ME411
Engineering Measurement & Instrumentation

Winter 2017 – Lecture 11
Flow Measurement

• Identify an effect that depends on flow rate
• Process control requires accurate measurement of flow control
  • Mixing of 2 streams
  • Feed rate into a combustion chamber
  • Heat exchangers
Flow Measurement

• Flow meter criteria
  • Size
  • Accuracy
  • Cost
  • Pressure drop
  • Pressure losses
  • Fluid compressibility
  • Other fluid properties
  • Use
Basic concepts

- Mass flow rate (mass/time)
- Sensitive to product of density and average velocity
- Not a problem if density is constant but if not...

- Volume flow rate (volume/time)
- Only sensitive to average velocity

- So if we can measure the average velocity or velocity across the entire control surface, we can calculate \( \dot{m} \) (constant density) or \( Q \)
Using velocity to calculate flow

- Pitot tubes, PIV, hot-wire anemometer etc provide $U(x,y)$
- 2 possible ways to go:

**VERSION 1**

1. Velocity measurement is the average velocity within the measurement volume
2. Flow rate in each measurement volume can be calculated by $Q = \bar{U}A$
3. Total flow rate can be calculated by summing flow for each measurement volume

This method requires measurement volumes to span the entire control surface and perfectly align with its nearest neighbors (no overlaps or gaps)
Using velocity to calculate flow

VERSION 2

1. Measure velocity at discrete points
2. Fit velocity measurements with regression curve
3. Integrate curve over the entire surface

Converting velocity measurements to flow rates can be done but may not be the easiest, cheapest or preferred method

Not a particularly useful measurement if you need to continuously monitor the flow rate so is generally used as a one-time verification or calibration procedure.
Volumetric Flow Meters

• Generally divided into 3 main types
  • Obstruction (O)
  • Insertion (I)
  • Non-invasive (NI)

OR:

“Bucket and stopwatch” method

• Accuracy: Depends on volume, time sample can be very accurate
• Used for: Liquids
• Pros: Useful as calibration
• Cons: Flow completely diverted, non-continuous
Orifice Plate (O)

• Intentional reduction of flow area $\rightarrow$ the local pressure drop across flow path is related to the average velocity through Bernoulli

$$\frac{p_1}{\gamma} + \frac{U_1^2}{2g} = \frac{p_2}{\gamma} + \frac{U_2^2}{2g} + h_{L_{1-2}}$$

$$U_1 = U_2 \frac{A_2}{A_1}$$

$$Q_I = \overline{U}_2 A_2 = \frac{A_2}{\sqrt{1 - (A_2/A_1)^2}} \sqrt{\frac{2(p_1 - p_2)}{\rho}} + 2gh_{L_{1-2}}$$
Orifice Plate (O)
Orifice Plate (O)

- Inertial and viscous causes losses that require the use of correction coefficients:
- $C_c$ (correction coefficient): $A_2/A_0$
- $C_f$ (friction coefficient)
- Usually combined to give discharge coefficient $C = C_c \times C_f$
- Typically bought in calibrated form:

\[ Q_I = C E A_0 \sqrt{\frac{2\Delta p}{\rho}} = K_0 A_0 \sqrt{\frac{2\Delta p}{\rho}} \]
Orifice Plate (O)

Figure 10.5 Flow coefficients for a square-edged orifice meter having flange pressure taps. (Courtesy of American Society of Mechanical Engineers, New York, NY; compiled from data in reference 1.)
Orifice Plate (O)

• Accuracy: Coefficients 0.6% but \( Y = \left(\frac{4(P_1-P_2)}{P_1}\right)\%\)

• Uses: Incompressible fluids, relatively clean (correction coefficients for many fluids are readily available)

• Pros: Interchangeable; relatively inexpensive; Can be used for flow control!

• Cons: Large pressure loss; mounting location; orifice corrodes over time
Venturi Meter
Venturi Meter

• Smooth converging conical contraction
• Can be used for measuring all incompressible flows (including gases) $\Rightarrow$ cf orifice which is only for liquids
• Accuracy: C .7% - 1%
• Uses: Most flows; incompressible fluids
• Pros: Relatively low pressure loss
• Cons: High initial cost; possible large size (long pipe lengths)
Flow Nozzle (O)

Figure 10.9 The ASME long-radius nozzle with the associated flow pressure drop along its axis.
Flow Nozzle (O)

• Extending on the idea of the Venturi
• Accuracy: C 2% \( \pm 2(P1-P2)/P1 \)
• Uses: Most flows; incompressible fluids
• Pros: Smaller installation space and 80% of initial cost of Venturi
• Cons: Moderate pressure loss; fluid completely diverted
Sonic nozzles (O)

- Can take any of the forms prev discussed, but involves gases
- Accuracy: 2-3%
- Uses: Gases! (very common in Combustion processes)

Pros: Calibration less important
Cons: Large change in pressure and pressure loss must be tolerated; flow can become choked → max mass flow rate through the nozzle!

Laminar Flow meter (O)

- Exploits the linear relationship between $Q$ and laminar flow rate!

- Accuracy: 0.25%

- Uses: Clean fluids (otherwise you might block the flow tubes)

- Pros: High sensitivity at low flow; bidirectional flow measurement, relatively wide range of flow rates

- Cons: Clogging (see above); moderate pressure loss

\[ Q = \frac{\pi d^4}{128 \mu} \frac{p_1 - p_2}{L} \quad \text{where} \quad Re_d < 2000 \]
Electromagnetic Flow meter (I or NI)

• Based on Faraday principle
• Accuracy: 1-5%, but down to 0.25%!
• Uses: Commercially available device; very common in medical and wine industries
• Pros: Works with all fluids eg. corrosive or dirty; Can be NI; Pressure loss minimal; No internal parts; Independent of density and viscosity; Depends on average velocity only; laminar or turbulent flows
• Cons: Needs conductive fluid (water OK?); Symmetrical fluid flow
Vortex Shedding Meter (I)

• Operates on the principle that frequency of vortex shedding depends on average velocity and body shape

• Accuracy: 0.5%

• Uses: Most fluids, but not good for higher viscosity fluids

• Pros: No moving parts; low pressure poss

• Cons: Mid-range viscosities only → too high, no vortices, too low, strength weak; limited meter size
Vortex Shedding Meter (I)

Figure 10.17 Smoke lines in this photograph reveal the vortex shedding behind a streamlined wing-shaped body in a moving flow. (Photograph by R. Figliola.)

Table 10.1 Shedder Shape and Strouhal Number

<table>
<thead>
<tr>
<th>Cross Section</th>
<th>Strouhal Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
</tr>
</tbody>
</table>

*For Reynolds number Re_d ≥ 10^4, Strouhal number St = f d / U.*
Rotameter (I)

• Accuracy: 2%
• Uses: Most fluids, including gases
• Pros: Easily read (linear), cheap, doesn’t need power
• Cons: Sensitive to temperature; corrosion; drag varies
Turbine meter (I)

- Related angular momentum to flow rate
- Accuracy: ~0.25%
- Uses: Clean fluids; more common than book implies
- Pros: Low pressure drops; accuracy; good repeatability
- Cons: Cost; potential fouling; installation errors; temperature dependence ($\mu$ and $\rho$)
Positive displacement (I)

• Mechanical element that define a well known volume → eg. A reciprocating pump
• Accuracy: As low as 0.25%
• Uses: Home water meter, gas pumps
• Pros: Reliable; good accuracy; Calibration technique (one step up from bucket method)
• Cons: Some flow limitations; causes pulsating flow
Transit Time Flow meter (NI)

- Uses ultrasonic waves to determine flow rate
- Accuracy: 1-5%
- Uses: Very common in combustion flows
- Pros: Non-invasive; independent of fluid properties; portable models; time dependent flows
- Cons: Installation errors possible
Doppler Flow meter

- Same general idea as transit time but measures average velocity of particles in fluid
- Accuracy: ~2%
- Uses: Applicable to most systems
- Pros: Non-invasive; independent of fluid properties; time dependent flows
- Cons: Needs particulates or bubbles in fluid
Mass flow meters

• Flow meters are designed to measure volumes of fluids
• Mass flow rate can be calculated from $Q$ if we know $\rho$
• What if we just want mass flow rate??
  • Mass flow rate is most important
  • Density not exactly known under experimental conditions (many cases)
• Then we need to use a mass flow meter $\rightarrow$ physical phenomenon that depends on mass flow rate and is independent of $Q$...
Thermal Flow meter

• Amount of energy put in is known
• Accuracy: 0.5%
• Uses: Gas flows – adapted for use in automotive fuel injection system because independent of barometric pressure or outside air temperature
• Pros: Reliable method

VARIATION: Use a hot wire anemometer $\rightarrow$ gives good repeatability and accuracy

\[ \dot{E} = mc_p \Delta T \]

\[ \dot{E} = \left[ C + B(p\bar{U})^{1/n} \right] (T_s - T_f) \]
Coriolis Flow meter

- Basic principle → Induce a Coriolis acceleration in fluid and then measure resulting force
- Pass fluid through rotating or vibrating pipe → induces twist which is then measured
- Accuracy: 0.1%
Image credits

• All images from Figliola and Beasley, Mechanical Measurements 5th edition unless otherwise stated