will of the operator. In order to use the piston gage for the measurement of pressure, one must take into account a number of parameters of the instrument and its environment.

Error in measurement results from failure to account for the parameters or from the uncertainty of the measured values of them. It is obvious that error results from the uncertainty of the mass of the loading weights and the measurement of the effective area of the piston and cylinder. Other sources of error may not be so easily recognized. Such sources include the air buoyancy on the weights, the fluid buoyancy on the piston, the value of local gravity, the force on the piston due to the surface tension of the fluid, the thermal expansion and elastic deformation of the piston and cylinder, and the fluid heads involved. These effects can be evaluated and corrections applied to reduce the magnitude of overall error of measurement.

Air buoyancy corrections amount to about 0.015 percent of the load. The corrections for the buoyancy of the pressure fluid on the piston have been found to range from zero to nearly 0.5 psi, and could be larger. A brief discussion of gravity error is given by Johnson and Newhall [1],[1] and detailed information can be found in the Smithsonian Meteorological Tables [2]. The values of local gravity differ by over 0.3 percent at different places in the United States. The pressure correction due to surface tension is usually negligible, but may amount to more than 0.003 psi. Thermal expansion of the effective piston area is usually about 0.003 percent per °C and elastic distortion may amount to 0.05 percent at 10,000 psi. Fluid head amounts to about 0.03 psi per inch for lubricating oils.

Other errors resulting from corkscrewing (vertical force caused by a helical scratch on the piston, cylinder, or guide bearing), vertical component of the force used to rotate or oscillate the piston, eccentric loading of the piston, and the force of air currents against the weights, are not readily evaluated. They may be kept small by good design and workmanship and by careful operating technique, but usually no attempt is made to apply corrections for them.

2. Pressure

The pressure in any system may be defined as

$$P=\frac{F}{A} \qquad (1)$$

where F=force and A=area over which the force is applied. When a piston gage is in equilibrium with a pressure system, the pressure, p_p, measured at the piston gage is

$$p_p=\frac{F_e}{A_e} \qquad (2)$$

where F_e=the force due to the load on the piston, A_e=the effective area of the piston.

[1] Figures in brackets indicate the literature references on page 6.

The pressure p_p, is not necessarily the quantity desired. It is the pressure measured by the piston gage at its reference level, whereas, the pressure that we may wish to measure may be at another level within a system which is connected to the piston gage by a length of tubing filled with a pressure transmitting fluid. The pressure exerted by the head of fluid in the connecting line, from the level within the system to the reference level of the piston gage, must be added to the piston gage pressure. If the total (absolute) pressure is to be determined, the atmospheric pressure at the reference level of the piston gage must also be added to the piston gage pressure, so we have

$$P=p_p+H_{fp}+P_a \tag{3}$$

where P=total pressure at a particular level in the system,

p_p=pressure at the reference level of the piston gage (piston gage pressure),

H_{fp}=pressure exerted by the head of pressure transmitting fluid,

P_a=atmospheric pressure at the reference level of the piston gage.

Usually the quantity to be measured is the difference between the total internal pressure in the system and the atmospheric pressure outside of the system. If the pressure is to be measured at a level in the system (which might be the reference level of another gage) which is different from the reference level of the piston gage, the atmospheric pressure at these levels is different and the equation for the difference between the internal and external pressure or gage pressure, p_g, of the system is

$$p_g=p_p+H_{fp}-H_a \tag{4}$$

where H_a=the difference in the atmospheric pressure between the reference level of the piston gage and the level in the system at which the pressure is to be measured.

3. Force and Fluid Heads

The force, F, due to the gravitational attraction between the earth and a mass, M, is numerically

$$F=kMg_L \tag{5}$$

where g_L is the local acceleration due to gravity, and k is a proportionality factor, the numerical value of which depends upon the units of F, M, and g_L as follows:

k=1, for F in dynes, M in grams, and g_L in cm/sec^2,

k=1, for F in newtons, M in kilograms, and g_L in meter/sec^2,

k=1, for F in poundals, M in pounds mass, and g_L in feet/sec^2,

k=1, for F in pounds force, M in slugs, and g_L in feet/sec^2,

$k=\frac{1}{32.174}$, for F in pounds force, M in pounds mass, and g_L in feet/sec^2,

$k=\frac{1}{980.665}$, for F in pounds force, M in pounds mass, and g_L in cm/sec^2,

$k=\frac{1}{980.665}$, for F in kilograms force (in some countries, kiloponds, kp), M in kilograms, and g_L in cm/sec^2.

There are several quantities that must be used in the determination of the force, F_e, (eq (2)) acting upon the effective area of the piston. These include, the mass of the weights, M_m, the mass of the air displaced by the load, M_a; the mass of the pressure fluid contributing to the load, M_f; the local acceleration due to gravity, g_L, and the force due to the surface tension, γ, of the pressure fluid acting upon the circumference of the piston, C, where it emerges from the surface of the fluid. The value for F_e can be determined from the following equation,

$$F_e=(M_m+M_f-M_a)kg_L+\gamma C. \tag{6}$$

3.1. Mass of Weights

The mass of the weights, including the piston and all parts which contribute to the load on the piston when in operation, is determined by comparison with the mass of accurately known standard weights. This is usually done by means of an equal arm balance.

3.2. Mass of Air

The mass of air displaced by the load on the piston is

$$M_a=\rho_a V_m, \tag{7}$$

where ρ_a=the mean density of the air displaced by the load. The volume of the load,

$$V_m=\frac{M_m}{\rho_m}+\frac{M_f}{\rho_f}, \tag{8}$$

where ρ_m=the density of the weights, M_m, and ρ_f=the density of the pressure fluid, M_f. Substituting eq (8) in eq (7) we get

$$M_a=\frac{\rho_a}{\rho_m}M_m+\frac{\rho_a}{\rho_f}M_f. \tag{9}$$