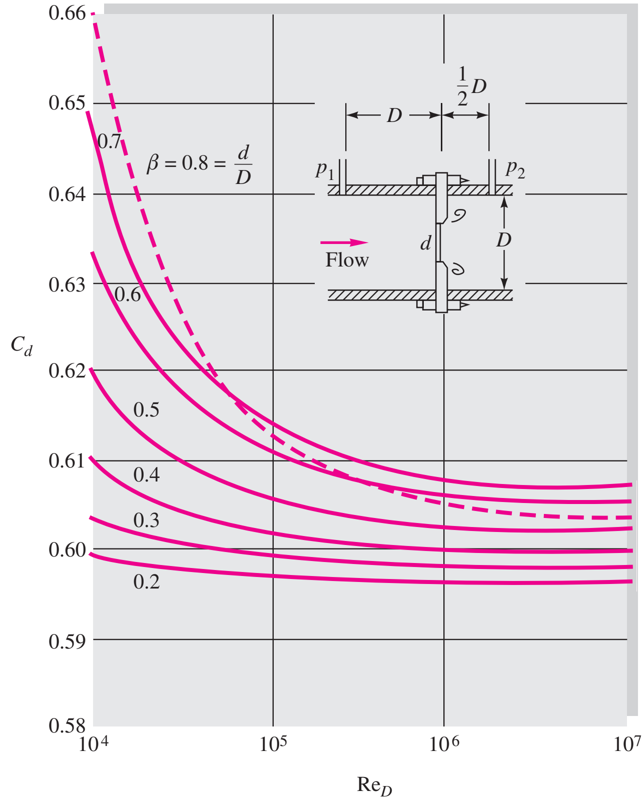

Fig. 6.41 Discharge coefficient for a thin-plate orifice with D: $\frac{1}{2}D$ taps, plotted from Eqs. (6.112) and (6.113*b*).

Thin-Plate Orifice. The thin-plate orifice, Fig. 6.40*b*, can be made with β in the range of 0.2 to 0.8, except that the hole diameter d should not be less than 12.5 mm. To measure p_1 and p_2, three types of tappings are commonly used:

1. Corner taps where the plate meets the pipe wall.
2. D: $\frac{1}{2}D$ taps: pipe-wall taps at D upstream and $\frac{1}{2}D$ downstream.
3. Flange taps: 1 in (25 mm) upstream and 1 in (25 mm) downstream of the plate, regardless of the size D.

Types 1 and 2 approximate geometric similarity, but since the flange taps 3 do not, they must be correlated separately for every single size of pipe in which a flange-tap plate is used [30, 31].

Figure 6.41 shows the discharge coefficient of an orifice with D: $\frac{1}{2}D$ or type 2 taps in the Reynolds number range $\mathrm{Re}_D = 10^4$ to 10^7 of normal use. Although detailed charts such as Fig. 6.41 are available for designers [30], the ASME recommends use of the curve-fit formulas developed by the ISO [31]. The basic form of the curve fit is [42]

$$C_d = f(\beta) + 91.71\beta^{2.5}\mathrm{Re}_D^{-0.75} + \frac{0.09\beta^4}{1-\beta^4}F_1 - 0.0337\beta^3 F_2 \tag{6.112}$$

where $$f(\beta) = 0.5959 + 0.0312\beta^{2.1} - 0.184\beta^8$$

The correlation factors F_1 and F_2 vary with tap position:

Corner taps: $$F_1 = 0 \quad F_2 = 0 \tag{6.113a}$$

D: $\frac{1}{2}D$ taps: $$F_1 = 0.4333 \quad F_2 = 0.47 \tag{6.113b}$$

Flange taps: $$F_2 = \frac{1}{D\text{ (in)}} \quad F_1 = \begin{cases} \dfrac{1}{D\text{ (in)}} & D > 2.3\text{ in} \\ 0.4333 & 2.0 \le D \le 2.3\text{ in} \end{cases} \tag{6.113c}$$

Note that the flange taps (6.113*c*), not being geometrically similar, use raw diameter in inches in the formula. The constants will change if other diameter units are used. We cautioned against such dimensional formulas in Example 1.4 and Eq. (5.17) and give Eq. (6.113*c*) only because flange taps are widely used in the United States.

Flow Nozzle. The flow nozzle comes in two types, a long-radius type shown in Fig. 6.40*a* and a short-radius type (not shown) called the ISA 1932 nozzle [30, 31]. The flow nozzle, with its smooth rounded entrance convergence, practically eliminates the vena contracta and gives discharge coefficients near unity. The nonrecoverable loss is still large because there is no diffuser provided for gradual expansion.

The ISO recommended correlation for long-radius-nozzle discharge coefficient is

$$C_d \approx 0.9965 - 0.00653\beta^{1/2}\left(\frac{10^6}{\text{Re}_D}\right)^{1/2} = 0.9965 - 0.00653\left(\frac{10^6}{\text{Re}_d}\right)^{1/2} \tag{6.114}$$

The second form is independent of the β ratio and is plotted in Fig. 6.42. A similar ISO correlation is recommended for the short-radius ISA 1932 flow nozzle:

$$C_d \approx 0.9900 - 0.2262\beta^{4.1} + (0.000215 - 0.001125\beta + 0.00249\beta^{4.7})\left(\frac{10^6}{\text{Re}_D}\right)^{1.15} \tag{6.115}$$

Flow nozzles may have β values between 0.2 and 0.8.

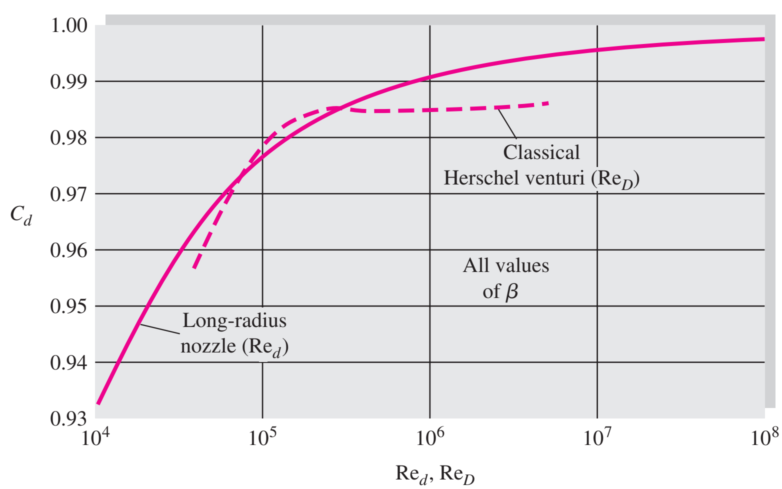

Fig. 6.42 Discharge coefficient for long-radius nozzle and classical Herschel-type venturi.

Venturi Meter. The third and final type of obstruction meter is the venturi, named in honor of Giovanni Venturi (1746–1822), an Italian physicist who first tested conical expansions and contractions. The original, or *classical,* venturi was invented by a U.S. engineer, Clemens Herschel, in 1898. It consisted of a 21° conical contraction, a straight throat of diameter d and length d, then a 7 to 15° conical expansion. The discharge coefficient is near unity, and the nonrecoverable loss is very small. Herschel venturis are seldom used now.

The modern venturi nozzle, Fig. 6.40c, consists of an ISA 1932 nozzle entrance and a conical expansion of half-angle no greater than 15°. It is intended to be operated in a narrow Reynolds number range of 1.5×10^5 to 2×10^6. Its discharge coefficient, shown in Fig. 6.43, is given by the ISO correlation formula

$$C_d \approx 0.9858 - 0.196\beta^{4.5} \tag{6.116}$$

It is independent of Re_D within the given range. The Herschel venturi discharge varies with Re_D but not with β, as shown in Fig. 6.42. Both have very low net losses.

The choice of meter depends on the loss and the cost and can be illustrated by the following table:

Type of meter	Net head loss	Cost
Orifice	Large	Small
Nozzle	Medium	Medium
Venturi	Small	Large

As so often happens, the product of inefficiency and initial cost is approximately constant.

The average nonrecoverable head losses for the three types of meters, expressed as a fraction of the throat velocity head $V_t^2/(2g)$, are shown in Fig. 6.44. The orifice

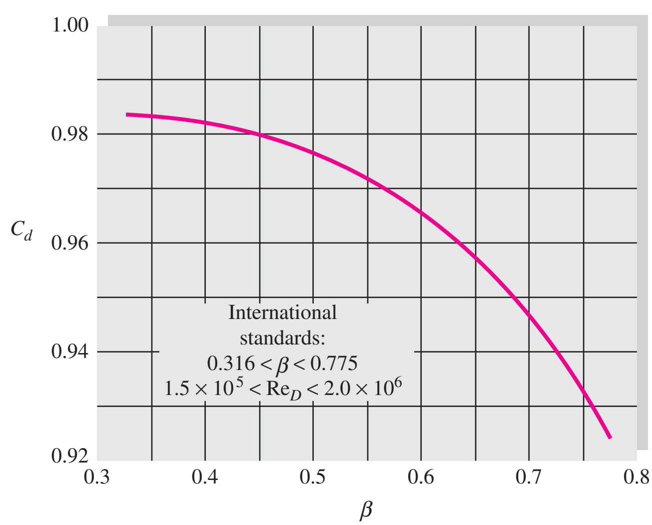

Fig. 6.43 Discharge coefficient for a venturi nozzle.

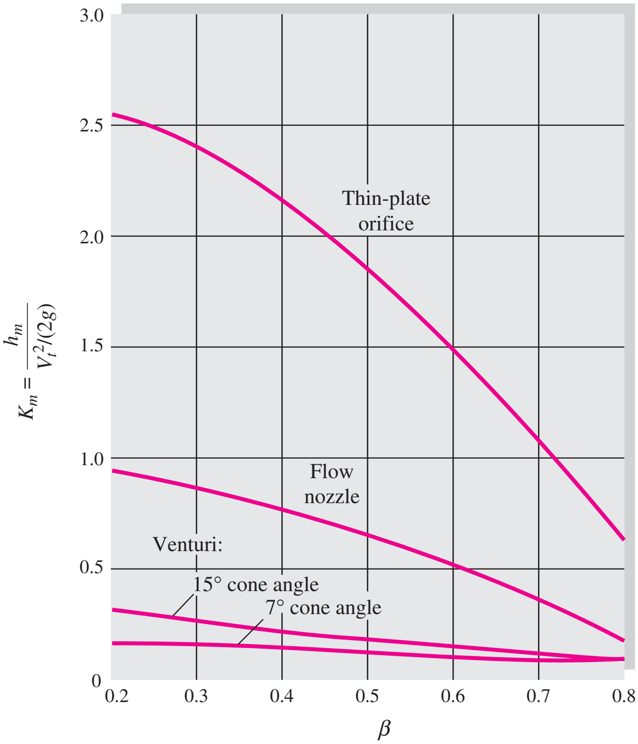

Fig. 6.44 Nonrecoverable head loss in Bernoulli obstruction meters. *(Adapted from Ref. 30.)*

has the greatest loss and the venturi the least, as discussed. The orifice and nozzle simulate partially closed valves as in Fig. 6.18*b*, while the venturi is a very minor loss. When the loss is given as a fraction of the measured *pressure drop,* the orifice and nozzle have nearly equal losses, as Example 6.21 will illustrate.

The other types of instruments discussed earlier in this section can also serve as flowmeters if properly constructed. For example, a hot wire mounted in a tube can be calibrated to read volume flow rather than point velocity. Such hot-wire meters are commercially available, as are other meters modified to use velocity instruments. For further details see Ref. 30.

Compressible Gas Flow Correction Factor. The orifice/nozzle/venturi formulas in this section assume incompressible flow. If the fluid is a gas, and the pressure ratio (p_2/p_1) is not near unity, a compressibility correction is needed. Equation (6.104) is rewritten in terms of mass flow and the upstream density ρ_1:

$$\dot{m} = C_d Y A_t \sqrt{\frac{2\rho_1(p_1 - p_2)}{1 - \beta^4}} \quad \text{where} \quad \beta = \frac{d}{D} \tag{6.117}$$

The dimensionless *expansion factor Y* is a function of pressure ratio, β, and the type of meter. Some values are plotted in Fig. 6.45. The orifice, with its strong jet contraction, has a different factor from the venturi or the flow nozzle, which are designed to eliminate contraction.