CVE 372
HYDROMECHANICS

FLOW IN CLOSED CONDUITS

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Overview

2.1 General Characteristics of Flow in Closed Conduits

2.1.1 Definition of Laminar and Turbulent Flows

2.1.2 Entrance Region and Fully Developed Flow

2.1.3 Head Losses in Pipes
General Characteristics of Flow in Closed Conduits

- The governing equations for mass, momentum and energy transfer are developed in CVE 371 Fluid Mechanics.

- Now, we will apply them to viscous, incompressible fluids in pipes or ducts.
General Characteristics of Flow in Closed Conduits

- We assume that pipe is **fully filled** with the fluid.
- Main driving force is likely to be a **pressure gradient** along the pipe.
- If the pipe is not full, it is not possible to maintain this pressure difference, $p_1 - p_2$.

(a) Pipe flow,  
(b) Open-channel flow
2. FLOW IN CLOSED CONDUITS

General Characteristics of Flow in Closed Conduits

2.1.1. Definition of Laminar and Turbulent Flow

- Osborne Reynolds (1842-1912), a British scientist and mathematician was the first to distinguish the difference.
- In pipe flow:

  \[ Re = \frac{\rho VA}{\mu} \]

  - \( Re \leq 2100 \rightarrow \text{Laminar} \)
  - \( 2100 < Re < 4000 \rightarrow \text{Transition} \)
  - \( Re \geq 4000 \rightarrow \text{Turbulent} \)

(a) Experiment to illustrate type of flow. (b) Typical dye streaks.
General Characteristics of Flow in Closed Conduits

2.1.1. Definition of Laminar and Turbulent Flow

Time dependence of fluid velocity at a point
2.1.1. Definition of Laminar and Turbulent Flow

$u(t)$: instantaneous velocity in the x-direction

$u'(t)$: fluctuating part of $u(t)$

\[ u(t) = \bar{u} + u'(t) \]

\[ \bar{u} = \frac{1}{T} \int_{0}^{T} u \, dt \]

The time-averaged, $\bar{u}$, and fluctuating, $u'$, description of a parameter for tubular flow.
General Characteristics of Flow in Closed Conduits

2.1.1. Definition of Laminar and Turbulent Flow

Example 1:

Water at a temperature of 10°C flows through a pipe of diameter $D=1.85\text{ cm}$.

a) Determine the minimum time taken to fill a 355 cm$^3$ glass with water if the flow in the pipe is to be laminar.

b) Determine the maximum time taken to fill the same glass if the flow is to be turbulent.

Repeat the calculation if the water temperature is 60°C.

Solved in the class room
Example 2:

Water is flowing through capillary tubes A and B into tube C. If \( Q_A = 2 \times 10^{-3} \) l/s in tube A, what is the largest \( Q_B \) allowable in tube B for laminar flow in tube C? If the water has a temperature of 40°C with the calculated \( Q_B \), what kind of flow exists in tubes A and B?

\( D_A = 5 \) mm, \( D_B = 4 \) mm, and \( D_C = 6 \) mm

Solved in the class room
2. FLOW IN CLOSED CONDUITS

General Characteristics of Flow in Closed Conduits

2.1.2. Entrance Region and Fully Developed Flow

Entrance length

\[
\frac{L_e}{D} = 0.06 \text{Re}
\]

Laminar flow

Entrance length

\[
\frac{L_e}{D} = 4.4(\text{Re})^{1/6}
\]

Turbulent flow
2. FLOW IN CLOSED CONDUITS

General Characteristics of Flow in Closed Conduits

2.1.2. Entrance Region and Fully Developed Flow

- Pressure and Shear Stress
  - If viscosity was zero, pressure would not vary along x direction.
  - The physical properties of the shear stress are quite different for laminar flow then for turbulent flow.

\[
\tau_{\text{laminar}} = \mu \frac{du}{dy} \\
\tau_{\text{turbulent}} = (\mu + \mu_t) \frac{du}{dy}
\]

- \( \mu \) = molecular viscosity
- \( \mu_t \) = turbulent viscosity

Pressure distribution along a horizontal pipe
We need to determine the head loss. For convenience, we will consider two types of energy losses; minor and major loss.

- Total head loss, $h_L$

$$h_L = h_f + h_m$$

- $h_f$: Friction (viscous, major) loss
- $h_m$: Local (minor) loss

Note that major and minor do not necessarily reflect the magnitude of the energy losses.
2.1.3. Head Losses in Pipes

- Darcy – Weisbach Equation for friction loss

\[ h_f = f \frac{L V^2}{D 2g} \]

if

\[ V^2 = \frac{Q^2}{A^2} = \frac{Q^2}{\pi^2 (D^2 / 4)^2} = \frac{16Q^2}{\pi^2 D^4} \]

\[ h_f = f \frac{L 16Q^2}{D^5 \pi^2 2g} = KQ^2 \]

where

\[ K = \frac{8fL}{g \pi^2 D^5} \]

- Darcy-Weisbach friction factor
- L: pipe length (m)
- D: Pipe diameter (m)
- V: average velocity (m/s)
- Q: discharge (flow rate) (m\(^3\)/s)
2.1.3. Head Losses in Pipes

- Hazen – Williams Equation for friction loss

\[ h_f = \frac{6.8}{C^{1.85}} \frac{L}{D^{1.165}} V^{1.85} \]

or

\[ h_f = \frac{10.6}{C^{1.85}} \frac{L}{D^{4.87}} Q^{1.85} \]

C: Hazen-Williams coefficient of roughness (unitless)
L: pipe length (m)
D: Pipe diameter (m)
V: average velocity (m/s)
Q: Discharge (flow rate) (m³/s)
2.1.3. Head Losses in Pipes

- **Major losses** are due to energy loss in long straight sections of pipe which can be calculated by use of the friction factor.

- However, most pipe systems are not straight and have valves, bends, etc. which result in additional losses. These energy losses are collectively called **minor losses**.

- Typically, minor losses are evaluated from

\[
h_m = K_m \frac{V^2}{2g}
\]

where \(K_L\) is the loss coefficient which depends on both the geometry of the system and the Reynolds number. For large \(Re\), it simply becomes a function of the geometry.
2. FLOW IN CLOSED CONDUITS

General Characteristics of Flow in Closed Conduits

2.1.3. Head Losses in Pipes

- Local (minor) Loss

Empirical equation (except for sudden enlargement)

\[
h_m = K_m \frac{V^2}{2g}
\]

K: constant
V: average velocity (m/s)

Entrance flow conditions and loss coefficient.
(a) Reentrant, \( K_m = 0.8 \), (b) Sharp-edged, \( K_m = 0.5 \),
(c) Slightly rounded, \( K_m = 0.2 \), (d) Well-rounded, \( K_m = 0.04 \)
2. FLOW IN CLOSED CONDUITS

General Characteristics of Flow in Closed Conduits

2.1.3. Head Losses in Pipes

Local (minor) Loss

Loss coefficient for a sudden contraction.

\[ h_L = K_L \frac{V^2}{2g} \]
General Characteristics of Flow in Closed Conduits

2.1.3. Head Losses in Pipes

Local (minor) Losses

\[ h_L = K_L \frac{V^2}{2g} \]

\[ K_L = \left(1 - \frac{A_1}{A_2}\right)^2 \]
2.1.3. Head Losses in Pipes

Local (minor) Loss

Character of the flow in a 90° bend and the associated loss coefficient
### Table 8.2

Loss Coefficients for Pipe Components \( h_L = K_L \frac{V^2}{2g} \) (Data from Refs. 5, 10, 27)

<table>
<thead>
<tr>
<th>Component</th>
<th>( K_L )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>a. Elbows</strong></td>
<td></td>
</tr>
<tr>
<td>Regular 90°, flanged</td>
<td>0.3</td>
</tr>
<tr>
<td>Regular 90°, threaded</td>
<td>1.5</td>
</tr>
<tr>
<td>Long radius 90°, flanged</td>
<td>0.2</td>
</tr>
<tr>
<td>Long radius 90°, threaded</td>
<td>0.7</td>
</tr>
<tr>
<td>Long radius 45°, flanged</td>
<td>0.2</td>
</tr>
<tr>
<td>Regular 45°, threaded</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>b. 180° return bends</strong></td>
<td></td>
</tr>
<tr>
<td>180° return bend, flanged</td>
<td>0.2</td>
</tr>
<tr>
<td>180° return bend, threaded</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>c. Tees</strong></td>
<td></td>
</tr>
<tr>
<td>Line flow, flanged</td>
<td>0.2</td>
</tr>
<tr>
<td>Line flow, threaded</td>
<td>0.9</td>
</tr>
<tr>
<td>Branch flow, flanged</td>
<td>1.0</td>
</tr>
<tr>
<td>Branch flow, threaded</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>d. Union, threaded</strong></td>
<td>0.08</td>
</tr>
<tr>
<td><strong>e. Valves</strong></td>
<td></td>
</tr>
<tr>
<td>Globe, fully open</td>
<td>10</td>
</tr>
<tr>
<td>Angle, fully open</td>
<td>2</td>
</tr>
<tr>
<td>Gate, fully open</td>
<td>0.15</td>
</tr>
<tr>
<td>Gate, ( \frac{1}{4} ) closed</td>
<td>0.26</td>
</tr>
<tr>
<td>Gate, ( \frac{1}{2} ) closed</td>
<td>2.1</td>
</tr>
<tr>
<td>Gate, ( \frac{3}{4} ) closed</td>
<td>17</td>
</tr>
<tr>
<td>Swing check, forward flow</td>
<td>2</td>
</tr>
<tr>
<td>Swing check, backward flow</td>
<td>( \infty )</td>
</tr>
<tr>
<td>Ball valve, fully open</td>
<td>0.05</td>
</tr>
<tr>
<td>Ball valve, ( \frac{1}{4} ) closed</td>
<td>5.5</td>
</tr>
<tr>
<td>Ball valve, ( \frac{1}{2} ) closed</td>
<td>210</td>
</tr>
</tbody>
</table>

*See Fig. 8.32 for typical valve geometry.