Fundamentals of Flow Measurement

Lecture Notes

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Outline

Introduction

- Flow measurement is essential in processes where material moves from one point to another.
- Ensures accurate quantification, control, and efficiency of transport operations.
- Typical applications: oil and chemical industries, water and wastewater systems, and more.

Basic Principles of Flow Measurement

- Flow can be measured in terms of:
  - **Volumetric flow**: Volume per unit time.
  - **Velocity-based flow**: Instantaneous fluid speed at a given cross-section (often converted to volumetric flow).
- Selection of a flowmeter depends on:
  - Material compatibility (viscosity, pressure, temperature).
  - Desired accuracy and repeatability.
  - Maintenance and installation constraints.

Streamlined (Laminar) and Turbulent Flow

- For certain (low) velocities, flow remains smooth and parallel (laminar).
- Above a critical velocity, flow becomes turbulent, mixing significantly.
- **Reynolds number (Re)** determines flow regime:
  - $\text{Re} < 2000 \rightarrow$ Laminar
  - $\text{Re} > 4000 \rightarrow$ Turbulent
  - In between: Transition region

Flow Profile

- Velocity distribution across a pipe's diameter is known as the *velocity profile*.
- In laminar flow, profile is parabolic; peak velocity at the center is about twice the mean velocity.
- In turbulent flow (after sufficient straight pipe run), the profile is *fully developed*, with the center at roughly 1.2 times the mean velocity.

Energy of a Fluid in Motion

- **Equation:** Total Energy = Potential + Kinetic + Pressure Energy
- Often expressed per unit mass:

$$E = zg + \frac{V^2}{2} + \frac{p}{\rho}$$

  where
  - z is elevation (m),
  - g is gravitational acceleration (m/s^2),
  - V is fluid velocity (m/s),
  - p is static pressure (Pa),
  - ρ is fluid density (kg/m^3).
- Conservation of energy applies along a streamline for inviscid, steady flow.

Viscosity

- Viscosity measures a fluid's resistance to flow.
- In liquids, viscosity generally **decreases** as temperature increases.
- In gases, viscosity **increases** with temperature.
- Viscosity helps dampen swirling or turbulent eddies, restoring a stable flow profile downstream of bends or valves.

Bernoulli's Theorem

- States that for a steady, incompressible, inviscid flow:

$$z\,g + \frac{V^2}{2} + \frac{p}{\rho} = \text{constant}$$

  where
  - $z\,g$ represents **potential** energy per unit mass,
  - $\frac{V^2}{2}$ is **kinetic** energy per unit mass,
  - $\frac{p}{\rho}$ is **pressure** energy per unit mass.
- Foundation of flow calculations in closed conduits.

Modification of Flow Equations from Bernoulli for Gases

- When gas density is not constant, corrections must account for expansion.
- Introduce γ (ratio of specific heats) and an *expansibility factor* ϵ.
- For ideal compressible fluids,

$$\epsilon = f(\gamma,\ \text{pressure drop}, \ldots)$$

- Adjusts the flow equation to handle changes in volume due to pressure variations.

Principles and Methods

- Accurate flow measurement ensures proper process control in piping systems.
- Methods vary in complexity, cost, accuracy, and suitability for fluid properties.
- Next, we explore common device types and their pros/cons.

Differential-Pressure Devices

- Use a constriction to create pressure drop proportional to flow rate.
- **Pros:** Simple, widely used, well-understood, many standard guidelines.
- **Cons:** Pressure losses can be significant; accuracy depends on flow regime and geometry.

Orifice Plate

- Thin plate with a precise opening centered in the flow path.
- Pressure taps measure differential pressure across the orifice.
- **Pros:**
  - Simple design
  - Low cost
  - Widely documented
- **Cons:**
  - Higher permanent pressure drop
  - Susceptible to wear or clogging

Venturi Tube

- Smoothly convergent inlet followed by a cylindrical throat and divergent outlet.
- Differential pressure is measured between inlet and throat.
- **Pros:**
  - Lower head loss than orifice
  - Suitable for high flow rates
  - Good accuracy
- **Cons:**
  - Larger size and higher cost
  - Installation may require more space

Rotameter (Variable-Area Meter)

- Tapered tube with a float; float rises as flow increases.
- Position of float indicates flow rate on a calibrated scale.
- **Pros:**
  - Direct visual indication
  - Simple, low cost
- **Cons:**
  - Orientation usually vertical
  - Limited to relatively low pressures

Pitot Tube

- Measures fluid velocity at a point by comparing stagnation pressure to static pressure.
- **Pros:**
  - Simple construction
  - Inexpensive
  - Good for velocity profiling
- **Cons:**
  - Can be invasive, prone to clogging
  - Requires careful alignment with the flow

Ultrasonic Flow Meter

- Uses sound pulses transmitted diagonally across the pipe:
  - **Transit-Time Method:** Measures time difference of upstream vs downstream signals.
  - **Doppler Method:** Detects frequency shift caused by particle reflection.
- **Pros:**
  - Noninvasive (clamp-on types)
  - Low pressure drop
  - Can measure dirty or corrosive fluids (depending on design)
- **Cons:**
  - Accuracy can decrease with highly turbulent or multiphase flows
  - Proper sensor alignment and maintenance needed

Magnetic Flow Meter

- Based on Faraday's Law of electromagnetic induction: voltage induced in a conductive fluid moving through a magnetic field.
- **Pros:**
    - No obstruction to flow
    - Excellent for slurries or dirty liquids
    - Wide range
- **Cons:**
    - Requires conductive fluid
    - More costly electronics

Conclusion

- Flow measurement techniques are numerous and must be matched to application needs.
- Understanding fluid behavior (laminar vs. turbulent), energy principles, and device capabilities is crucial.
- The correct selection optimizes performance, accuracy, and cost-effectiveness in industrial processes.