Fluid Flow Measurement

Objective of measurement is either:

- Velocity, or
- Flow rate (mass or volumetric).

Methods used may be categorized as:

1. Primary or quantity methods:
   a. Weight or volume tanks, burettes, etc.
   b. Positive displacement meters
      i. "Water" meter
      ii. Wet test meter (measures gas flow)

Categories of Measurement

2. Secondary or rate devices:
   a. Obstruction meters
      i. Venturi
      ii. Flow Nozzles
      iii. Orifice
   b. Variable Area
      i. Vertical rotameter
      ii. Spring-loaded rotameter

Categories (Cont'd)

c. Velocity probes
   i. Pitot tube
   ii. Anemometer (propeller)
   iii. Hot-wire anemometer
d. Special methods
   i. Turbine meters
   ii. Paddlewheel meters
   iii. Thermal mass flow meters
   iv. Coriolis effect flow meters
   v. Vortex shedding meters, etc., etc. etc.

Flow Field Visualization

- Methods described before suitable for pipe or duct flows, 1- or 2-D.
- Methods to see, or *visualize*, velocities in a complex flow field include:
  - Using tufts
  - Using smoke, dyes, suspended particles
  - Shadowgraphs
  - Schlieren photography
  - 2-D and 3-D laser/optic systems

Shadowgraph Example

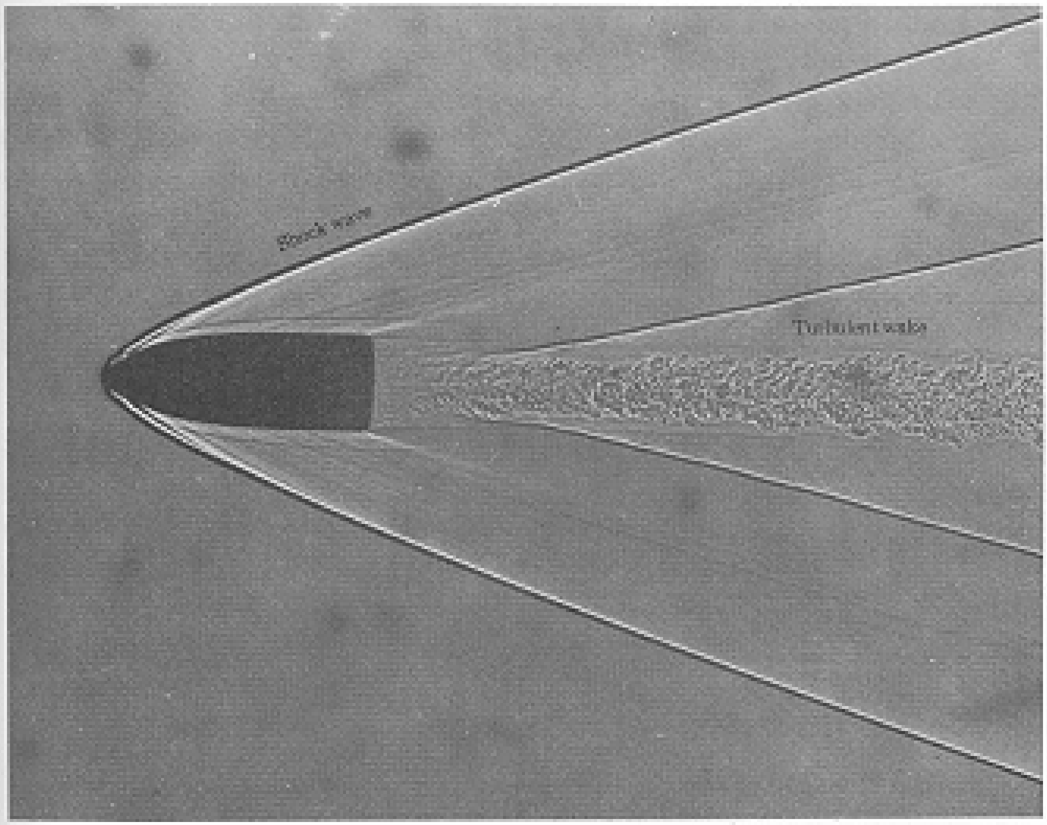


FIGURE 7-31
Direct shadowgram of flight of a 0.220-caliber Remington Swift shell. Velocity = 1250 m/s; free-stream pressure is atmospheric. Exposure time was 0.13 μs. Note clear definition of shock wave and turbulent wake. (*Courtesy of ARO, Inc., Arnold Air Force Base, Tenn.*)

Schlieren Example

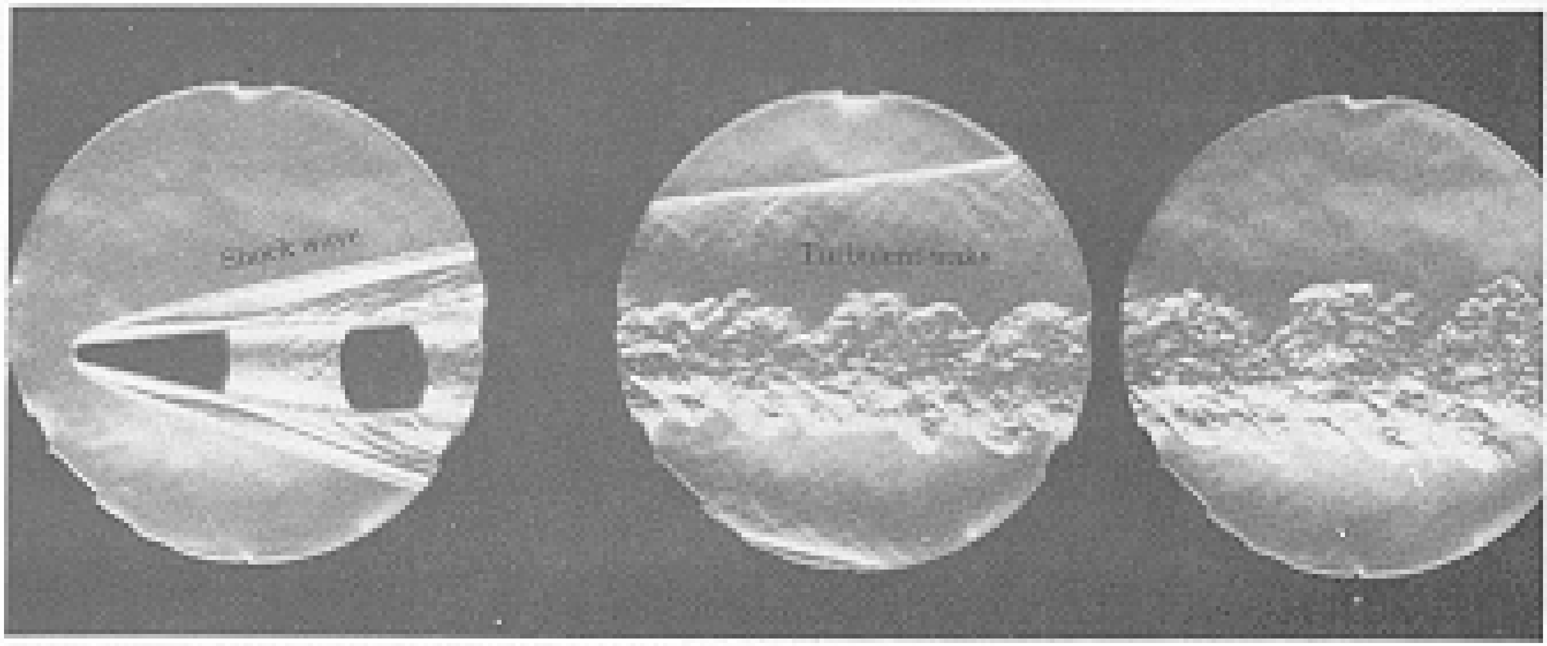


FIGURE 7-33
Schlieren photograph of 4.45-cm-diameter blunt cone and wake after separation of rear portion. Velocity = 1792 m/s; free-stream pressure = 12.5 kN/m^2; cone angle = 18°. (*Courtesy of ARO, Arnold Inc., Air Force Base, Tenn.*)

Interferometer Photograph

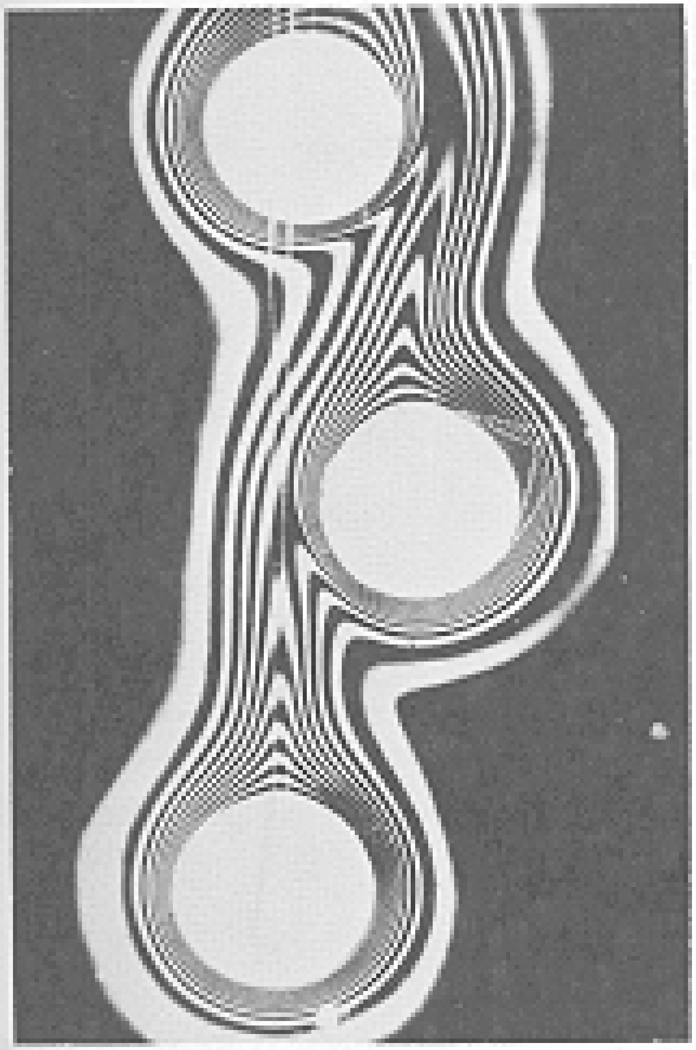


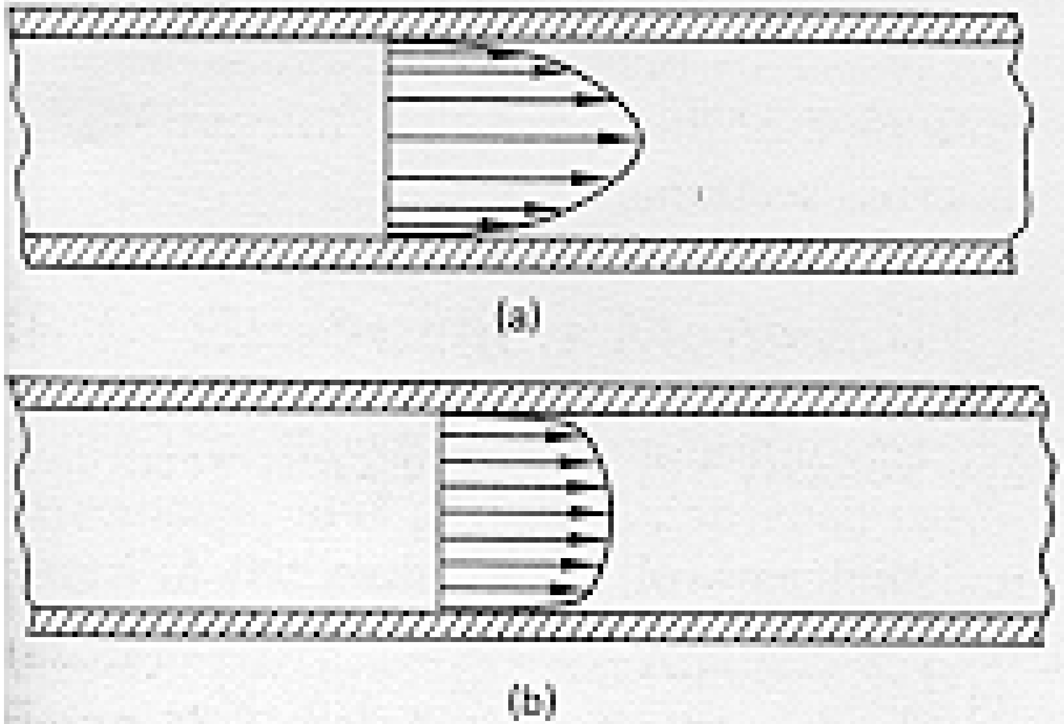
FIGURE 7-37
Interferometer photograph of the interaction of free-convection boundary layers on three horizontal heated cylinders. Fluid is air, and each fringe line represents a line of constant temperature. (*Photograph courtesy of E. Soehngen.*)

Fluid Flow Characteristics

- Laminar Flow - relatively low velocity flow in which the streamlines are identifiable and are essentially parallel.
- Turbulent Flow - viscous forces present in the fluid no longer dominate to suppress random flow patterns. Eddies and recirculation zones are typical.

Velocity Distributions

Figure 15.1 Velocity distribution for: (a) laminar flow in a pipe or tube and, (b) turbulent flow in a pipe or tube



Reynolds Number

- For pipe flow, the flow field is characterized by the Reynolds number (no apostrophe s!)

$$Re_D = \rho VD/\mu$$

where: ρ = density V = velocity

D = diameter μ = dynamic viscosity

- $Re_D < 2300 \rightarrow$ flow is laminar
- $Re_D > 10{,}000 \rightarrow$ flow is turbulent
- In between $\rightarrow$ transition- could be either

Bernoulli's Equation

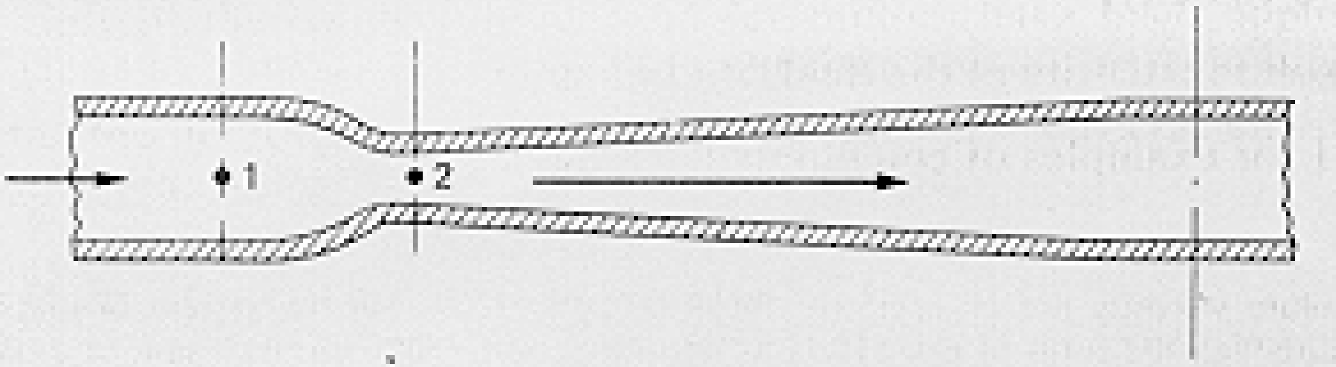
- Several methods of velocity measurement are based on Bernoulli's equation.

$$\frac{V_1^2}{2} + \frac{P_1}{\rho} + gz_1 = \frac{V_2^2}{2} + \frac{P_2}{\rho} + gz_2$$

- If the elevation effects are negligible, then we have a direct relationship between velocity and pressure loss across a sensor.

Applying Bernoulli's Eq.

Figure 15.2 Section through a restriction in a pipe or tube



- Strictly, Bernoulli's Eq. is applicable to frictionless, incompressible flow along a streamline. These conditions hold approximately in many useful circumstances.

Pitot Tubes

- A pitot tube is used to measure the static and stagnation pressures of a flowing fluid, which in turn can be related to the local velocity by direct application of the Bernoulli Equation:

$$\frac{V_1^2}{2} = \frac{P_{stag} - P_{stat}}{\rho} + \cancel{\frac{V_2^2}{2}} + g\cancel{\left(z_2 - z_1\right)}$$

$V_2 = 0$ because flow is stopped

$\Delta z = 0$ because no height change

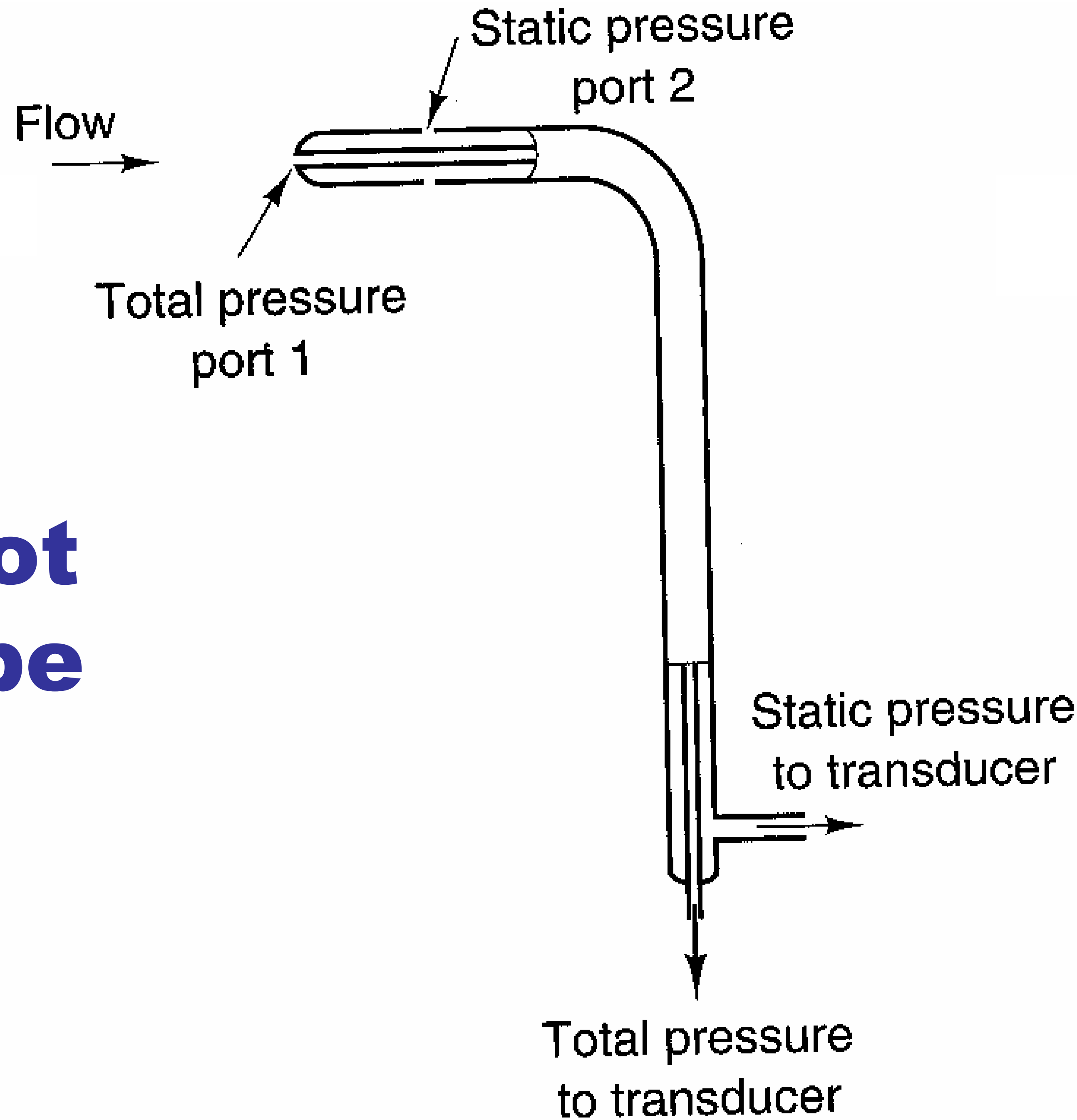
Pitot Tube (Cont'd)

- Rearranging this relationship:

$$V_1 = \sqrt{2 \cdot \frac{P_{stag} - P_{stat}}{\rho}}$$

- A pitot probe yields a "local" velocity.
- Several measurements are averaged to get volumetric flow rate from the measured V's.
- Velocities should be weighted according to the flow area that they represent.

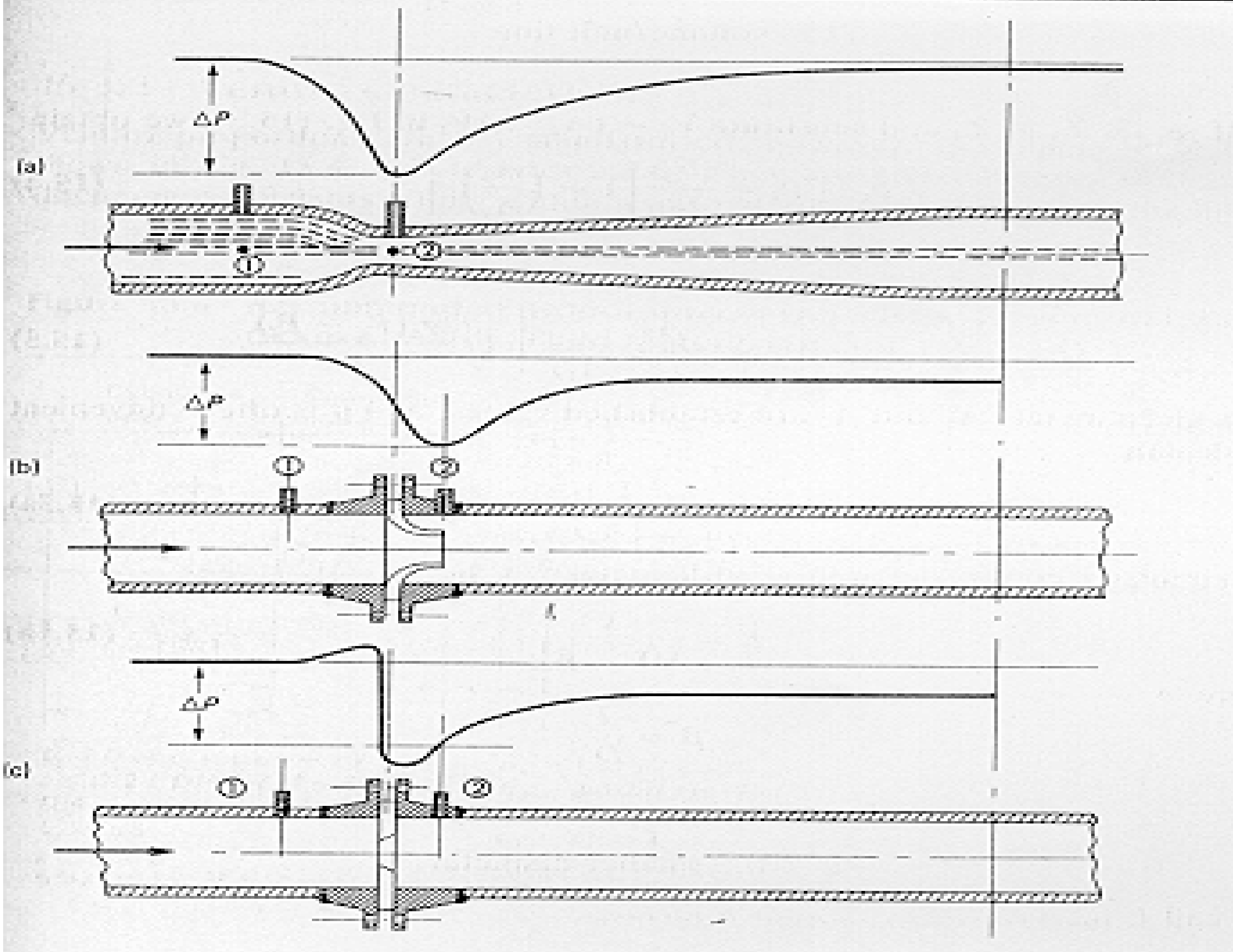
Pitot Tube


Flow
Static pressure port 2
Total pressure port 1
Static pressure to transducer
Total pressure to transducer

Obstruction Meters

- To get volumetric flow rate (Q) of the entire tube with a single measurement of ΔP, obstruction meters are used.
- Obstruction meters are based roughly on the Bernoulli principle, but with correction to account for non-ideal flow.
- Three common obstruction meters include: a) venturi, b) flow nozzle and c) orifice meters.

Figure 15.3 (a) A venturi, (b) a flow nozzle, (c) an orifice flowmeter



Modifying Bernoulli's Eq…

$$\frac{V_1^2}{2}+\frac{P_1}{\rho}+gz_1=\frac{V_2^2}{2}+\frac{P_2}{\rho}+gz_2$$

- Assuming constant z and $A_1 \neq A_2$, and noting that $V_1 \cdot A_1 = V_2 \cdot A_2$, the Bernoulli Eq. can be rewritten as:

$$V_2=\frac{1}{\sqrt{1-\left(A_2^2/A_1^2\right)}}\sqrt{\frac{2\left(P_1-P_2\right)}{\rho}}$$

Modifying Bernoulli (Cont'd)

- Define the velocity of approach factor, M:

$$M = \frac{1}{\sqrt{1 - \left(A_2^2 / A_1^2\right)}}$$

- Noting that volume flow rate is $Q = V_2 \cdot A_2$:

$$Q = M \cdot A_2 \cdot \sqrt{\frac{2\left(P_1 - P_2\right)}{\rho}}$$

Obstruction Meter Correction

- Bernoulli's equation, assumes ideal flow, such as no friction, no compressible flow.
- Flow rate predicted from Bernoulli Eq. is the "ideal" flow rate.
- A friction correction factor, called the "discharge coefficient" C, is defined as:

$$C = Q_{actual}/Q_{ideal}$$

- If C is known, the ideal flow rate can be corrected to actual flow rate.

Compressible Flow Correction

- For compressible flow, a correction factor called the expansion factor, Y, is used.
- All obstruction meters, then, are covered by the "YMCA" equation:

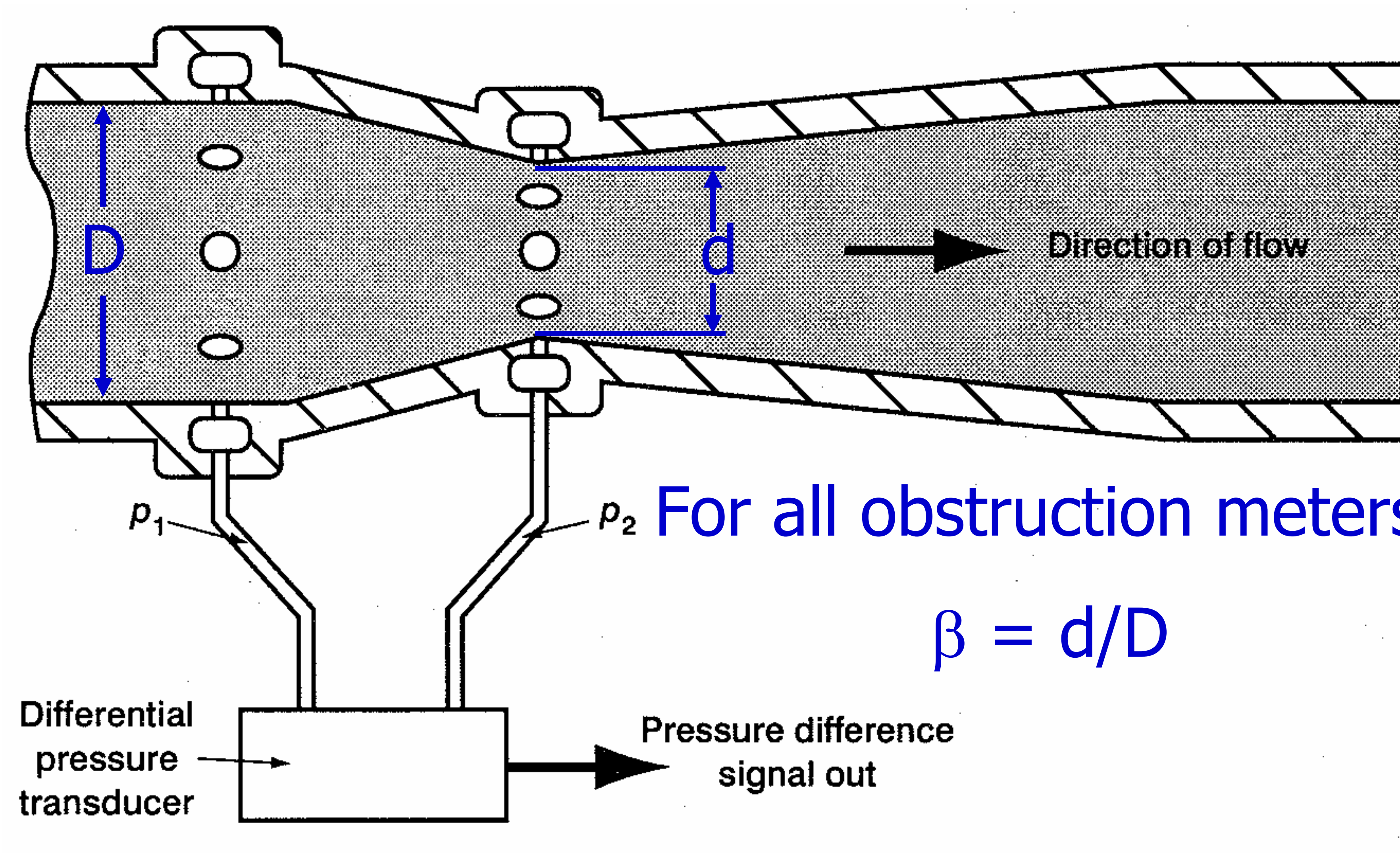
$$Q = Y \cdot M \cdot C \cdot A_2 \cdot \sqrt{\frac{2\left(P_1 - P_2\right)}{\rho}}$$

- $Y < 1$ if $\Delta P/P_1 > 0.02$ or so.
- $Y = 1$ for incompressible fluids (including *all* liquids!)

Obstruction Meters

- Obstruction meter measurement consists of measuring ΔP, determining Y and C, then applying the YMCA equation.
- Mass flow rate is: $\dot{m} = \rho_1 \cdot Q$
- Y and C vary with meter type, geometry, flow rate and (for Y) gas composition.
- Various charts and equations are available to determine Y and C for meters built to strict specifications (e.g., ASME).

Venturi Schematic



For all obstruction meters:

$$\beta = d/D$$

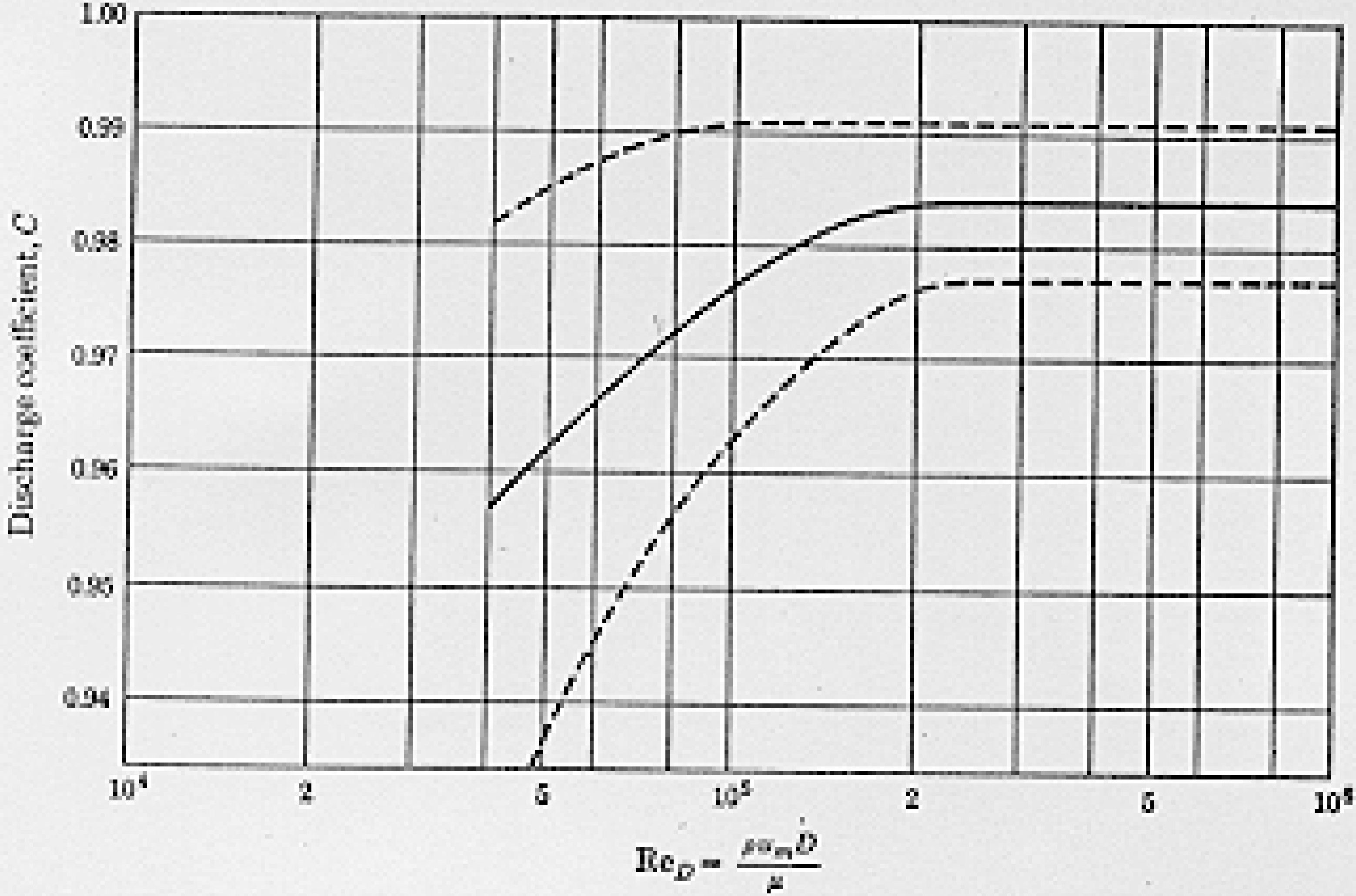


Fig. 7-9 Discharge coefficients for the venturi tube shown in Fig. 7-6 according to Ref. [1]. Values are applicable for $0.25 < \beta < 0.75$ and $D > 2$ in.

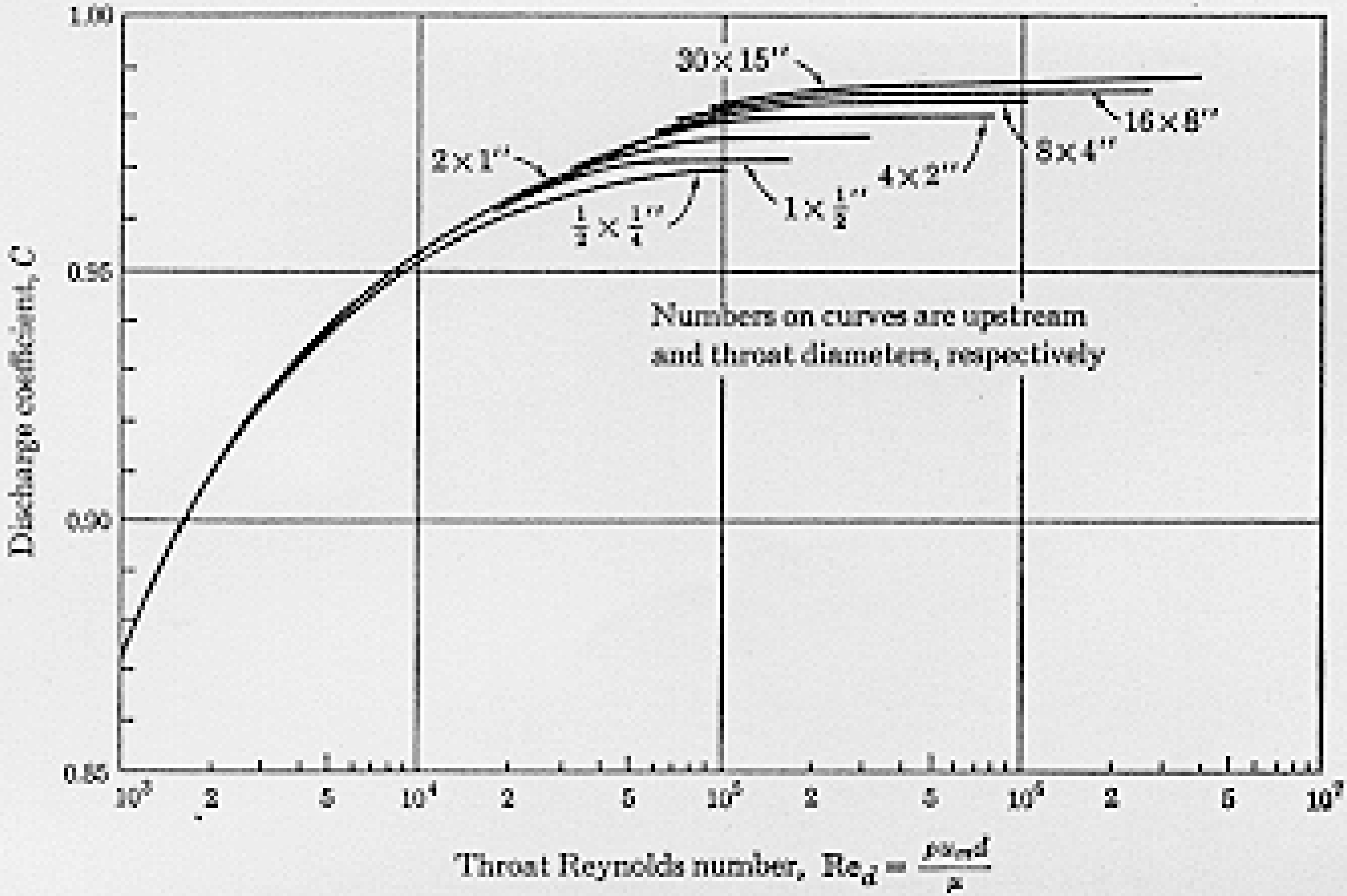
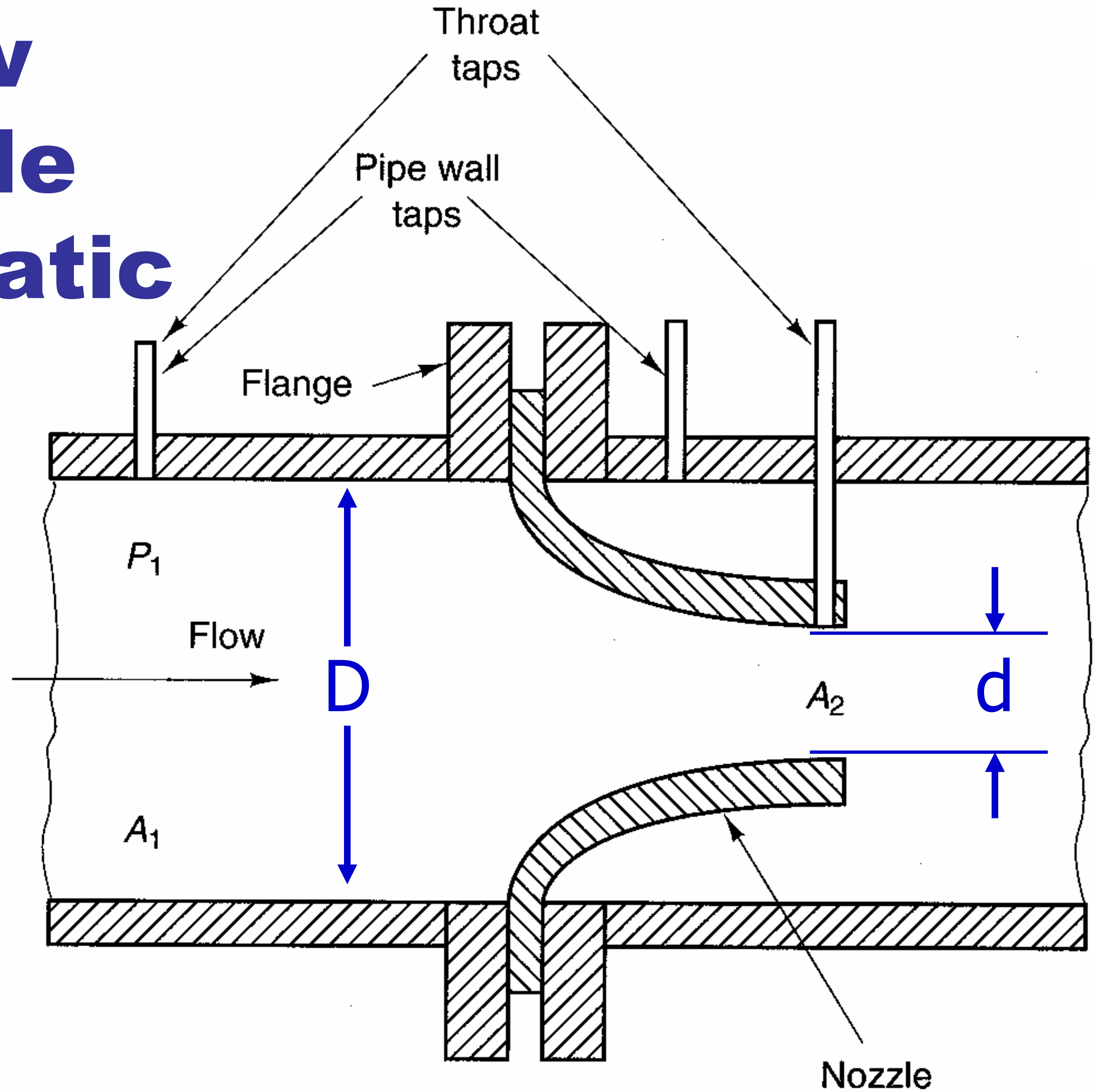


Fig. 7-10 Approximate venturi discharge coefficients for various throat diameters according to Ref. [15].

Flow Nozzle Schematic



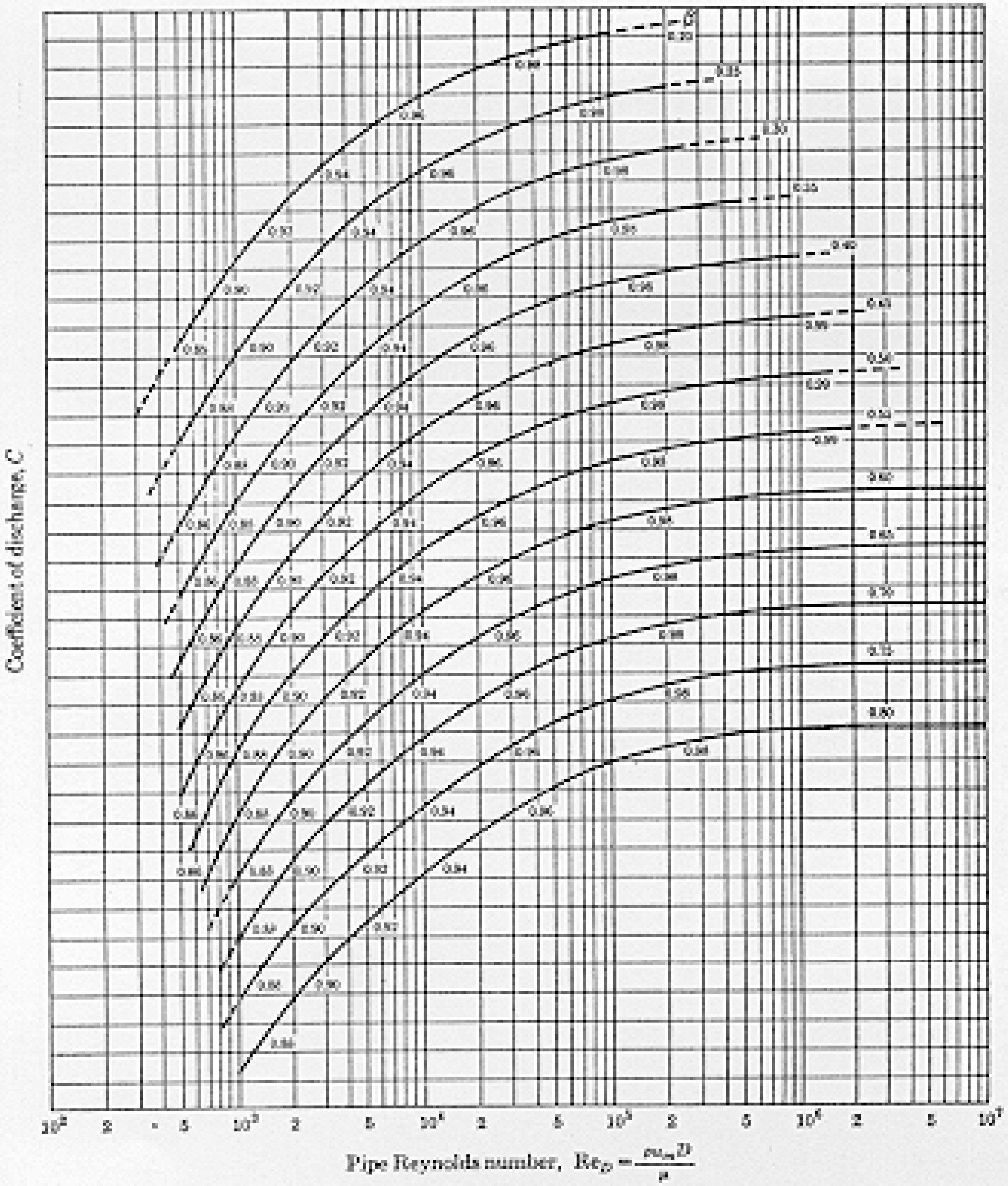
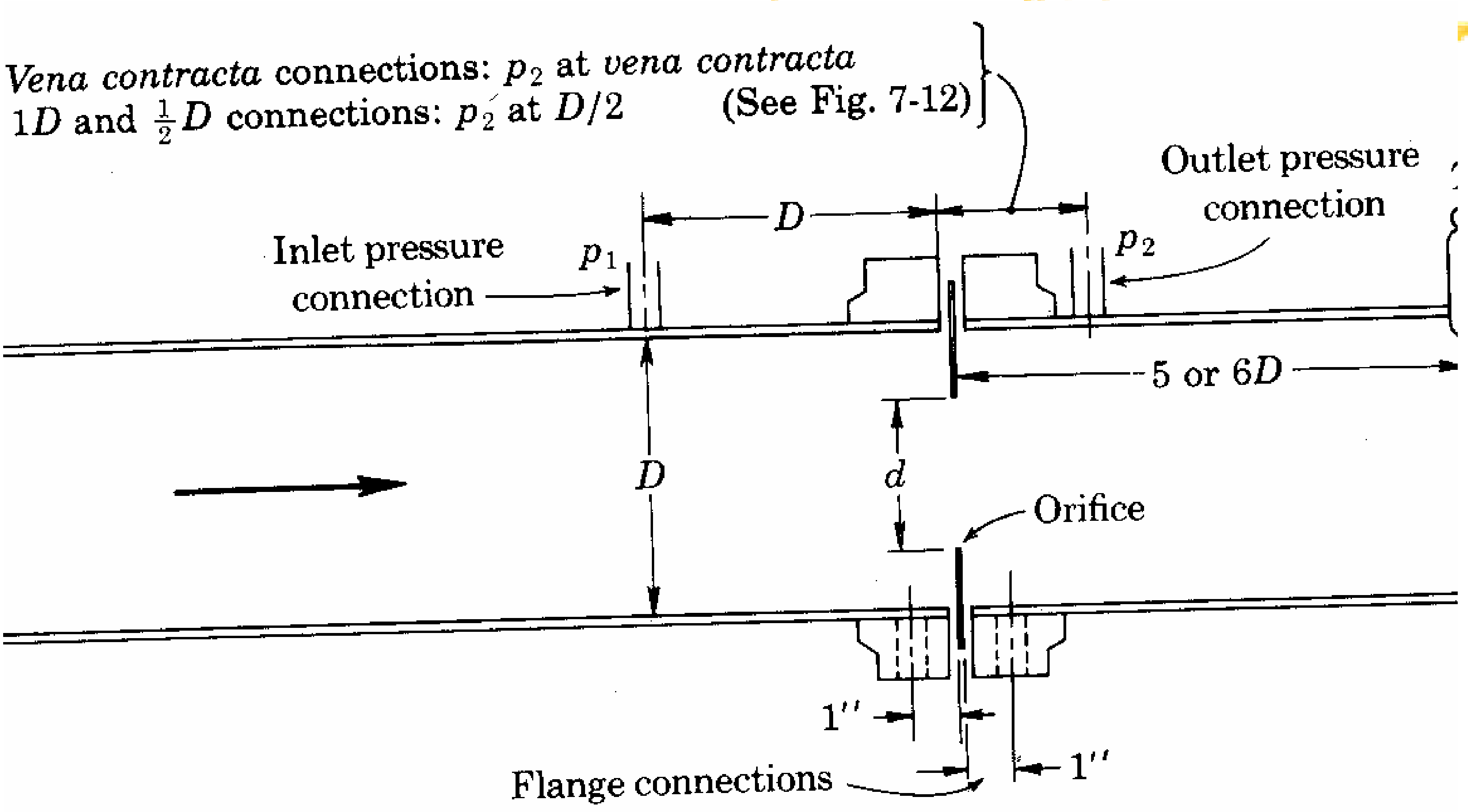
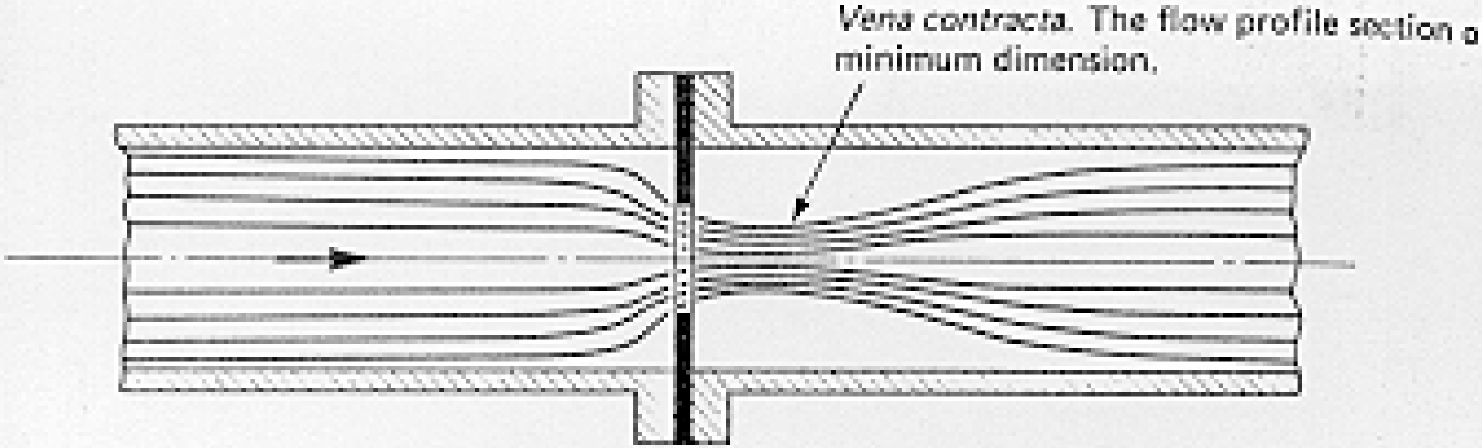


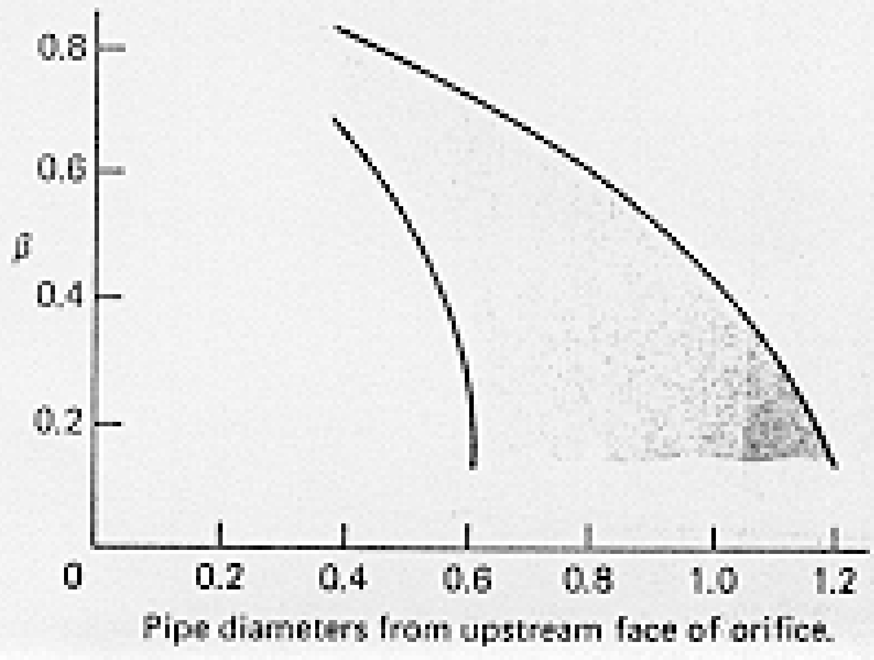
Fig. 7-11 Discharge coefficients for ASME long-radius nozzles shown in Fig. 7-7 according to Ref. [1].

Orifice Schematic




Vena contracta. The flow profile section of
minimum dimension.

(a)


0.8
0.6
β
0.4
0.2
0
0.2
0.4
0.6
0.8
1.0
1.2
Pipe diameters from upstream face of orifice.

Relative Merits of the Venturi, Nozzle and Orifice

Venturi:

Advantages:

- High accuracy
- Good pressure recovery
- Resistance to abrasion

Disadvantages

- More difficult to manufacture
- More expensive than nozzle or orifice
- Scaling lowers accuracy more than orifice

Relative Merits (Cont'd)

Flow Nozzles:

Advantages:

- Good accuracy
- Good pressure recovery (but < venturi)
- More compact and cheaper than venturi

Disadvantages

- More difficult to install properly
- More expensive than orifice
- Scaling lowers accuracy more than orifice

Relative Merits (Cont'd)

<u>Orifices</u>:

Advantages:

- Easy to install (between flanges)
- easy to change β (substituting plates)
- relatively inexpensive

Disadvantages

- High permanent pressure loss
- Susceptible to wear from particulates
- Can be damaged by pressure transients