TABLE 1. VALUES OF e/d FOR DIFFERENT KINDS OF PIPE

| TYPE OF PIPE | e/d |
|---|---|
| Smooth drawn tubing | 0.000005 |
| Commercial steel or wrought iron | 0.00015 |
| Asphalted cast-iron | 0.0004 |
| Galvanized iron | 0.0005 |
| Cast-iron | 0.00085 |
| Wood stave | 0.0006 to 0.003 |
| Concrete | 0.001 to 0.01 |
| Riveted steel | 0.003 to 0.03 |

The curves in Fig. 4 may be approximated very closely by the empirical formula:[1]

$$f = .0055\left[1 + \left(20{,}000\,\frac{e}{d} + \frac{10^6}{r}\right)^{1/3}\right] \tag{12}$$

Equation 8 is applicable to all liquids, and to gases when the pressure loss is less than 10 per cent of the initial pressure. When the loss in head is high, the formula to be used for gases is

$$\frac{p_1^2 - p_2^2}{p_1^2} = \frac{flV_1^2}{gd\,p_1v_1} \tag{13}$$

which may be rearranged to give the loss in pressure,

$$p_1 - p_2 = p_1\left[1 - \sqrt{1 - \frac{flV_1^2}{gd\,p_1v_1}}\right] \tag{14}$$

### Pressure Loss in Non-Circular Pipes

The formulas for flow in pipes are based upon the use of pipes of circular cross-section. The formulas may be used with conduits of other shapes, and in conduits not flowing full, when the flow is turbulent, by using the hydraulic radius, $R_H$, which is really a ratio:

$$R_H = \frac{\text{area of cross-section}}{\text{wetted perimeter of cross-section}} \tag{15}$$

For instance, in a square duct, 1 ft on a side, handling air, the hydraulic radius is $\frac{1}{4}$ or 0.25. If the same duct is handling water, flowing 9 in. deep, the hydraulic radius is 0.75/2.5 or 0.30. Note in this latter case that the wetted perimeter does not include the distance across the free surface.

In the case of a round pipe

$$R_H = \frac{\pi d^2/4}{\pi d} = \frac{d}{4} \text{ or } d = 4R_H \tag{16}$$

Substituting Equation 16 in Equation 9,

$$N_{Re} = \frac{4R_HV\rho}{\mu} \tag{17}$$

and in the flow Equation 8,

$$h_f = \frac{flV^2}{8gR_H} \tag{18}$$



and finally in the compressible fluid flow Equation 14,

$$p_1 - p_2 = p_1\left[1 - \sqrt{1 - \frac{flV_1^2}{4gR_Hp_1v_1}}\right] \tag{19}$$

Equations 17, 18, and 19 may be used to compute the flow in pipes and ducts of non-circular section and in any type of conduit not flowing full. *They should not be used when the flow is laminar.*

## FLOW OF COMPRESSIBLE FLUIDS

In the flow of compressible fluids, the large density variations make impracticable the use of the Bernoulli equation, (Equation 7). In certain special cases, however, the exact equations for compressible flow may be stated. If flow occurs with no friction or other internal irreversibility, Equation 6 becomes

$$\frac{1}{2g}\,dV^2 + \frac{dp}{\rho} = 0 \tag{20}$$

If in addition the flow is adiabatic,

$$p\rho^{-k} = p_1\rho_1^{-k} \tag{21}$$

so that Equation 20 becomes

$$\frac{1}{2g}\,dV^2 + \frac{p_1^{1/k}}{\rho_1}\,\frac{dp}{\rho^{1/k}} = 0 \tag{22}$$

or by integration,

$$\frac{1}{2g}(V_2^2 - V_1^2) + \frac{k}{k-1}\,\frac{p_1}{\rho_1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right] = 0 \tag{23}$$

This extension to compressible flow of Bernoulli's equation reduces to the more familiar form if the pressure change is small.

The ratio of specific heats, $k$, is used extensively in fluid dynamics; values of $k$ for various gases are given in Table 2.

TABLE 2. RATIO OF SPECIFIC HEAT AT CONSTANT PRESSURE TO SPECIFIC HEAT AT CONSTANT VOLUME FOR COMPRESSIBLE FLUIDS

| COMPRESSIBLE FLUID | RATIO $k = c_p/c_v$ |
|---|---|
| Helium and other monatomic gases | 1.66 |
| Air and other diatomic gases | 1.40 |
| Ammonia and hydrogen sulfide | 1.34 |
| Carbon dioxide, methane, natural gas, superheated steam, moist steam down to a quality of 97 per cent | 1.28 to 1.32 |
| Sulfur dioxide, ethylene, acetylene | 1.24 to 1.26 |

It is convenient in the analysis of compressible flow to introduce the velocity of propagation of pressure impulses or, more familiarly, the sonic velocity, $a$. For perfect gases this is given by the equation:

$$a^2 = kgp/\rho = kgRT \tag{24}$$

Accordingly, Equation 23 may be written

$$\tfrac{1}{2}(V_2^2 - V_1^2) + \frac{a_1^2}{k-1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1\right] = 0 \tag{25}$$