

(Coefficient shown as a function of Reynolds Number and Ratio, A/A_1.)
From Reference 4. Used by permission.

Fig. 7 .... Dimensions and Flow Coefficient for Standard Square-edged Orifice with Corner Taps or Annular Slits

the flow in the nozzle. If the ratio of p_2 to p_1 is decreased from unity, the mass rate of discharge, as well as the volume, increases from zero to a maximum, as shown by the solid section of the curve in Fig. 6; thereafter, as p_2/p_1 is decreased further, the discharge is constant, as indicated by the horizontal line. The value of p_2 at the maximum point is called the critical pressure, or p_c, and it is seen that p_c is approximately 53 percent of p_1 when air is flowing.

To find the velocity at the critical pressure, it is assumed that the upstream velocity V_1 is so small as to be negligible. Using the subscript c to indicate conditions at the critical point, from Equation 29

$$\frac{p_c}{p_1} = \frac{1}{\left(1 + \frac{k-1}{2} M_c^2\right)^{\frac{k}{k-1}}} \tag{41}$$

or

$$M_c = \sqrt{\frac{2}{k-1}\left[\left(\frac{p_1}{p_c}\right)^{\frac{k-1}{k}} - 1\right]} \tag{42}$$

Substituting the critical pressure ratio from Equation 40 it follows that

$$M_c = 1 \tag{43}$$

or that the velocity at the throat is equal to the local sonic velocity.

In developing the working equations for orifices and nozzles, it is customary to start with the incompressible form of the flow Equation 38. In this case both M_1 and M_2 are small quantities, $\rho_1 = \rho_2$, and $(p_1 - p_2)/p_2 = \Delta p/p_2$ is small. Retaining only first order terms, it follows from Equation 35 that

$$\frac{M_1}{M_2} = \frac{A_2}{A_1} \tag{44}$$

so that

$$\sqrt{\frac{1 + \frac{k-1}{2} M_1^2}{1 - M_1^2/M_c^2}} \cong \frac{1}{\sqrt{1 - (A_2/A_1)^2}} = \frac{1}{\sqrt{1 - \beta^4}} \tag{45}$$

where $\beta = D_2/D_1$. The quantity $1/\sqrt{1-\beta^4}$ is the velocity of approach factor as generally used, with β being the ratio of the throat or orifice diameter to the pipe diameter.

Since $\Delta p/p_2$ is small

$$\frac{2k}{k-1}\left[\left(\frac{p_1}{p_2}\right)^{\frac{k-1}{k}} - 1\right] \cong \frac{2\Delta p}{p_2} \tag{46}$$

and the mass flow is

$$w = \frac{A_2}{\sqrt{1-\beta^4}} \sqrt{2g\rho\Delta p} \tag{47}$$

The volume flow is then

$$Q = A_2 \frac{1}{\sqrt{1-\beta^4}} \sqrt{2g\Delta p/\rho} = A_2 \frac{1}{\sqrt{1-\beta^4}} \sqrt{2gh_f} \tag{48}$$

FLOW MEASUREMENT

The measurement of quantity of flow of fluids is generally accomplished either by making observations on the change of state due to flow system configuration, such as the pressure drop across a metering orifice, or by the displacement of some device, such as a rotating vane system. The selection of the metering system will be determined by the type of fluid, the precision of measurement desired, the cost of equipment and installation, the range of flow quantity, the ease of maintenance, and the method of observation and recording.

Fluid meters may be classified as follows: (1) *Head Meters* (Pressure Sensitive), which may be of *Venturi, flow nozzle, orifice plate,* or *Pitot tube* types; (2) *Area Meters,* which may be of *gate, tapered tube,* or *tapered plug* types; (3) *Force Meters,* which may be of *vane, propellor,* or *turbine* types; (4) *Quantity Meters,* which may be of *weighing tank, reciprocating piston,* or *geared impeller* types.

Rate meters are generally of the first three groups, although rates are obtainable from timed observations of quantity meters. Similar quantity measurements can be obtained by suitable integration of rate meter indications.

Head Meters

The head meter is of sufficient flexibility so that almost any type of flow measurement can be handled. For this reason, standard and reference measurements are usually made in this way. With proper care, extreme precision can be obtained. Also, an inexpensive installation can be made to give moderate precision. In general, a head meter requires fairly competent installation and maintenance to give satisfactory service.

Among the types of head meters, the Venturi has the advantage of having a low pressure loss, but requires considerable length of space. The orifice plate reduces the required length to a minimum at the cost of considerable pressure drop. The flow nozzle represents a compromise, but must be calibrated individually, or made with extreme care from standard specifications, to obtain a good precision of measurement. Standard configurations, for representative orifice plates and flow nozzles, are shown in Figs. 7 and 8, respectively. Additional specifications are given in References 2, 3, and 4 at end of chapter.

The measurement of flow in head meters is dependent

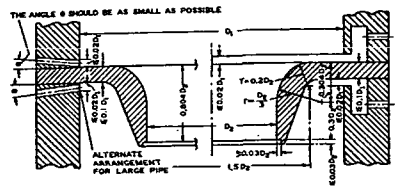

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Fig. 8 .... Dimensions for International Standards Association Flow Nozzle

upon observations of a static pressure difference between two parts of the system. Standard locations for these static pressure measurements are illustrated in Figs 8 and 16. In general, there exists a reduction in area, either by a smooth contour as in the case of a Venturi or flow nozzle, or by a vena contracta following an orifice. In either case, the flow will be given by a suitable modification of Equations 47 and 48. Adding a correction term, these become

$$w = \frac{A_2 C}{\sqrt{1-\beta^4}} \sqrt{2g\rho\Delta p} \tag{49}$$

and

$$Q = \frac{A_2 C}{\sqrt{1-\beta^4}} \sqrt{2gh_f} \tag{50}$$

In all cases, A_2 refers to the minimum area of the Venturi, nozzle, or orifice. The correction factor C is introduced to account for any loss due to departure from isentropic flow, and for any deviation between the downstream measured pressure and the actual pressure at the minimum section. Since these corrections are usually dependent on configuration, as described by the ratio of upstream to minimum area A_1/A_2, it is often convenient to introduce a combined flow coefficient, K which is

$$K = \frac{C}{\sqrt{1-\beta^4}} \tag{51}$$

so that

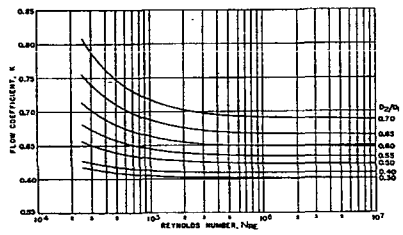
$$w = KA_2\sqrt{2g\rho\Delta p} \tag{52}$$

and

$$Q = KA_2\sqrt{2gh_f} \tag{53}$$

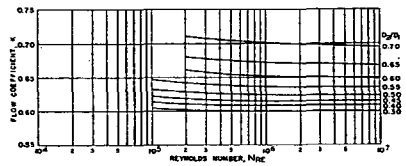
The coefficients K and C will be determined by the area ratio A_1/A_2, or by the diameter ratio D_1/D_2 and the Reynolds number. Extensive data are available from various sources.[3, 4] Figs. 9, 10, 11, 12 show representative values of K based on N_{Re}, the Reynolds number, and the ratio of diameter of the orifice or nozzle throat to pipe diameter.

In any specific application, numerical values for areas, densities, and pressure units can be substituted in Equations 52 and 53 to obtain compact working formulas. In planning flow measurements, standard flow meter dimensions and standard pressure tap locations should preferably be used so



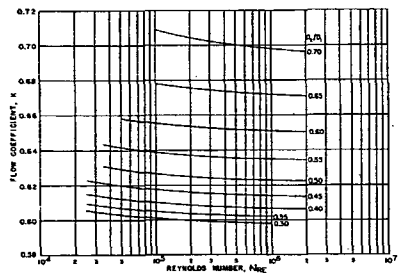
From Table 6 of Reference 2.

Fig. 9 .... Flow Coefficients, K, for Square-edged Orifice Plates and Flange Taps in Smooth Pipe



From Fig. 36d of Reference 3.

Fig. 10 .... Flow Coefficients, K, for Square-edged Orifice Plates and Radius Taps in Smooth Pipe



From Table 7 of Reference 2.

Fig. 11.... Flow Coefficients, K, for Square-edged Orifice Plates and Vena Contracta Taps, in Smooth Pipe