Unit 1: Introduction and basic hydraulics of water transport

Contents:

1. Historical aspects of water distribution system
2. Concept of water flow in piping system
3. Components of water distribution
4. Water Supply pumping system
5. Water distribution system hydraulic calculation
6. Exercise
7. References
Historical aspects of water distribution system
INTRODUCTION

The cornerstone of any healthy population is access to safe drinking water.

The population growth in developing countries almost entirely wiped out the gains. In fact, nearly as many people lack those services.


<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban</td>
<td>243</td>
<td>570</td>
<td>813</td>
</tr>
<tr>
<td>Rural</td>
<td>989</td>
<td>312</td>
<td>1301</td>
</tr>
<tr>
<td>Total</td>
<td>1232</td>
<td>882</td>
<td>2114</td>
</tr>
</tbody>
</table>
Because of the importance of safe drinking water for the needs of society and for industrial growth, considerable emphasis recently has been given to the condition of the infrastructure.

One of the most vital services to industrial growth is an adequate water supply system—without it, industry cannot survive.

The lack of adequate water supply systems is due to both the deterioration of water supplies in older urbanized areas and to the nonexistence of water supply systems.

Consideration not only rehabilitation of existing urban water supply systems but also the future development of new water supply systems to serve expanding population centers.

Both the adaptation of existing technologies and the development of new innovative technologies will be required to improve the efficiency and cost-effectiveness of future and existing water supply systems and facilities necessary for domestic and industrial growth.
Humans have spent most of their history as hunters and food gatherers. Only in the last 9000-10,000 years have human beings discovered how to raise crops and tame animals.

This agricultural revolution probably took place first in the hills to the north of present day Iraq and Syria.

During the time of this agricultural breakthrough, people began to live in permanent villages instead of leading a wandering existence. About 6000-7000 years ago, farming villages of the Near and Middle East became cities.

The first successful efforts to control the flow of water were made in Mesopotamia (بلاد الرافدين) and Egypt.

Water knowledge relied on geological and meteorological observation plus social consensus and administrative organization, particularly among the ancient Greeks.

Knossos, approximately 5 km from Herakleon, the modern capital of Crete, was one of the most ancient and unique cities of the Aegean Sea area and of Europe.
Knossos was first inhabited shortly after 6000 B.C., and within 3000 years it had became the largest Neolithic (Neolithic Age, ca. 5700-28 B.C.) settlement in the Aegean.

During the Bronze Age (ca. 2800-1100 B.C.), the Minoan civilization developed and reached its culmination as the first Greek cultural miracle of the Aegean world.

The Acropolis in Athens, Greece, has been a focus of settlement starting in the earliest times. Not only its defensive capabilities, but also its water supply made it the logical location for groups who dominated the region.

The location of the Acropolis on an outcropping of rock, the naturally occurring water, and the ability of the location to save the rain and spring water resulted in a number of diverse water sources, including cisterns, wells, and springs.

Anatolia, also called Asia Minor, which is part of the present-day Republic of Turkey, has been the crossroads of many civilizations during the last 10,000 years. In this region, there are many remains of ancient water supply systems dating back to the Hittite period (2000-200 B.C.), including pipes, canals, tunnels, inverted siphons, aqueducts, reservoirs, cisterns, and dams.
Shaft of water holder at the Acropolis at Athens, Greece. (Photograph by L. W. Mays).
Water distribution pipe in Ephesus, Turkey. (Photographs by L. W. Mays).
Most Roman piping was made of lead, and even the Romans recognized that water transported by lead pipes was a health hazard.

The water source for a typical water supply system of a Roman city was a spring or a dug well, usually with a bucket elevator to raise the water. If the well water was clear and of sufficient quantity, it was conveyed to the city by aqueduct. Also, water from several sources was collected in a reservoir, then conveyed by aqueduct or pressure conduit to a distributing reservoir (castellum).

Three pipes conveyed the water—one to pools and fountains, the second to the public baths, and the third to private houses for revenue to maintain the aqueducts.

Water flow in the Roman aqueducts was basically by gravity.

Water flowed through an enclosed conduit (*specus* or *rivus*), which was typically underground, from the source to a terminus or distribution tanks (*castellum*). Aqueducts above ground were built on a raised embankment (*substructio*) or on an arcade or bridge. *Settling tanks* (*piscinae*) were located along the aqueducts to remove sediments and foreign matter.
<table>
<thead>
<tr>
<th>Prehistorical period</th>
<th>Springs</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd-2nd millennium B.C.</td>
<td>Cisterns</td>
</tr>
<tr>
<td>*3rd millennium B.C.</td>
<td>Dams</td>
</tr>
<tr>
<td>3rd millennium B.C.</td>
<td>Wells</td>
</tr>
<tr>
<td>? Probably very early</td>
<td>Reuse of excrement as fertilizer</td>
</tr>
<tr>
<td>*2 millennium B.C.</td>
<td>Gravity flow supply, pipes or channels and drains, pressure pipes (subsequently forgotten)</td>
</tr>
<tr>
<td>8th-6th c B.C.</td>
<td>Long-distance water supply lines with tunnels and bridges as well as intervention in and harnessing of karstic water systems</td>
</tr>
<tr>
<td>6th c. B.C. at latest</td>
<td>Public as well as private bathing facilities consisting of: bathtubs or showers, footbaths, washbasins, latrines المراحيض or toilets, laundry and dishwashing facilities</td>
</tr>
<tr>
<td>6th c. B.C. at latest</td>
<td>Utilization of definitely two and probably three qualities of water: potable, subpotable, and nonpotable, including irrigation using storm runoff, probably combined with waste waters</td>
</tr>
<tr>
<td>6th-3rd c. B.C.</td>
<td>Pressure pipes and siphon systems.</td>
</tr>
</tbody>
</table>
Status of Water Distribution Systems in the 19th Century

v Cast iron has been the material most used for water distribution mains in older cities since its introduction in the United States in the early 1800s.

v A survey done in the late 1960s by the Cast Iron Pipe Research Association (now called the Ductile Iron Pipe Research Association) reported that in the 100 largest cities, about 90 percent (87,000 miles) of water mains 4 inches and larger were cast iron.

v Twenty-eight of the cities reported having cast iron mains 100 years old or older. Based on this survey, this association estimated that the United States had over 400,000 miles of cast iron water mains in 1970.

v In Boston, 99 percent of the distribution system is cast and ductile iron; in Washington, D.C., 95 percent; and in New Orleans, 69 percent.
FLOWERS STOP-VALVE.—(Flowers Brothers, Detroit. From Fanning, 1890)
Coffin's stop-valve (Courtesy of Boston Machine Co., Boston) (From Fanning, 1890).
Check-valve. (From Fanning, 1890).

Lowry's flush hydrant (Courtesy of Boston Machine Co., Boston) (From Fanning, 1890).
Early Pipe Flow Computational Methods

In Fanning's *A Practical Treatise on Hydraulic and Water-Supply Engineering* (1980). This book did not cover the flow in any type of pipe system, even in a simple branching system or a parallel pipe system.

Le Conte (1926) and King et al. (1941) discussed branching pipes connecting three reservoirs and pipes in series and parallel.

The book *Water Supply Engineering*, by Babbitt and Doland (1939), stated, "A method of successive approximations has recently (1936) been developed by Prof. Hardy Cross which makes it possible to analyze rather complicated systems with the simple equipment."
CONCEPT OF WATER FLOW IN PIPING SYSTEM
Bernoulli equation states that for constant flow, an energy balance between two pipes cross section can be written as: $E_1 = E_2 + \sigma E$ or expressed in developed form, per unit weight (in $MWC$):

$$Z_1 + \frac{P_1}{\rho g} + \frac{V_1^2}{2g} = Z_2 + \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + \sigma E$$
Elevation Head: this is an amount of flow potential energy in one cross section defined by the elevation. This correspond to $Z$ in cross section

$$\frac{P}{\rho g}$$

Pressure Head $\frac{P}{\rho g}$: this is an amount of the flow potential energy in one cross section defined by the water pressure.

Piezometric Head $Z + \frac{P}{\rho g}$: this is the sum of elevation and pressure head in one cross section.

Velocity Head $\frac{V^2}{2g}$: this is an amount of flow kinetic energy in one cross section defined by the water velocity.
Head (Energy) Losses

When a fluid is flowing through a pipe, the fluid experiences some resistance due to which some of energy (head) of fluid is lost.
A. Major losses

*Useful Formulas to find the Major losses*

1. Darcy-Weisbach formula
2. The Hazen -Williams Formula
3. The Manning Formula
4. The Chezy Formula
1. Darcy-Weisbach formula

\[ h_f = f \left( \frac{L}{D} \right) \frac{V^2}{2g} \]

- \( f = \text{Friction factor} \)
- \( L = \text{Length of considered pipe (m)} \)
- \( D = \text{Pipe diameter (m)} \)
- \( \frac{V^2}{2g} = \text{Velocity head (m)} \)

**Friction Factor: (f)**

- For Laminar flow: \((Re < 2000)\) is \( f = \frac{64}{Re} \)
- For turbulent flow in smooth pipes \((\varepsilon/D = 0)\) with \( 4000 < Re < 10^5 \) is \( f = \frac{0.316}{Re^{1/4}} \)
- For turbulent flow \((Re > 4000)\) the friction factor can be founded from moody chart

\[ \text{Re} = \frac{VD}{\mu} \]

\( \mu = \frac{497 \times 10^{-6}}{(T + 42.5)^{1.5}} \)

Where:

- \( D = \text{Pipe diameter} \)
- \( V = \text{mean velocity} \)
- \( \mu = \text{Kinetic viscosity, m2/s which can be expressed as} \)
- \( T = \text{temperature C} \)
Typical value of the absolute roughness are given

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>$e (mm)$</th>
<th>$e (ft)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass, drawn brass, copper (new)</td>
<td>0.0015</td>
<td>0.000005</td>
</tr>
<tr>
<td>Seamless commercial steel (new)</td>
<td>0.004</td>
<td>0.000013</td>
</tr>
<tr>
<td>Commercial steel (enamel coated)</td>
<td>0.0048</td>
<td>0.000016</td>
</tr>
<tr>
<td>Commercial steel (new)</td>
<td>0.045</td>
<td>0.00015</td>
</tr>
<tr>
<td>Wrought iron (new)</td>
<td>0.045</td>
<td>0.00015</td>
</tr>
<tr>
<td>Asphalted cast iron (new)</td>
<td>0.12</td>
<td>0.0004</td>
</tr>
<tr>
<td>Galvanized iron</td>
<td>0.15</td>
<td>0.0005</td>
</tr>
<tr>
<td>Cast iron (new)</td>
<td>0.26</td>
<td>0.00085</td>
</tr>
<tr>
<td>Wood Stave (new)</td>
<td>0.18 ~ 0.9</td>
<td>0.0006 ~ 0.003</td>
</tr>
<tr>
<td>Concrete (steel forms, smooth)</td>
<td>0.18</td>
<td>0.0006</td>
</tr>
<tr>
<td>Concrete (good joints, average)</td>
<td>0.36</td>
<td>0.0012</td>
</tr>
<tr>
<td>Concrete (rough, visible, form marks)</td>
<td>0.60</td>
<td>0.002</td>
</tr>
<tr>
<td>Riveted steel (new)</td>
<td>0.9 ~ 9.0</td>
<td>0.003-0.03</td>
</tr>
<tr>
<td>Corrugated metal</td>
<td>45</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Colebrook formula: the Moody chart is a graphical representation of this equation

$$\frac{1}{\sqrt{f}} = -2 \log \left( \frac{e/D}{3.7} + \frac{2.51}{Re \sqrt{f}} \right)$$

Friction factor for fully developed flow in circular pipes. (Data from [8], used by permission.)
**Example 1:** Find the head loss due to friction in galvanized-iron pipe of 30 cm diameter and 50 m long through which water is flowing at a velocity of 3 m/s assume that water flowing at 20 C.

**Solution**

\[
\mu = \frac{497 \times 10^{-6}}{(T + 42.5)^{1.5}} \quad \mu = \frac{497 \times 10^{-6}}{(20 + 42.5)^{1.5}} = 1.01 \times 10^{-6} \text{ m}^2/\text{s}
\]

\[
R_e = \frac{VD}{\mu} = 3 \times 0.3 / 1.01 \times 10^{-6} = 8.9 \times 10^5
\]

For galvanized iron \( e = 0.15 \text{ mm from table 2.1} \)

\[
e/D = 0.15 \times 10^{-3} / 0.3 = 0.0005
\]

Using \( R_e \) and \( e/D \) from Moody diagram

\[f = 0.0172\]

Using Darcy-Weisback formula:

\[
h_f = 0.0172 \left( \frac{50}{0.3} \right) \frac{3^2}{2(9.81)} = 1.315 \text{ m}
\]
2. The Hazen-Williams formula

It has been used extensively for designing of water-supply systems

\[ V = 0.85 \, C_{HW} \, R_h^{0.63} \, S^{0.54} \]

\[ h_f = 10.7 \, \frac{L}{D^{4.87}} \left( \frac{Q}{C_{HW}} \right)^{1.85} \]

\[ h_f = 7.62 \, \frac{L}{D} \left( \frac{V}{C_{HW}} \right)^{1.85} \]

- \( V \) = mean velocity (m/s)
- \( R_h \) = hydraulic radius
- \( S \) = head loss per unit length of pipe
- \( C_{HW} \) = Hazen-williams Coefficient

\[ \frac{h_f}{L} = \text{head loss per unit length of pipe} \]
Example 2: A 100 m long pipe with D = 20 cm. It is made of riveted steel and carries a discharge of 30 l/s. Determine the head loss in the pipe using Hazen-Williams formula.

Solution:

\[ V = 0.85 \ C_{HW} \ R_h^{0.63} \ S^{0.54} \]

\[ R_h = D/4 = 0.2/4 = 0.05 \text{ m} \]

\[ C_{HW} = 110 \text{ from the table} \]

\[ V = Q/A = V = 0.85(110)(0.05)^{0.63}(hf / 100)^{0.54} \]

\[ = \frac{30\times(10)^{-3}}{(3.14/4)(0.2)^2} \]

\[ h_f = 0.68 \text{ m} \]

<table>
<thead>
<tr>
<th>Pipe Materials</th>
<th>( C_{HW} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asbestos Cement</td>
<td>140</td>
</tr>
<tr>
<td>Brass</td>
<td>130–140</td>
</tr>
<tr>
<td>Brick sewer</td>
<td>100</td>
</tr>
<tr>
<td>Cast-iron</td>
<td></td>
</tr>
<tr>
<td>New, unlined</td>
<td>130</td>
</tr>
<tr>
<td>10 yr. old</td>
<td>107–113</td>
</tr>
<tr>
<td>20 yr. old</td>
<td>89–100</td>
</tr>
<tr>
<td>30 yr. old</td>
<td>75–90</td>
</tr>
<tr>
<td>40 yr. old</td>
<td>64–83</td>
</tr>
<tr>
<td>Concrete or concrete lined</td>
<td></td>
</tr>
<tr>
<td>Steel forms</td>
<td>140</td>
</tr>
<tr>
<td>Wooden forms</td>
<td>120</td>
</tr>
<tr>
<td>Centrifugally spun</td>
<td>135</td>
</tr>
<tr>
<td>Copper</td>
<td>130–140</td>
</tr>
<tr>
<td>Galvanized iron</td>
<td>120</td>
</tr>
<tr>
<td>Glass</td>
<td>140</td>
</tr>
<tr>
<td>Lead</td>
<td>130–140</td>
</tr>
<tr>
<td>Plastic</td>
<td>140–150</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
</tr>
<tr>
<td>Coal-tar enamel lined</td>
<td>145–150</td>
</tr>
<tr>
<td>New unlined</td>
<td>140–150</td>
</tr>
<tr>
<td>Riveted</td>
<td>110</td>
</tr>
<tr>
<td>Tin</td>
<td>130</td>
</tr>
<tr>
<td>Vitrified clay (good condition)</td>
<td>110–140</td>
</tr>
<tr>
<td>Wood stave (average condition)</td>
<td>120</td>
</tr>
</tbody>
</table>
3. The Manning Formula

\[ V = \frac{1}{n} R_h^{2/3} S^{1/2} \]

\[ h_f = 10.3 n^2 L \frac{Q^2}{D^{16/3}} \]

\[ h_f = 6.35 \frac{L}{D^{1.33}} n^2 V^2 \]

<table>
<thead>
<tr>
<th>Type of Pipe</th>
<th>Manning's n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass, brass, or copper</td>
<td>0.009</td>
</tr>
<tr>
<td>Smooth cement surface</td>
<td>0.010</td>
</tr>
<tr>
<td>Wood-stave</td>
<td>0.010</td>
</tr>
<tr>
<td>Vitrified sewer pipe</td>
<td>0.010</td>
</tr>
<tr>
<td>Cast-iron</td>
<td>0.011</td>
</tr>
<tr>
<td>Concrete, precast</td>
<td>0.011</td>
</tr>
<tr>
<td>Cement mortar surfaces</td>
<td>0.011</td>
</tr>
<tr>
<td>Common-clay drainage tile</td>
<td>0.011</td>
</tr>
<tr>
<td>Wrought iron</td>
<td>0.012</td>
</tr>
<tr>
<td>Brick with cement mortar</td>
<td>0.012</td>
</tr>
<tr>
<td>Riveted-steel</td>
<td>0.017</td>
</tr>
<tr>
<td>Cement rubble surfaces</td>
<td>0.017</td>
</tr>
<tr>
<td>Corrugated metal storm drain</td>
<td>0.020</td>
</tr>
</tbody>
</table>
Example 3: A horizontal pipe with 10 cm uniform diameter is 200 m long. It is made of uncoated cast iron and is in bad condition. The measured pressure drop is 24.6 m in water column. Determine the discharge using manning formula.

**Solution**

\[Q = \frac{\pi (D^2)}{4} \frac{1}{n} \left( \frac{d}{4} \right)^{2/3} \left( \frac{h_f}{S} \right)^{1/2} \]

\[n = 0.015 \quad \text{(Table 2.3a)}\]

\[R_h = \frac{D}{4} = \frac{0.10}{4} = 0.025 \text{ m}\]

Since \( \frac{P_1 - P_2}{S} = h_f \) for horizontal pipe

then \[\frac{h_f}{L} = \frac{24.6}{200} = 0.123\]

Sub. values in eq. (1) : 

\[Q = \frac{\pi (0.1)^2}{4} \frac{1}{0.015} (0.025)^{2/3} (0.123)^{1/2}\]

\[Q = 0.0157 \text{ m}^3/\text{s}\]

\[= 15.7 \text{ c} / \text{s} \]
4. The Chezy Formula

\[ V = C \left( \frac{R}{h} \right)^{1/2} S^{1/2} \]

where \( C = \text{Chezy coefficient} \)

\[ h_f = 4 \frac{L}{D} \left( \frac{V}{C} \right)^2 \]

- It can be shown that this formula, for circular pipes, is equivalent to Darcy’s formula with the value for

\[ C = \sqrt{\frac{8g}{f}} \]

\( [f \text{ is Darcy Weisbeich coefficient}] \)

- The following formula has been proposed for the value of \( C \):

\[ C = \frac{23 + \frac{0.00155}{S} + \frac{1}{n}}{1 + (23 + \frac{0.00155}{S}) \frac{n}{\sqrt{R_h}}} \]

\( [n \text{ is the Manning coefficient}] \)
B. Minor losses

It is due to the change of the velocity of the flowing fluid in the magnitude or in direction [turbulence within bulk flow as it moves through and fitting]

The minor losses occurs at:

- Valves
- Tees
- Bends
- Reducers
- Valves
- And other appurtenances

It has the common form

$$\begin{bmatrix} K_L & \frac{V^2}{2g} \end{bmatrix}$$
1. Head Loss Due to a Sudden Expansion (Enlargement)

\[ h_L = K_L \frac{V_1^2}{2g} \]

\[ K_L = \left(1 - \frac{A_1}{A_2}\right)^2 \]

or:

\[ h_L = \frac{(V_1 - V_2)^2}{2g} \]
2. Head Loss Due to a Sudden Contraction

\[ h_L = K_L \frac{V_2^2}{2g} \]

\[ h_L = 0.5 \frac{V_2^2}{2g} \]
3. Head Loss Due to Gradual Enlargement (conical diffuser)

\[ h_L = K_L \frac{(V_1^2 - V_2^2)}{2g} \]

<table>
<thead>
<tr>
<th>( a )</th>
<th>10(^0)</th>
<th>20(^0)</th>
<th>30(^0)</th>
<th>40(^0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_L )</td>
<td>0.39</td>
<td>0.80</td>
<td>1.00</td>
<td>1.06</td>
</tr>
</tbody>
</table>

Gibson Test: Loss coefficient for conical enlargement
4. Head Loss Due to Gradual Contraction (reducer or nozzle)

\[ h_L = K_L \frac{(V_2^2 - V_1^2)}{2g} \]

<table>
<thead>
<tr>
<th>a</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_L )</td>
<td>0.2</td>
<td>0.28</td>
<td>0.32</td>
<td>0.35</td>
</tr>
</tbody>
</table>

A different set of data is:

**Table**

Loss Coefficients (\( K \)) for Gradual Contractions.

<table>
<thead>
<tr>
<th>Included Angle, ( \theta ), Degrees</th>
<th>A₂/A₁</th>
<th>10</th>
<th>15–40</th>
<th>50–60</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>180</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₂/A₁</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>0.12</td>
<td>0.18</td>
<td>0.24</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>0.05</td>
<td>0.04</td>
<td>0.07</td>
<td>0.17</td>
<td>0.27</td>
<td>0.35</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>0.10</td>
<td>0.05</td>
<td>0.05</td>
<td>0.08</td>
<td>0.19</td>
<td>0.29</td>
<td>0.37</td>
<td>0.43</td>
<td></td>
</tr>
</tbody>
</table>

*Note:* Coefficients are based on \( h_{lm} = K(\bar{V}_2^2/2) \).
5. Head Loss at the Entrance of a Pipe (flow leaving a tank)

Reentrant (embedded)\n\[ K_L = 0.8 \]

Sharp edge\n\[ K_L = 0.5 \]

Slightly rounded\n\[ K_L = 0.2 \]

Well rounded\n\[ K_L = 0.04 \]

\[ h_L = K_L \frac{V^2}{2g} \]
Another Typical values for various amount of rounding of the lip
6. Head Loss at the Exit of a Pipe  (flow entering a tank):

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

the entire kinetic energy of the exiting fluid (velocity \( V_1 \)) is dissipated through viscous effects as the stream of fluid mixes with the fluid in the tank and eventually comes to rest (\( V_2 = 0 \)).
7. Head Loss Due to Bends in Pipes

![Diagram of a pipe bend with high and low pressure areas and a formula for head loss.]

\[ h_b = K_b \frac{V^2}{2g} \]

**Figure** Head loss at a bend: (a) flow separation in a bend; (b) secondary flow at a bend.

<table>
<thead>
<tr>
<th>(R/D)</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>10</th>
<th>16</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_b)</td>
<td>0.35</td>
<td>0.19</td>
<td>0.17</td>
<td>0.22</td>
<td>0.32</td>
<td>0.38</td>
<td>0.42</td>
</tr>
</tbody>
</table>
8. **Miter bends**: For situations in which space is limited

**FIGURE**: Character of the flow in a 90° miter bend and the associated loss coefficient: (a) without guide vanes, (b) with guide vanes.
9. Head Loss Due to Pipe Fittings (valves, elbows, bends, and tees)

TABLE: Values of $K_v$ for Certain Common Hydraulic Valves

A. Gate valves

- Closed
  
  $K_v = 0.15$ (fully open)

- Open

B. Globe valves:

- Closed
  
  $K_v = 10.0$ (fully open)

- Open

$$h_v = K_v \frac{V^2}{2g}$$
C. Check valves:

Closed

Hinge (Swing type)

Open

Swing type $K_V = 2.5$ (fully open)
Ball type $K_V = 70.0$ (fully open)
Lift type $K_V = 12.0$ (fully open)

D. Rotary valves:

Closed

Open

$K_V = 10.0$ (fully open)
10. The loss coefficient for elbows, bends, and tees

<table>
<thead>
<tr>
<th>Component</th>
<th>$K_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Elbows</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>b. 180° return bends</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>c. Tees</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>
</tbody>
</table>
Flow Through Single & Compound Pipes

Any water conveying system may include the following elements:
  - pipes (in series, pipes in parallel)
  - elbows
  - valves
  - other devices.

- If all elements are connected in series, The arrangement is known as a pipeline.
- Otherwise, it is known as a pipe network.

How to solve flow problems

Calculate the total head loss (major and minor)
Apply the energy equation (Bernoulli’s equation)

This technique can be applied for different systems.
A simple pipe flow: It is a flow that takes place in one pipe having a constant diameter with no branches. This system may include bends, valves, pumps and so on.
To solve such system:

- Apply Bernoulli’s equation

\[
\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L - h_p
\]

where

\[
h_L = h_f + h_m = \sum \frac{fL}{D} \frac{V^2}{2g} + \sum K_L \frac{V^2}{2g}
\]

For the same material and constant diameter (same \( f \), same \( V \)) we can write:

\[
h_L = h_f + h_m = \frac{V^2}{2g} \left[ \frac{fL_{\text{Total}}}{D} + \sum K_L \right]
\]
Compound Pipe flow

The system is called compound pipe flow: When two or more pipes with different diameters are connected together head to tail (in series) or connected to two common nodes (in parallel)

A. Flow Through Pipes in Series

• pipes of different lengths and different diameters connected end to end (in series) to form a pipeline
• **Discharge:** The discharge through each pipe is the same

\[ Q = A_1 V_1 = A_2 V_2 = A_3 V_3 \]

• **Head loss:** The difference in liquid surface levels is equal to the sum of the total head loss in the pipes:

\[
\frac{P_A}{\gamma} + \frac{V_A^2}{2g} + z_A = \frac{P_B}{\gamma} + \frac{V_B^2}{2g} + z_B + h_L
\]
\[
\frac{P_A}{\gamma} + \frac{V_A^2}{2g} + z_A = \frac{P_B}{\gamma} + \frac{V_B^2}{2g} + z_B + h_L
\]

\[z_A - z_B = h_L = H\]

Where

\[h_L = \sum_{i=1}^{3} h_{fi} + \sum_{j=1}^{4} h_{mj}\]

\[h_L = \sum_{i=1}^{3} f_i \frac{L_i}{D_i} \frac{V_i^2}{2g} + K_{ent} \frac{V_1^2}{2g} + K_c \frac{V_2^2}{2g} + K_{enl} \frac{V_2^2}{2g} + K_{exit} \frac{V_3^2}{2g}\]
B. Flow Through Parallel Pipes:

If a main pipe divides into two or more branches and again join together downstream to form a single pipe, then the branched pipes are said to be connected in parallel (compound pipes).

• Points A and B are called nodes.

**Discharge:**

\[
Q = Q_1 + Q_2 + Q_3 = \sum_{i=1}^{3} Q_i
\]

**Head loss:** the head loss for each branch is the same

\[
h_L = h_{f1} = h_{f2} = h_{f3}
\]

\[
f_1 \frac{L_1}{D_1} \frac{V_1^2}{2g} = f_2 \frac{L_2}{D_2} \frac{V_2^2}{2g} = f_3 \frac{L_3}{D_3} \frac{V_3^2}{2g}
\]
Example

- Four pipes connected in parallel as shown. The following details are given:

<table>
<thead>
<tr>
<th>Pipe</th>
<th>L (m)</th>
<th>D (mm)</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>200</td>
<td>0.020</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>250</td>
<td>0.018</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>300</td>
<td>0.015</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>200</td>
<td>0.020</td>
</tr>
</tbody>
</table>

- If $Z_A = 150 \text{ m}$, $Z_B = 144 \text{ m}$, determine the discharge in each pipe (assume $P_A = P_B = P_{atm}$)
Solution

\[ Z_A - Z_B = h_f = h_{f_1} = h_{f_2} = h_{f_3} = h_{f_4} \text{ (neglect minor losses)} \]

\[ 150 - 144 = 6 h_{f_i} = f_i \frac{L_i V_i^2}{D_i^2 2g} \]

But \( V_i = \left( \frac{Q_i}{A_i} \right) = \left( \frac{Q_i}{\frac{\pi}{4} \times D_i^2} \right) \)

\[ 6 = \frac{8f_i L_i Q_i^2}{\pi^2 g D_i^2} \text{ Substitute for Pipe 1, 2, 3 and 4} \]

\[ Q = 0.0762 + 0.1146 + 0.28 + 0.1078 = 0.579 \text{ m}^3/\text{s} \]
COMPONENTS OF WATER DISTRIBUTION SYSTEM
MODERN WATER DISTRIBUTION SYSTEMS

All water transport and distribution system and devices have to satisfy the following criteria:

a) To be constructed and/or manufactured of materials that are not harmful for human being life.

b) To be resistant to mechanical; and chemical attacks possible in distribution system

c) To be constructed and manufactured of durable materials.
Urban water distribution is composed of three major components:
- distribution piping
- distribution storage
- pumping stations

These components can be further divided into subcomponents, which can in turn be divided into sub-subcomponents.

The pumping station component consists of structural, electrical, piping, and pumping unit subcomponents.

The pumping unit can be further divided into sub-subcomponents:
- pump, driver, controls, power transmission, piping and valves.

The exact definition of components, subcomponents, and sub-subcomponents is somewhat fluid and depends on the level of detail of the required analysis and, to a somewhat greater extent, the level of detail of available data.
Hierarchical relationship of Components, Subcomponent, and sub-subcomponent.
(Cullinane, 1989)
System Components

Transmission: This is the basic part of water transport and distribution system that represents a large proportion of investment. It consists of various types of pipes, joints, fittings and connections, that operate together with miscellaneous control equipment.

Pipes

- Pipe sections or links are the most abundant elements in the network. These sections are constant in diameter and may contain fittings and other appurtenances, such as valves, storage facilities, and pumps.

- Pipes are the largest capital investment in a distribution system.

- Pipes used in water supply are made of various materials. They can be categorized in three large groups:
  - Rigid (iron, prestressed concrete, asbestos cement)
  - Semi-rigid (steel, ductile iron)
  - Flexible (PVC, PE, HDPE, glass reinforced plastic)
Trunk main: To transport water from the source to the distribution area. (usually above 400mm to few meters).

Secondary main: To link main distribution pipes with the service reservoir or and with the trunk distribution mains.

Distribution Main: carry water from the secondary main to the smaller consumers. These are in particular pipes laid in the roads and streets of urban areas with diameters in principal 100-200mm.

Service pipe: To bring water from distribution main directly to a public dwelling. In case of domestic supplies service pipes are generally less than 25mm diameter.
Water distribution network pipelines classification
Nodes

- A node refers to either end of a pipe. Two categories of nodes are junction nodes and fixed-grade nodes.

- Nodes where the inflow or the outflow is known are referred to as junction nodes. These nodes have lumped demand, which may vary with time.

- Nodes to which a reservoir is attached are referred to as fixed-grade nodes. These nodes can take the form of tanks or large constant-pressure mains.
Valves

Control valves regulate the flow or pressure in water distribution systems. If conditions exist for flow reversal, the valve will close and no flow will pass.

The most common type of control valve is the pressure-reducing (pressure-regulating) valve (PRV), which is placed at pressure zone boundaries to reduce pressure.

The PRV maintains a constant pressure at the downstream side of the valve for all flows with a pressure lower than the upstream head. When connecting high-pressure and low-pressure water distribution systems, the PRV permits flow from the high-pressure system if the pressure on the low side is not excessive.

Another types of control (check) valve:

A horizontal swing valve, operates under similar principle.

Pressure-sustaining valves operate similarly to PRVs monitoring pressure at the upstream side of the valve.
Check Valve

- Valve only allows flow in one direction
- The valve automatically closes when flow begins to reverse

Pressure Relief Valve

Valve will begin to open when pressure in the pipeline **exceeds** a set pressure (determined by force on the spring).
Where high pressure could cause an explosion (boilers, water heaters, …)
Pressure Regulating Valve

sets maximum pressure downstream

Valve will begin to open when the pressure is Less than the downstream setpoint pressure (determined by the force of the spring).

Similar function to pressure break tank
Pressure Sustaining Valve

sets minimum pressure upstream

Valve will begin to open when the pressure upstream is greater than the setpoint pressure (determined by the force of the spring).

Similar to pressure relief valve
Flow control valve (FCV)

- Limits the flow rate through the valve to a specified value, in a specified direction
- Commonly used to limit the maximum flow to a value that will not adversely affect the provider’s system

Pressure Break Tanks

- In the developing world, small water supplies in mountainous regions can develop too much pressure for the PVC pipe.
- They don’t want to use PRVs because they are too expensive and are prone to failure.
- Pressure break tanks have an inlet, an outlet, and an overflow.
Air Release Valves

Air in Pipelines

- Three sources of air
  - Startup
  - Low flow
  - Air super saturation
  - All downward sloping pipe downstream of a high point (other than the source) could be filled with air

Air handling strategies

- Air release valve at all high point. Valves must be placed carefully
  - Design high flow rates that carry air downstream
Pressure-reducing and pressure-sustaining valve

Typical application of a pressure-reducing and pressure-sustaining valve. (Courtesy of Bermad).

Pressure-reducing and pressure sustaining valve
Distribution-system storage is needed to equalize pump discharge near an efficient operating point in spite of varying demands, to provide supply during outages of individual components, to provide water for fire fighting, and to dampen out hydraulic transients.

Distribution storage in a water distribution network is closely associated with the water tank. Tanks are usually made of steel and can be built at ground level or be elevated at a certain height from the ground.

The water tank is used to supply water to meet the requirements during high system demands or during emergency conditions when pumps cannot adequately satisfy the pressure requirements at the demand nodes.

If a minimum volume of water is kept in the tank at all times, then unexpected high demands cannot be met during critical conditions.

The higher the pump discharge, the lower the pump head becomes. Thus, during a period of peak demands, the amount of available pump head is low.
Flow Measurements

The metering (flow measurement) of water mains involves a wide array of metering devices. These include electromagnetic meters, ultrasonic meters, propeller or turbine meters, displacement meters, multijet meters, proportional meters, and compound meters.

Electromagnetic meters measure flow by means of a magnetic field generated around an insulated section of pipe.

Ultrasonic meters utilize sound-generating and sound receiving sensors (transducers) attached to the sides of the pipe.

Turbine meters have a measuring chamber that is turned by the flow of water.

Multijet meters have a multiblade rotor mounted on a vertical spindle within a cylindrical measuring chamber.

Proportional meters utilize restriction in the water line to divert a portion of water into a loop that holds a turbine or displacement meter, with the diverted flow being proportional to the flow in the main line.

Compound meters connect different sized meters in parallel. This meter has a turbine meter in parallel with a multijet meter.
A dual-body (DB) compound meter, which combines a turbine meter on the main flow line and appropriately sized multijet meter on the low flow or bypass line.
Turbine meter with integral strainer. (Courtesy of Master Meter).
Typical compound meter installation. (Courtesy of Master Meter).
Water supply pumping system

Pumps are used to increase the energy in a water distribution system. There are many different types of pumps (positive-displacement pumps, kinetic pumps, turbine pumps, horizontal centrifugal pumps, vertical pumps, and horizontal pumps). The most commonly used type of pump used in water distribution systems is the centrifugal pump.

Horizontal pumps (Photograph by T. Walski).

Vertical pumps (Photograph by T. Walski).
Pump Classification

All forms of water pumps may be classified into two basic categories:

1. Turbo-hydraulic (kinetic) pumps: Which includes three main types:
   
   A. Centrifugal pumps (Radial-flow pumps).
   
   B. Propeller pumps (Axial-flow pumps).
   
   C. Jet pumps (Mixed-flow pumps).
In the mixed-flow pump the water leaves the impeller in an inclined direction having both radial and axial components.

In radial-flow pump the water leaves the impeller in radial direction.

While in the axial-flow pump the water leaves the propeller in the axial direction.

This classification is based on the way by which the water leaves the rotating part of the pump.
Schematic diagram of basic elements of centrifugal pump
Turbo-hydraulic (kinetic) pumps types

- Propeller pump
- Centrifugal or radial flow pump
- Propeller or Axial flow pump
- Mixed flow pump

Diagram showing various types of pumps with their respective flow patterns.
Main Parts of Centrifugal Pumps:

1. Impeller:
   - which is the rotating part of the centrifugal pump.
   - It consists of a series of backwards curved vanes (blades).
   - The impeller is driven by a shaft which is connected to the shaft of an electric motor.

2. Casing
   - Which is an air-tight passage surrounding the impeller
   - designed to direct the liquid to the impeller and lead it away
   - *Volute casing*. It is of spiral type in which the area of the flow increases gradually.
3. **Suction Pipe.**

4. **Delivery Pipe.**

5. **The Shaft:** which is the bar by which the power is transmitted from the motor drive to the impeller.

6. **The driving motor:** which is responsible for rotating the shaft. It can be mounted directly on the pump, above it, or adjacent to it.
Installation of centrifugal pump either submersible (wet) or dry

Dry execution situation (vertical and horizontal)

Wet execution (vertical and submersible)
Sump (wet well)/reservoir capacity

- Very often the capacity of pumps does not comply with the required discharge.

- This is felt especially in wastewater pumping stations and also in supply stations for water distribution reservoirs.

- This means that pumps will have to be stopped occasionally and re-started later.

- The number of starts must be limited for two reasons:
  - Electricity supply companies wish to limit the number of times the relatively high start-up power is required;
  - The overheating of motors must be prevented.

- For these reasons the number of starts per hour must be limited to 3-4 times for large pumps and 6-8 times for small pumps.
The sump capacity (also named: wet well capacity) may be calculated with the formula:

\[ V = \frac{3600}{S \cdot Q_p} \left( Q_p \cdot Q - Q^2 \right) \]

in which

- \( V \) = The sump volume (or reservoir volume) between switch-on and switch-off levels (in m\(^3\));
- \( S \) = The number of starts per hour;
- \( Q_p \) = Pumping rate (in m\(^3\)/sec);
- \( Q \) = Waste water inflow (or water demand) (also in m\(^3\)/sec).

The required volume is a minimum if the inflow (or demand in case of reservoir supply) equals half the pumping rate, in which case

\[ V = \frac{900 \cdot Q_p}{S} \]
2. Positive Displacement pumps

A. Screw pumps

In the screw pump a revolving shaft fitted with blades rotates in an inclined trough and pushes the water up the trough.
B. Reciprocating pumps

In the reciprocating pump a piston sucks the fluid into a cylinder then pushes it up causing the water to rise.
Hydraulic Analysis of Pumps and Piping Systems

Pump can be placed in two possible positions in reference to the water levels in the reservoirs.

\[ H_t = H_{md} + \frac{V_d^2}{2g} - (H_{ms} + \frac{V_s^2}{2g}) \]
\[ H_t = H_{md} + \frac{V_d^2}{2g} + \left( H_{ms} - \frac{V_s^2}{2g} \right) \]
The **following terms** can be defined

- **$h_s$ (static suction head):** it is the difference in elevation between the suction liquid level and the centerline of the pump impeller.

- **$h_d$ (static discharge head):** it is the difference in elevation between the discharge liquid level and the centerline of the pump impeller.

- **$H_{stat}$ (static head):** it is the difference (or sum) in elevation between the static discharge and the static suction heads:

  $$H_{stat} = h_d \pm h_s$$
• \( H_{ms} \) (manometric suction head): it is the suction gage reading expressed in \( mwc \) (if a manometer is installed just at the inlet of the pump, then \( H_{ms} \) is the height to which the water will rise in the manometer).

• \( H_{md} \) (manometric discharge head): it is the discharge gage reading expressed in \( mwc \) (if a manometer is installed just at the outlet of the pump, then \( H_{md} \) is the height to which the water will rise in the manometer).

• \( H_m \) (manometric head): it is the increase of pressure head generated by the pump:

• \( H_t \) (total dynamic head): it is the total head delivered by the pump

\[
H_m = H_{md} \pm H_{ms}
\]
Pump Efficiency

\[ \eta_p = \frac{\text{Power output}}{\text{Power input}} = \frac{P_o}{P_i} = \frac{\gamma Q H_t}{P_i} \]

or

\[ P_i = \frac{\gamma Q H_t}{\eta_p} \]

Which is the power input delivered from the motor to the impeller of the pump.
Cavitation of Pumps and NPSH (Net Positive Suction Head)

- **In general**, cavitation occurs when the liquid pressure at a given location is reduced to the vapor pressure of the liquid.

- **For a piping system** that includes a pump cavitation occurs when the absolute pressure at the inlet falls below the vapor pressure of the water.

- This phenomenon may occur at the inlet to a pump and on the impeller blades, particularly if the pump is mounted above the level in the suction reservoir.

- Under this condition, vapor bubbles form (water starts to boil) at the impeller inlet and when these bubbles are carried into a zone of higher pressure, they collapse abruptly and hit the vanes of the impeller (near the tips of the impeller vanes).

  **causing**
  - Damage to the pump (pump impeller)
  - Violet vibrations (and noise).
  - Reduce pump capacity.
  - Reduce pump efficiency.
Inception of cavitation

Pressure drop in impeller of rotodynamic pump
How we avoid Cavitation ??

• For proper pump operation (no cavitation):

\[(NPSH)_A > (NPSH)_R\]

• \((NPSH)_A\) is the available NPSH.

• \((NPSH)_A\) is the absolute total energy available at the inlet of the pump above the vapor pressure which is responsible for pushing the water into the pump.

• \((NPSH)_R\) is the required NPSH that must be maintained or exceeded at the eye of the impeller so that cavitation will not occur.

• \((NPSH)_R\) is usually determined experimentally and provided by the manufacturer.
The available NPSH is found by subtracting vapour pressure of the liquid and energy suction head from the atmospheric pressure:

\[ \text{NPSH}_{av} = H_{atm} - H_{vap} + H_s \]

in which formula:

- \( H_{atm} \) = Atmospheric Pressure in mwc;
- \( H_{vap} \) = Vapour pressure for given water temperature;
- \( H_s \) = the static suction head (\( H_1 \)) from which hydraulic losses and energy head are deducted (see fig.). (please, note that \( H_1 \) should be taken negative if the pump is situated above the suction level).
Table 1. Relation between temperature and vapour pressure.

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Vapour pressure of water (m water column)</th>
<th>Altitude above sea level</th>
<th>Average atmospheric pressure (MWC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.12</td>
<td>0</td>
<td>10.33</td>
</tr>
<tr>
<td>15</td>
<td>0.17</td>
<td>250</td>
<td>10.0</td>
</tr>
<tr>
<td>20</td>
<td>0.23</td>
<td>500</td>
<td>9.75</td>
</tr>
<tr>
<td>30</td>
<td>0.43</td>
<td>1000</td>
<td>9.20</td>
</tr>
<tr>
<td>40</td>
<td>0.77</td>
<td>1500</td>
<td>8.60</td>
</tr>
<tr>
<td>50</td>
<td>1.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>7.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>10.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Example:** Determine the available NPSH for the pump at 1000 altitude, 40°C temperature and static suction head 4 mwc. The hydraulic losses in the suction line can be computed for the required discharge.

For the purpose of this example it is assumed that these losses are 0.75 mwc. The energy head at the pump entrance can be calculated as $V^2/2g$: for $V = 3$ m/s the energy head equals: 0.46 mwc.

**Calculation NPSH:** Atmospheric pressure (table 2) = 9.20 mwc

- Static suction head = -4.00 mwc
- Vapour pressure (table 1) = -0.77 mwc
- Suction losses = -0.75 mwc
- Energy head = -0.46 mwc

**Theoretical available NPSH** = 3.22 mwc

**Safety margin 1.5 to 2.0 m** = 1.72 mwc

**Available NPSH** = 1.50 mwc
If it proves that available NPSH is less than required NPSH, the available NPSH will have to be increased. This can be done by reducing suction losses by using a wider suction pipe; this is not very effective. Generally it can only be done by decreasing the static suction head; so the pump is to be positioned at a lower elevation with respect to suction water level.
Selection of A Pump

In selecting a particular pump for a given system:

• the design conditions are specified and a pump is selected for the range of applications.

• A system characteristic curve (H-Q) is then prepared.

• The H-Q curve is then matched to the pump characteristics chart which is provided by the manufacturer.

• The matching point (operating point) indicates the actual working conditions.

In selecting equipment for a pumping station, many different and often conflicting aspects of the overall pumping system must be considered. The following factors must be evaluated:

• Design flow rates and flow ranges.

• Location of the pumping station.

• Force main design.

• System head-capacity characteristics.

• When these factors are evaluated properly, the number and sizes of the pumps, and the optimum of force main can be selected.
System Characteristic Curve

• It is a graphic representation of the system head and is developed by plotting the total head, $H_t$, over a range of flow rates starting from zero to the maximum expected value of $Q$.

• This curve is usually referred to as a system characteristic curve or simply system curve.

• For a given pipeline system (including a pump or a group of pumps), a unique system head-capacity (H-Q) curve can be plotted.

• The total head, $H_t$, that the pump delivers includes the elevation head and the head losses incurred in the system. The friction loss and other minor losses in the pipeline depend on the velocity of the water in the pipe, and hence the total head loss can be related to the discharge rate.

$$H_t = H_{stat} + h_{fd} + \sum h_{md} + h_{fs} + \sum h_{ms} + \frac{V_d^2}{2g}$$

$h_{fs}$: is the friction losses in the suction pipe.
$h_{fd}$: is the friction losses in the discharge (delivery) pipe.
$h_{ms}$: is the minor losses in the suction pipe.
$h_{md}$: is the minor losses in the discharge (delivery) pipe.
Pump Characteristic Curves

- Pump manufacturers provide information on the performance of their pumps in the form of curves, commonly called pump characteristic curves (or simply pump curves).
- In pump curves the following information may be given:
  - the discharge on the x-axis,
  - the head on the left y-axis,
  - the pump power input on the right y-axis,
  - the pump efficiency as a percentage,
  - the speed of the pump (rpm = revolutions/min).
  - the NPSH of the pump.

- The pump characteristic curves are very important to help select the required pump for the specified conditions.
- If the system curve is plotted on the pump curves we may produce.
- The point of intersection is called the operating point.
- This matching point indicates the actual working conditions, and therefore the proper pump that satisfy all required performance characteristic is selected.
What happens as the static head changes (a tank fills)?
Multiple-Pump Operation

- To install a pumping station that can be effectively operated over a large range of fluctuations in both discharge and pressure head, it may be advantageous to install several identical pumps at the station.
(a) Parallel Operation

- Pumping stations frequently contain several (two or more) pumps in a parallel arrangement.

\[ Q_{\text{total}} = Q_1 + Q_2 + Q_3 \]
• In this configuration any number of the pumps can be operated simultaneously.

• The objective being to deliver a range of discharges, i.e.; the discharge is increased but the pressure head remains the same as with a single pump.

• This is a common feature of sewage pumping stations where the inflow rate varies during the day.

• By automatic switching according to the level in the suction reservoir any number of the pumps can be brought into operation.
How to draw the pump curve for pumps in parallel?

- The manufacturer gives the pump curve for a single pump operation only.
- If two or more pumps are in operation, the pumps curve should be calculated and drawn using the single pump curve.
- For pumps in parallel, the curve of two pumps, for example, is produced by adding the discharges of the two pumps at the same head (assuming identical pumps).
(b) Series Operation

- The series configuration which is used whenever we need to increase the pressure head and keep the discharge approximately the same as that of a single pump.

- This configuration is the basis of multistage pumps; the discharge from the first pump (or stage) is delivered to the inlet of the second pump, and so on.

- The same discharge passes through each pump receiving a pressure boost in doing so.
How to draw the pump curve for pumps in series?

- the manufacturer gives the pump curve for a single pump operation only.
- For pumps in series, the curve of two pumps, for example, is produced by adding the heads of the two pumps at the same discharge.
- Note that, of course, all pumps in a series system must be operating simultaneously.

![Diagram](image-url)
Example

A centrifugal pump has the following relation between head and discharge:

<table>
<thead>
<tr>
<th>Discharge (m³/min)</th>
<th>0</th>
<th>4.5</th>
<th>9.0</th>
<th>13.5</th>
<th>18.0</th>
<th>22.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head (m)</td>
<td>22.5</td>
<td>22.2</td>
<td>21.6</td>
<td>19.5</td>
<td>14.1</td>
<td>0</td>
</tr>
</tbody>
</table>

- A pump system is connected to a 300 mm suction and delivery pipe the total length of which is 87 m and the discharge to atmosphere is 15 m above sump level. $f$ is assumed as 0.024.
- Assume the total losses (major and minors) can be find by

$$H_l = \frac{8fLQ^2}{\pi^2gD^5}$$

1. Find the **discharge and head** at the following cases.
- One pump of this type connected to the system
- Two pumps in series.
- Two pumps in parallel.
### System Curve

<table>
<thead>
<tr>
<th>Q (m³/min)</th>
<th>H (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>15.00</td>
</tr>
<tr>
<td>2.00</td>
<td>15.09</td>
</tr>
<tr>
<td>4.00</td>
<td>15.36</td>
</tr>
<tr>
<td>6.00</td>
<td>15.81</td>
</tr>
<tr>
<td>8.00</td>
<td>16.44</td>
</tr>
<tr>
<td>10.00</td>
<td>17.26</td>
</tr>
<tr>
<td>12.00</td>
<td>18.25</td>
</tr>
<tr>
<td>14.00</td>
<td>19.42</td>
</tr>
<tr>
<td>16.00</td>
<td>20.77</td>
</tr>
<tr>
<td>18.00</td>
<td>22.31</td>
</tr>
<tr>
<td>20.00</td>
<td>24.02</td>
</tr>
<tr>
<td>22.00</td>
<td>25.92</td>
</tr>
<tr>
<td>24.00</td>
<td>27.99</td>
</tr>
</tbody>
</table>

\[
H = 15 + \frac{8 \times 0.024 \times 87 \times Q^2}{\pi^2 \times 9.81 \times 0.3^5} + \left(\frac{Q}{\frac{\pi}{4} \times 0.3^2} \right)^2
\]

<table>
<thead>
<tr>
<th>Q (m³/min)</th>
<th>H (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.92</td>
<td>30.25</td>
</tr>
<tr>
<td>27.99</td>
<td>32.69</td>
</tr>
<tr>
<td>30.00</td>
<td>35.30</td>
</tr>
<tr>
<td>32.00</td>
<td>38.10</td>
</tr>
<tr>
<td>34.00</td>
<td>41.08</td>
</tr>
<tr>
<td>36.00</td>
<td>44.24</td>
</tr>
<tr>
<td>38.00</td>
<td>47.57</td>
</tr>
<tr>
<td>40.00</td>
<td>51.09</td>
</tr>
<tr>
<td>42.00</td>
<td>54.79</td>
</tr>
<tr>
<td>44.00</td>
<td>58.67</td>
</tr>
<tr>
<td>46.00</td>
<td>62.73</td>
</tr>
</tbody>
</table>
One pump

<table>
<thead>
<tr>
<th>Pump Curve</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Q (m³/min)</strong></td>
<td><strong>H (m)</strong></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>22.50</td>
<td></td>
</tr>
<tr>
<td>4.50</td>
<td>22.20</td>
<td></td>
</tr>
<tr>
<td>9.00</td>
<td>21.60</td>
<td></td>
</tr>
<tr>
<td>13.50</td>
<td>19.50</td>
<td></td>
</tr>
<tr>
<td>18.00</td>
<td>14.10</td>
<td></td>
</tr>
<tr>
<td>22.50</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

**operation point**

Q = 13.80 m³/min  
H = 19.25 m
Two pumps in series

<table>
<thead>
<tr>
<th>Q (m³/min)</th>
<th>H (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>45.00</td>
</tr>
<tr>
<td>4.50</td>
<td>44.40</td>
</tr>
<tr>
<td>9.00</td>
<td>43.20</td>
</tr>
<tr>
<td>13.50</td>
<td>39.00</td>
</tr>
<tr>
<td>18.00</td>
<td>28.20</td>
</tr>
<tr>
<td>22.50</td>
<td>0.00</td>
</tr>
</tbody>
</table>

operation point
Q = 19.00 m³/min     H = 23.10 m
## Two pumps in parallel

<table>
<thead>
<tr>
<th>Q (m³/min)</th>
<th>H (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>22.50</td>
</tr>
<tr>
<td>9.00</td>
<td>22.20</td>
</tr>
<tr>
<td>18.00</td>
<td>21.60</td>
</tr>
<tr>
<td>27.00</td>
<td>19.50</td>
</tr>
<tr>
<td>36.00</td>
<td>14.10</td>
</tr>
<tr>
<td>45.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Operation point
- Q = 17.50 m³/min
- H = 21.70 m
Constant- and Variable-Speed Pumps

- The speed of the pump is specified by the angular speed of the impeller which is measured in revolution per minutes (rpm).
- Based on this speed, $N$, pumps can be divided into two types:
  - Constant-speed pumps
  - Variable-speed pumps

**Constant-speed pumps**

- For this type, the angular speed, $N$, is constant.
- There is only one pump curve which represents the performance of the pump.

![Pump Curve Graph](image-url)
Variable-speed pumps

- For this type, the angular speed, \( N \), is variable, i.e.; pump can operate at different speeds.
- The pump performance is presented by several pump curves, one for each speed.
- Each curve is used to suit certain operating requirements of the system.
WATER DISTRIBUTION SYSTEM
HYDRAULIC CALCULATION
**Network Layout**

- Estimate pipe sizes on the basis of water demand and local code requirements.

- The pipes are then drawn on a digital map (using AutoCAD, for example) starting from the water source.

- All the components (pipes, valves, fire hydrants) of the water network should be shown on the lines.

**Hydraulic Analysis**

After completing all preliminary studies and layout drawing of the network, one of the methods of hydraulic analysis is used to

- Size the pipes and
- Assign the pressures and velocities required.
Hydraulic Analysis of Water Networks

- The solution to the problem is based on the same basic hydraulic principles that govern simple and compound pipes that were discussed previously.
- The following are the most common methods used to analyze the Grid-system networks:
  1. Hardy Cross method.
  2. Sections method.
  3. Circle method.
Hardy Cross Method

• This method is applicable to closed-loop pipe networks (a complex set of pipes in parallel).

• It depends on the idea of head balance method

• Was originally devised by professor Hardy Cross.
Assumptions / Steps of this method:

1. Assume that the water is withdrawn from nodes only; not directly from pipes.

2. The discharge, \( Q \), entering the system will have (+) value, and the discharge, \( Q \), leaving the system will have (-) value.

3. Usually neglect minor losses since these will be small with respect to those in long pipes, i.e.; or could be included as equivalent lengths in each pipe.

4. Assume flows for each individual pipe in the network.

5. At any junction (node), as done for pipes in parallel,

\[
\sum Q_{in} = \sum Q_{out} \quad \text{or} \quad \sum Q = 0
\]
6. Around any loop in the grid, the sum of head losses must equal to zero:

\[ \sum_{\text{loop}} h_f = 0 \]

- Conventionally, clockwise flows in a loop are considered (+) and produce positive head losses; counterclockwise flows are then (-) and produce negative head losses.

- This fact is called the head balance of each loop, and this can be valid only if the assumed \( Q \) for each pipe, within the loop, is correct.
The probability of initially guessing all flow rates correctly is virtually null. Therefore, to balance the head around each loop, a flow rate correction ($\Delta$) for each loop in the network should be computed, and hence some iteration scheme is needed.

7. After finding the discharge correction, $\Delta$ (one for each loop), the assumed discharges $Q_0$ are adjusted and another iteration is carried out until all corrections (values of $\Delta$) become zero or negligible. At this point the condition of:

$$\sum_{loop} h_f \approx 0.0$$

is satisfied.
Notes

• The flows in pipes common to two loops are positive in one loop and negative in the other.

• When calculated corrections are applied, with careful attention to sign, pipes common to two loops receive both corrections.
How to find the correction value ($\Delta$)

$$h_f = k \ Q^x$$

$$Q = Q_0 + \Delta$$

$$h_f = k \ Q^x = k(Q_0 + \Delta)^x = k \left[ Q_0^x + x Q_0^{(x-1)} \Delta + \frac{x(x-1)}{2} Q_0^{(x-2)} \Delta^2 + .... \right]$$

$$h_f = k \ Q^x = k \left[ Q_0^x + x Q_0^{(x-1)} \Delta \right]$$

Since for each loop in the grid

$$\sum_{\text{loop}} h_f = \sum_{\text{loop}} ^{(5)} k \ Q^x = 0$$

$$\sum k \ Q^x = \sum k \ Q_0^x + \sum x k \ Q_0^{(x-1)} \Delta = 0$$

therefore we have (for each loop in the network)

$$\Delta = \frac{-\sum k \ Q_0^x}{\sum x k \ Q_0^{(x-1)}} = \frac{-\sum h_f}{x \sum \frac{h_f}{Q}}$$
• Note that if Hazen Williams (which is generally used in this method) is used to find the head losses, then

\[ h_f = k \ Q^{1.85} \]

\[ (x = 1.85) \], then

\[ \Delta = \frac{-\sum h_f}{1.85 \sum \frac{h_f}{Q}} \]

• If Darcy-Wiesbach is used to find the head losses, then

\[ h_f = k \ Q^2 \]

\[ (x = 2) \], then

\[ \Delta = \frac{-\sum h_f}{2 \sum \frac{h_f}{Q}} \]
Exercise
Problem 1.
Calculate the friction loss in the cast iron pipe of the diameter, $D = 150$ mm, over the length of 200m. The flow rate is 75 m$^3$/h and the water temperature 10$^\circ$C.

**Sol:**

$$v = \frac{Q}{A} = \frac{75}{60 \times 60 \times \frac{\pi}{4} \times (0.15)^2} = 1.18 m/s$$

from table 2.1 $e = 0.25 mm$ $\Rightarrow \frac{e}{D} = \frac{0.25}{150} = 1.67 \times 10^{-3}$

$$\mu = \frac{497 \times 10^{-6}}{(T + 42.5)^{1.5}} = \frac{497 \times 10^{-6}}{(10 + 42.5)^{1.5}} = 1.306 \times 10^{-6} m^2/s$$

$$R_e = \frac{vD}{\mu} = \frac{1.18 \times 0.15}{1.306 \times 10^{-6}} = 1.35 \times 10^5$$

From moody diagram $f = 0.035$

$$h_f = f \left( \frac{L}{D} \right) \left( \frac{v^2}{2g} \right) = 0.035 \left( \frac{200}{0.15} \right) \left( \frac{1.18^2}{2 \times 9.81} \right) = 3.31 m$$
Friction factor for fully developed flow in circular pipes. (Data from [6], used by permission.)
**Problem 2.**

Determine the equivalent diameter of a pipe that replaces a system of 3 parallel galvanized iron pipes, each with diameter of 100 mm. Consider for both alternatives: L=2 km, S=1%, T= 25°C.

**Sol:**

\[ v = 0.85C_{hw}R_h^{0.63}S^{0.54} = 0.85(120)\left(\frac{0.1}{4}\right)^{0.63}(0.01)^{0.54} = 0.83m/s \]

\[ Q_{one\ pipe} = Av = \frac{\pi}{4} (0.1)^2 (0.83) = 0.0065m^3/s \]

\[ h_f = 7.62 \left(\frac{L}{D}\right) \left(\frac{V}{C_{hw}}\right)^{1.85} = 7.62 \left(\frac{2000}{0.1}\right) \left(\frac{0.83}{120}\right)^{1.85} = 15.37m \]

To replace the three pipes by one pipe the flow will be in this pipe \( Q = 3 \times 0.0065 = 0.0195m^3/s \) and the head loss \( h_f = 15.37m \)

\[ h_f = 10.7 \left(\frac{L}{D^{4.87}}\right) \left(\frac{Q}{C_{hw}}\right)^{1.85} \Rightarrow 15.37 = 10.7 \left(\frac{2000}{D^{4.87}}\right) \left(\frac{0.0195}{120}\right)^{1.85} \]

\[ \therefore D = 0.16m = 160mm \]
Problem 3.
Three pipes connected in series have to be replaced by one pipe of the same total length. The diameters are 200mm, 250mm, and 300mm, and the lengths are 250 m, 500 m, and 250 m, respectively. Determine the slope of the new pipe that can transport flow of 40 l/s. All pipes are galvanized iron.

Sol: \[ h_{f1} = 10.7 \left( \frac{L}{D^{4.87}} \right) \left( \frac{Q}{C_{hw}} \right)^{1.85} = 10.7 \left( \frac{250}{0.2^{4.87}} \right) \left( \frac{0.04}{120} \right)^{1.85} = 2.5m \]
\[ h_{f2} = 10.7 \left( \frac{500}{0.25^{4.87}} \right) \left( \frac{0.04}{120} \right)^{1.85} = 1.7m \]
\[ h_{f3} = 10.7 \left( \frac{250}{0.3^{4.87}} \right) \left( \frac{0.04}{120} \right)^{1.85} = 0.35m \]
\[ h_f = h_{f1} + h_{f2} + h_{f3} = 2.5 + 1.7 + 0.35 = 4.55m \]
\[ h_f = 10.7 \left( \frac{L}{D^{4.87}} \right) \left( \frac{Q}{C_{hw}} \right)^{1.85} \Rightarrow 4.55 = 10.7 \left( \frac{1000}{D^{4.87}} \right) \left( \frac{0.04}{120} \right)^{1.85} \]
\[ \therefore D = 0.235m \]
\[ \therefore v = \frac{Q}{A} = \frac{0.04}{\frac{\pi}{4} \times 0.235^2} = 0.922m/s \]
\[ v = 0.85C_{hw}R_h^{0.63}S^{0.54} \Rightarrow 0.922 = 0.85 \times 120 \times \left( \frac{0.235}{4} \right)^{0.63} \times S^{0.54} \]
\[ \therefore S = 0.0045 = 0.45\% \]
Problem 4
A pumping system is laid out as shown in the figure. The pipe is rising at a steady rate from level 9 msl at the pumping station, to 42 msl at the reservoir. The system conveys 250 m$^3$/h. At the pumping station and at the reservoir, the diameter is 200mm. The wall friction over this length of 200mm pipe may be neglected, the other losses at the pumping station and at the reservoir may be calculated assuming $K_L = 15$ at the pumping station, and $K_L = 5$ at the reservoir, using the velocity in the 200mm pipe.

a) Calculate friction gradient (s) and loss over the main pipeline (D=300mm). Cast iron pipes
b) Calculate losses at the pumping station and reservoir.
c) Calculate total loss.
d) Calculate manometric head in mwc to be delivered by the pump in case the water level is +30 msl respectively +20 msl.
e) Sketch the energy line, and determine water pressure (in mwc) at L=500m and L=1000m (level at the sump is +30msl)
a. Calculate friction gradient (s) and loss over the main pipeline (D=300mm). Assume cast iron pipes

**Sol:**

\[
Q = \frac{250}{60 \times 60} = 0.0694 \text{ m}^3 / \text{s}
\]

*The velocity in the 200mm diameter pipe* \( \Rightarrow v_1 = \frac{Q}{A} = \frac{0.0694}{\frac{\pi}{4} \times 0.2^2} = 2.21 \text{ m/s} \)

*The velocity in the 300mm diameter pipe* \( \Rightarrow v_2 = \frac{Q}{A} = \frac{0.0694}{\frac{\pi}{4} \times 0.3^2} = 0.98 \text{ m/s} \)

*Assume new cast iron* \( \Rightarrow \) *from table* \( C_{HW} = 130 \)

\[
v = 0.85 C_{hw} R_h^{0.63} S^{0.54} \Rightarrow 0.98 = 0.85(130) \left( \frac{0.3}{4} \right)^{0.63} S^{0.54}
\]

\[
S = 0.00325 = 0.32\%
\]

\[
h_f = 10.7 \left( \frac{L}{D^{4.87}} \right) \left( \frac{Q}{C_{hw}} \right)^{1.85} = 10.7 \left( \frac{1500}{0.3^{4.87}} \right) \left( \frac{0.0694}{130} \right)^{1.85} = 5 \text{ m}
\]
B. Calculate losses at the pumping station and reservoir.

Sol:

*The losses at the pump station* \( h_p = 15 \frac{v_1^2}{2g} = 15 \times \frac{2.21^2}{2 \times 9.81} = 3.73m \)

*The losses at the reservoir* \( h_r = 5 \frac{v_1^2}{2g} = 5 \times \frac{(2.21)^2}{2 \times 9.81} = 1.25m \)

c. Calculate total loss.

Sol:

\[
H_{total} = h_p + h_r + h_f = 1.24 + 3.73 + 5 = 8.975 \approx 9m
\]
d) Calculate manometric head in mwc to be delivered by the pump in case the water level is +30 msl respectively +20 msl.

\[(i) \text{ water level 30 msl} \]

Apply Bernoulli's equation between the surfaces of the reservoirs

\[E_1 = E_2\]

\[\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + H_{\text{total}} - H_{\text{pump}}\]

\[0 + 0 + 30 = 0 + 0 + 45 - H_{\text{pump}} + 9\]

\[H_{\text{pump}} = 24 \text{m}\]
(ii) water level 20 msl

Apply Bernoulli's equation between the surfaces of the reservoirs

\[ E_1 = E_2 \]

\[ \frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + H_{\text{total}} - H_{\text{pump}} \]

\[ 0 + 0 + 20 = 0 + 0 + 45 - H_{\text{pump}} + 9 \]

\[ H_{\text{pump}} = 34 m \]
e) Sketch the energy line, and determine water pressure (in mwc) at L=500m and L=1000m (level at the sump is +30msl)

(i) at $L = 500\text{m} \Rightarrow z = 20\text{msl}$

Apply Bernoulli's equation between the surfaces of the reservoir and at $L=500\text{m}$

$E_1 = E_2$

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + H_{\text{total}} - H_{\text{pump}}$$

$$0 + 0 + 30 = \frac{p_2}{\gamma} + \frac{0.98^2}{2g} + 20 - 24 + \left[10.7 \left( \frac{500}{0.3^{4.87}} \right) \left( \frac{0.0694}{130} \right)^{1.85} \right]$$

$$\frac{p_2}{\gamma} = 32.29\text{m}$$
(ii) at $L = 1000m \Rightarrow z = 29\text{msl}$

Apply Bernoulli's equation between the surfaces of the reservoir and at $L=1000m$

$$E_1 = E_2$$

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + H_{total} - H_{pump}$$

$$0 + 0 + 30 = \frac{p_2}{\gamma} + \frac{0.98^2}{2g} + 29 - 24 + \left[ 10.7 \left( \frac{1000}{0.3^{4.87}} \right) \frac{0.0694}{130} \right]^{1.85}$$

$$\frac{p_2}{\gamma} = 21.62m$$
L = 1500 m

D = 200 mm

D = 300 mm
Problem 5: (Hardy Cross)

- The figure below represents a simplified pipe network.

- Flows for the area have been disaggregated to the nodes, and a major fire flow has been added at node \( G \).

- The water enters the system at node \( A \).

- Pipe diameters and lengths are shown on the figure.

- Find the flow rate of water in each pipe using the Hazen-Williams equation with \( C_{HW} = 100 \).

- Carry out calculations until the corrections are less than 0.2 \( m^3/min \).
First Correction

Loop 1

<table>
<thead>
<tr>
<th>Line</th>
<th>Flow, ( m^3/\text{min} )</th>
<th>Dia, ( m )</th>
<th>Length, ( m )</th>
<th>( s )</th>
<th>( h, m )</th>
<th>( h/Q, m/m^3/\text{min} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( AB )</td>
<td>13</td>
<td>0.40</td>
<td>1250</td>
<td>0.0110</td>
<td>13.75</td>
<td>1.058</td>
</tr>
<tr>
<td>( BH )</td>
<td>2</td>
<td>0.25</td>
<td>1100</td>
<td>0.0033</td>
<td>3.63</td>
<td>1.815</td>
</tr>
<tr>
<td>( HI )</td>
<td>-9.8</td>
<td>0.30</td>
<td>1000</td>
<td>-0.0260</td>
<td>-26.00</td>
<td>2.653</td>
</tr>
<tr>
<td>( IA )</td>
<td>-12</td>
<td>0.30</td>
<td>1000</td>
<td>-0.0380</td>
<td>-37.80</td>
<td>3.150</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(-46.42)</td>
<td>(8.676)</td>
</tr>
</tbody>
</table>

\[ \Delta_t = -\frac{-46.42}{1.85(8.676)} = 2.9 \]
### Loop II

<table>
<thead>
<tr>
<th>Line</th>
<th>Flow, $m^3/min$</th>
<th>Dia, m</th>
<th>Length, m</th>
<th>$s$</th>
<th>$h$, m</th>
<th>$h/Q$, $m/m^3/min$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BE$</td>
<td>7.5</td>
<td>0.35</td>
<td>400</td>
<td>0.0075</td>
<td>3.00</td>
<td>0.400</td>
</tr>
<tr>
<td>$EF$</td>
<td>7.0</td>
<td>0.35</td>
<td>600</td>
<td>0.0066</td>
<td>3.96</td>
<td>0.566</td>
</tr>
<tr>
<td>$FG$</td>
<td>4.7</td>
<td>0.30</td>
<td>1000</td>
<td>0.0067</td>
<td>6.68</td>
<td>1.423</td>
</tr>
<tr>
<td>$GH$</td>
<td>-9.3</td>
<td>0.30</td>
<td>1250</td>
<td>-0.0236</td>
<td>-29.54</td>
<td>3.177</td>
</tr>
<tr>
<td>$HB$</td>
<td>-2.0</td>
<td>0.25</td>
<td>1100</td>
<td>-0.0033</td>
<td>-3.63</td>
<td>1.815</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-19.53</td>
</tr>
<tr>
<td>$\Delta_{II} = \frac{-19.53}{1.85(7.381)} = 1.4$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Loop III

<table>
<thead>
<tr>
<th>Line</th>
<th>Flow, $m^3/min$</th>
<th>Dia, m</th>
<th>Length, m</th>
<th>$s$</th>
<th>$h$, m</th>
<th>$h/Q$, $m/m^3/min$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BC$</td>
<td>1.5</td>
<td>0.20</td>
<td>500</td>
<td>0.0058</td>
<td>2.91</td>
<td>1.937</td>
</tr>
<tr>
<td>$CD$</td>
<td>1.0</td>
<td>0.20</td>
<td>400</td>
<td>0.0028</td>
<td>1.10</td>
<td>1.110</td>
</tr>
<tr>
<td>$DE$</td>
<td>-0.5</td>
<td>0.20</td>
<td>500</td>
<td>-0.0008</td>
<td>-0.38</td>
<td>0.762</td>
</tr>
<tr>
<td>$EB$</td>
<td>-7.5</td>
<td>0.35</td>
<td>400</td>
<td>-0.0075</td>
<td>-3.00</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.63</td>
</tr>
<tr>
<td>$\Delta_{III} = \frac{-0.63}{1.85(4.209)} = -0.1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Second Correction

#### Loop I

<table>
<thead>
<tr>
<th>Line</th>
<th>Flow, m³/min</th>
<th>Dia, m</th>
<th>Length, m</th>
<th>s</th>
<th>h, m</th>
<th>h/Q, m/m³/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>15.9</td>
<td>0.40</td>
<td>1250</td>
<td>0.0157</td>
<td>19.65</td>
<td>1.236</td>
</tr>
<tr>
<td>BH</td>
<td>3.5</td>
<td>0.25</td>
<td>1100</td>
<td>0.0094</td>
<td>10.34</td>
<td>2.954</td>
</tr>
<tr>
<td>HI</td>
<td>-6.9</td>
<td>0.30</td>
<td>1000</td>
<td>-0.0136</td>
<td>-13.60</td>
<td>1.971</td>
</tr>
<tr>
<td>IA</td>
<td>-9.1</td>
<td>0.30</td>
<td>1000</td>
<td>-0.0227</td>
<td>-22.70</td>
<td>2.495</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-6.31</td>
<td>8.656</td>
</tr>
</tbody>
</table>

\[ \Delta_1 = 0.4 \]

#### Loop II

<table>
<thead>
<tr>
<th>Line</th>
<th>Flow, m³/min</th>
<th>Dia, m</th>
<th>Length, m</th>
<th>s</th>
<th>h, m</th>
<th>h/Q, m/m³/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>BE</td>
<td>9.0</td>
<td>0.35</td>
<td>400</td>
<td>0.0105</td>
<td>4.20</td>
<td>0.467</td>
</tr>
<tr>
<td>EF</td>
<td>8.4</td>
<td>0.35</td>
<td>600</td>
<td>0.0093</td>
<td>5.58</td>
<td>0.664</td>
</tr>
<tr>
<td>FG</td>
<td>6.1</td>
<td>0.30</td>
<td>1000</td>
<td>0.0108</td>
<td>10.80</td>
<td>1.770</td>
</tr>
<tr>
<td>GH</td>
<td>-7.9</td>
<td>0.30</td>
<td>1250</td>
<td>-0.0175</td>
<td>-21.88</td>
<td>2.769</td>
</tr>
<tr>
<td>HB</td>
<td>-3.5</td>
<td>0.25</td>
<td>1100</td>
<td>-0.0094</td>
<td>-10.34</td>
<td>2.954</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-11.64</td>
<td>8.624</td>
</tr>
</tbody>
</table>

\[ \Delta_2 = 0.7 \]
Loop III

<table>
<thead>
<tr>
<th>Line</th>
<th>Flow, m³/min</th>
<th>Dia, m</th>
<th>Length, m</th>
<th>s</th>
<th>$h$, m</th>
<th>$h/Q$, m/m³/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>1.4</td>
<td>0.20</td>
<td>500</td>
<td>0.0051</td>
<td>2.55</td>
<td>1.821</td>
</tr>
<tr>
<td>CD</td>
<td>0.9</td>
<td>0.20</td>
<td>400</td>
<td>0.0023</td>
<td>0.92</td>
<td>1.022</td>
</tr>
<tr>
<td>DE</td>
<td>-0.6</td>
<td>0.20</td>
<td>500</td>
<td>-0.0011</td>
<td>-0.55</td>
<td>0.917</td>
</tr>
<tr>
<td>EB</td>
<td>-9.0</td>
<td>0.35</td>
<td>400</td>
<td>-0.0105</td>
<td>-4.20</td>
<td>0.467</td>
</tr>
</tbody>
</table>

$\Delta_{III} = 0.2$
### Third Correction

#### Loop I

<table>
<thead>
<tr>
<th>Line</th>
<th>Flow, m$^3$/min</th>
<th>Dia, m</th>
<th>Length, m</th>
<th>$s$</th>
<th>$h$, m</th>
<th>$h/Q$, m/m$^3$/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AB$</td>
<td>16.3</td>
<td>0.40</td>
<td>1250</td>
<td>0.0165</td>
<td>20.63</td>
<td>1.265</td>
</tr>
<tr>
<td>$BH$</td>
<td>3.2</td>
<td>0.25</td>
<td>1100</td>
<td>0.0080</td>
<td>8.80</td>
<td>2.750</td>
</tr>
<tr>
<td>$HI$</td>
<td>-6.5</td>
<td>0.30</td>
<td>1000</td>
<td>-0.0122</td>
<td>-12.20</td>
<td>1.877</td>
</tr>
<tr>
<td>$IA$</td>
<td>-8.7</td>
<td>0.30</td>
<td>1000</td>
<td>-0.0209</td>
<td>-20.90</td>
<td>2.402</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-3.67</td>
<td>8.294</td>
</tr>
</tbody>
</table>

$\Delta_i = 0.2$

#### Loop II

<table>
<thead>
<tr>
<th>Line</th>
<th>Flow, m$^3$/min</th>
<th>Dia, m</th>
<th>Length, m</th>
<th>$s$</th>
<th>$h$, m</th>
<th>$h/Q$, m/m$^3$/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BE$</td>
<td>9.5</td>
<td>0.35</td>
<td>400</td>
<td>0.0116</td>
<td>4.64</td>
<td>0.488</td>
</tr>
<tr>
<td>$EF$</td>
<td>9.1</td>
<td>0.35</td>
<td>600</td>
<td>0.0107</td>
<td>6.42</td>
<td>0.705</td>
</tr>
<tr>
<td>$FG$</td>
<td>6.8</td>
<td>0.30</td>
<td>1000</td>
<td>0.0132</td>
<td>13.20</td>
<td>1.941</td>
</tr>
<tr>
<td>$GH$</td>
<td>-7.2</td>
<td>0.30</td>
<td>1250</td>
<td>-0.0147</td>
<td>-18.38</td>
<td>2.552</td>
</tr>
<tr>
<td>$HB$</td>
<td>-3.2</td>
<td>0.25</td>
<td>1100</td>
<td>-0.0080</td>
<td>-8.80</td>
<td>2.750</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-2.92</td>
<td>8.436</td>
</tr>
</tbody>
</table>

$\Delta_{ii} = 0.2$
### Loop III

<table>
<thead>
<tr>
<th>Line</th>
<th>Flow, $m^3/min$</th>
<th>Dia, m</th>
<th>Length, m</th>
<th>$s$</th>
<th>$h$, m</th>
<th>$h/Q$, m/m$^3$/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>$BC$</td>
<td>1.6</td>
<td>0.20</td>
<td>500</td>
<td>0.0066</td>
<td>3.30</td>
<td>2.063</td>
</tr>
<tr>
<td>$CD$</td>
<td>1.1</td>
<td>0.20</td>
<td>400</td>
<td>0.0033</td>
<td>1.32</td>
<td>1.200</td>
</tr>
<tr>
<td>$DE$</td>
<td>$-$0.4</td>
<td>0.20</td>
<td>500</td>
<td>$-$0.0005</td>
<td>$-$0.25</td>
<td>0.625</td>
</tr>
<tr>
<td>$EB$</td>
<td>$-$9.5</td>
<td>0.35</td>
<td>400</td>
<td>$-$0.0116</td>
<td>$-$4.64</td>
<td>0.488</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$-$0.27</td>
<td>4.376</td>
</tr>
</tbody>
</table>

$\Delta_{III} = 0.03$
General Notes

• Occasionally the assumed direction of flow will be incorrect. In such cases the method will produce corrections larger than the original flow and in subsequent calculations the direction will be reversed. Even when the initial flow assumptions are poor, the convergence will usually be rapid. Only in unusual cases will more than three iterations be necessary.

• The method is applicable to the design of new system or to evaluation of proposed changes in an existing system.

• The pressure calculation in the above example assumes points are at equal elevations. If they are not, the elevation difference must be included in the calculation.

• The balanced network must then be reviewed to assure that the velocity and pressure criteria are satisfied. If some lines do not meet the suggested criteria, it would be necessary to increase the diameters of these pipes and repeat the calculations.
References


4. Websites

   http://www.lmnoeng.com
   http://www.ipexinc.com/industrial/airreleasevalves.html