# Briefing on Core Principles of Hydraulics

## Executive Summary

This document synthesizes fundamental principles and applications of hydraulics, focusing on pressurized pipe flow, pump systems, open channel flow, and outlet control structures. The analysis reveals two primary flow regimes: pressurized pipe flow, where energy loss is governed by friction and local fittings, and open channel flow, which is characterized by a free surface and is typically analyzed using empirical methods like Manning's Equation.

Key takeaways include the critical role of the Moody Diagram in determining friction factors for pipe flow based on the Reynolds Number and relative pipe roughness. For local energy losses, standardized loss coefficients (K) for various fittings and transitions are essential. In pump systems, the required power is directly proportional to the flow rate and the dynamic head added to the system.

For open channel and gravity-driven systems like storm sewers, Manning's Equation is the primary tool for relating flow rate to channel geometry, slope, and roughness. The design of such systems must balance velocities to prevent both sediment deposition and pipe scour. Finally, outlet structures, including orifices, weirs, and culverts, are critical for controlling flow rates in stormwater management systems, with their performance dictated by specific hydraulic equations and empirically derived coefficients.

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# 1.0 Pressurized Pipe Flow

Pressurized pipe flow occurs in a conduit without a free surface, where flow is driven by hydraulic pressure. A key challenge in analyzing this type of flow is quantifying energy losses, which are categorized as frictional and local losses.

### 1.1 Head Loss Components

Energy loss in pressurized pipe systems is accounted for by two primary components:

- **Frictional Head Loss (hf):** Loss due to shear stress between the fluid and the pipe wall along the length of the pipe.
- **Local Head Loss (hL):** Loss due to disruptions in flow caused by components such as valves, bends, contractions, and entrances.

## 1.2 The Moody Diagram and Frictional Loss

The Moody Diagram is a fundamental tool used to determine the friction factor (*f*) for a given pipe flow, which is then used to calculate frictional head loss. The diagram plots the friction factor against the Reynolds Number (*Re*) for various levels of relative pipe roughness (ε/d).

- **Reynolds Number (Re):** A dimensionless quantity representing the ratio of inertial forces to viscous forces. It is calculated as:
    - $Re = (\rho Vd)/\mu$ where ρ is fluid density, V is mean velocity, d is pipe diameter, and μ is dynamic viscosity.
- **Friction Factor (f):** A dimensionless quantity that depends on the Reynolds Number and pipe roughness. It relates pressure drop (ΔP) to flow parameters:
    - $f = (2d / \rho V^2 l) * \Delta P$
- **Flow Regimes identified on the Diagram:**
    - **Laminar Flow:** Occurs at low Reynolds Numbers. The flow is smooth, and the friction factor is independent of pipe roughness, defined by the formula: $f = 64/Re$.
    - **Transition Region:** An unstable region where flow is transitioning from laminar to turbulent.
    - **Complete Turbulence:** Occurs at high Reynolds Numbers. The flow is chaotic, and the friction factor becomes independent of the Reynolds Number, depending only on the relative pipe roughness.

## 1.3 Pipe Roughness (ε)

The absolute roughness (ε) of a pipe's inner surface is a critical parameter in determining the friction factor in turbulent flow.

| Material | Roughness ε (mm) |
|---|---|
| Concrete, coarse | 0.25 |
| Concrete, new smooth | 0.025 |
| Drawn tubing | 0.0025 |
| Glass, Plastic Perspex | 0.0025 |
| Iron, cast | 0.15 |
| Sewers, old | 3.0 |
| Steel, mortar lined | 0.1 |
| Steel, rusted | 0.5 |
| Steel, structural or forged | 0.025 |
| Water mains, old | 1.0 |

## 1.4 Local Losses from Transitions and Fittings

Local or "minor" losses are calculated using a loss coefficient (*K*) specific to the fitting or transition. The head loss (*hL*) is determined by the formula $hL = K * (V^2/2g)$, where *V* is the velocity at a reference section.

**Table 5-3: Representative Loss Coefficients (K)**

| Description | Additional Data | K Value |
|---|---|---|
| **Pipe Entrance** | | |
| Reentrant | r/d = 0.0 | $K_c$ = 0.50 |
| Sharp-edged | r/d = 0.0 | $K_c$ = 0.50 |
| Slightly rounded | r/d = 0.1 | $K_c$ = 0.12 |
| Well-rounded | r/d > 0.2 | $K_c$ = 0.03 |
| Flush | | $K_c$ = 1.00 |
| **Contraction** | $D_2/D_1$ = 0.0 | $K_c$ (θ=60°) = 0.08 |
| | $D_2/D_1$ = 0.20 | $K_c$ (θ=60°) = 0.08 |
| | $D_2/D_1$ = 0.40 | $K_c$ (θ=60°) = 0.07 |
| | $D_2/D_1$ = 0.60 | $K_c$ (θ=60°) = 0.06 |
| | $D_2/D_1$ = 0.80 | $K_c$ (θ=60°) = 0.05 |
| | $D_2/D_1$ = 0.90 | $K_c$ (θ=60°) = 0.04 |
| **Expansion** | $D_1/D_2$ = 0.0 | $K_E$ (θ=10°) = 0.13 |
| | $D_1/D_2$ = 0.20 | $K_E$ (θ=10°) = 0.13 |
| | $D_1/D_2$ = 0.40 | $K_E$ (θ=10°) = 0.11 |
| | $D_1/D_2$ = 0.60 | $K_E$ (θ=10°) = 0.06 |
| | $D_1/D_2$ = 0.80 | $K_E$ (θ=10°) = 0.03 |
| **90° Miter Bend** | Without vanes | $K_b$ = 1.1 |
| | With vanes | $K_b$ = 0.2 |
| **Smooth Bend** | r/d = 1 | $K_b$ (θ=45°) = 0.10, $K_b$ (θ=90°) = 0.35 |
| | r/d = 2 | $K_b$ (θ=45°) = 0.09, $K_b$ (θ=90°) = 0.19 |
| | r/d = 4 | $K_b$ (θ=45°) = 0.10, $K_b$ (θ=90°) = 0.16 |
| | r/d = 6 | $K_b$ (θ=45°) = 0.12, $K_b$ (θ=90°) = 0.21 |
| **Threaded Pipe Fittings** | | |
| Globe valve - wide open | | $K_L$ = 10.0 |
| Angle valve - wide open | | $K_L$ = 5.0 |
| Gate valve - wide open | | $K_b$ = 0.2 |
| Gate valve - half open | | $K_L$ = 5.6 |
| Return bend | | $K_b$ = 2.2 |
| Tee | | $K_L$ = 1.8 |
| 90° elbow | | $K_b$ = 0.9 |
| 45° elbow | | $K_b$ = 0.4 |

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# 2.0 Pump Flow and Power

Pumps are used to add energy to a fluid system, typically to overcome elevation changes and head losses.

## 2.1 Pump Power Calculation

The power required by a pump is directly proportional to the dynamic head it must provide and the flow rate of the water. The formula is:

- $P = (\gamma Q H) / (\eta * 1000)$
  - **P:** Power required (kW)
  - **γ:** Specific weight of water (9,810 N/m³)
  - **Q:** Water flow rate (m³/s)
  - **H:** Energy or dynamic head difference (m)
  - **η:** Pump efficiency (dimensionless)

## 2.2 Illustrative Problem: Pump Energy Calculation

An example from *Elementary Fluid Mechanics* demonstrates the application of the work-energy equation to determine pump power.

- **Problem:** A pump delivers a flow rate of 0.15 m³/s, with a suction side reading of 250 mm mercury vacuum and a discharge side pressure of 275 kPa.
- **Work-Energy Equation:** $z_1 + p_1/\gamma + V_1^2/2g + Ep = z_2 + p_2/\gamma + V_2^2/2g$
  - *Ep* represents the energy head added by the pump (equivalent to *H*).
- **Solution Steps:**
  1. **Pressure Conversion:** The suction and discharge pressures are converted to meters of water head.
     - Discharge pressure ($p_2/\gamma$) = 28.1 m
     - Suction pressure ($p_1/\gamma$) = -3.4 m
  2. **Velocity Calculation:** Velocities are calculated from the flow rate and pipe diameters (200 mm suction, 150 mm discharge).
     - $V_1 = 4.77$ m/s
     - $V_2 = 8.48$ m/s
  3. **Energy Head (Ep):** Substituting the values into the work-energy equation yields the energy added by the pump.
     - *Ep* = 37.0 J/N
  4. **Power Calculation:** Using the pump power formula (assuming 100% efficiency, η=1).
     - Power = (0.15 m³/s * 9800 N/m³ * 37.0 J/N) / 1000 = 54.4 kW

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# 3.0 Open Channel Flow

Open channel flow is distinct from pipe flow in one critical aspect: it must have a *free surface* that is subject to atmospheric pressure.

## 3.1 Manning's Equation for Uniform Flow

Manning's Equation is an empirical formula used to calculate the mean velocity and flow rate in an open channel under uniform flow conditions. The equation is presented in both U.S. Customary and Metric units.

| Unit System | Velocity (V) | Flow Rate (Q) |
|---|---|---|
| **U.S. Customary** | *V = (1.486/n) * R^(2/3) * S^(1/2)* | *Q = AV = (1.486/n) * A * R^(2/3) * S^(1/2)* |
| **Metric** | *V = (1/n) * R^(2/3) * S^(1/2)* | *Q = AV = (1/n) * A * R^(2/3) * S^(1/2)* |

- **V:** Mean velocity (ft/s or m/s)
- **Q:** Flow rate ($ft^3$/s or $m^3$/s)
- **n:** Manning's coefficient of roughness
- **A:** Cross-sectional area of flow ($ft^2$ or $m^2$)
- **R:** Hydraulic radius (A / P, where P is the wetted perimeter) (ft or m)
- **S:** Hydraulic slope (head loss per unit length) (ft/ft or m/m)

## 3.2 Channel Geometry

The geometric properties of the channel are essential for applying Manning's Equation.

| Property | Rectangle | Trapezoid | Circle (partially full) |
|---|---|---|---|
| **Area, A** | by | (b+xy)y | $(1/8)(\varphi - \sin\varphi)D^2$ |
| **Wetted perimeter, P** | b + 2y | $b + 2y\sqrt{(1+x^2)}$ | $\frac{1}{2}\varphi D$ |
| **Hydraulic radius, R** | by / (b+2y) | $(b+xy)y / (b+2y\sqrt{(1+x^2)})$ | $\frac{1}{4}(1 - \sin\varphi/\varphi)D$ |

### 3.3 Manning's Roughness Coefficients (n)

The value of 'n' depends on the surface material and condition of the channel.

| Channel/Stream Description | Typical 'n' Value |
|---|---|
| **Lined or Built-Up Channels** | |
| Concrete, trowel finish | 0.013 |
| Concrete, float finish | 0.015 |
| Concrete, unfinished | 0.017 |
| Masonry, cemented rubble | 0.025 |
| **Excavated or Dredged Channels** | |
| Clean, recently completed | 0.018 |
| Earth, winding and sluggish | 0.027 |
| Dense weeds or aquatic plants | 0.035 |
| **Natural Streams** | |
| Clean, straight, full stage | 0.030 |
| Clean, winding, some pools | 0.040 |
| Sluggish reaches, weedy | 0.070 |
| **Flood Plains** | |
| Pasture, no brush, high grass | 0.035 |
| Light brush and trees, in winter | 0.050 |
| Medium to dense brush, in summer | 0.100 |

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# 4.0 Storm Sewer Design

Storm sewers are typically designed to operate as open channels under gravity, approaching but not exceeding full-pipe, pressurized conditions.

### 4.1 Design Principles and Constraints

- **Flow Type:** Designed for open channel (gravity) flow.
- **Capacity:** Maximum design water depth (h) is set equal to the pipe diameter (d).
- **Velocity Constraints:** To ensure functionality and longevity, flow velocity must be maintained within a specific range:
  - **Minimum Velocity > 2 ft/s:** To prevent the deposition of sediment.
  - **Maximum Velocity < 10 ft/s:** To prevent scouring and erosion of the pipe walls.

### 4.2 Design Example: Sizing a Concrete Sewer Pipe

- **Problem:** A concrete sewer pipe on a 0.5% slope must carry 15 $ft^3/s$.

- **Given Data:** $Q = 15\ ft^3/s$; $S = 0.005$.
- **Assumptions:** Manning's n = 0.013 (for concrete pipe); pipe is flowing full.
- **Calculations for full pipe:**
  - Area (A) = $\frac{1}{4} \pi D^2$
  - Hydraulic Radius (Rh) = D/4
- **Solution:** By substituting these into the U.S. Customary Manning's equation, the required pipe diameter (D) is solved to be **2 ft**.
- **Verification:** The resulting flow velocity is calculated as $V = Q/A = 15\ ft^3/s / 3.14\ ft^2 =$ **4.78 ft/s**. This velocity is within the acceptable range of 2 ft/s to 10 ft/s.

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# 5.0 Outlet Flow and Control Structures

Outlet structures are engineered components designed to control the discharge rate from culverts, detention basins, and other hydraulic systems. Common types include orifices and weirs.

## 5.1 Orifice Flow

An orifice is a submerged or unsubmerged opening through which fluid flows.

- **Flow Rate Equation (Free Discharge):** $Q = C * A * \sqrt{2gh}$
  - **Q:** Flow rate
  - **C:** Coefficient of discharge (combines coefficients of contraction, *Cc*, and velocity, *Cv*)
  - **A:** Area of the orifice
  - **g:** Acceleration due to gravity
  - **h:** Head (height of fluid above the orifice centerline)
- **Nominal Coefficients for Orifices:**

| Orifice Type | Discharge (C) | Contraction (Cc) | Velocity (Cv) |
|---|---|---|---|
| Sharp-edged | 0.61 | 0.62 | 0.98 |
| Rounded | 0.98 | 1.00 | 0.98 |
| Short tube | 0.80 | 1.00 | 0.80 |
| Borda | 0.51 | 0.52 | 0.98 |

## 5.2 Weir Flow

A weir is an obstruction over which fluid flows, commonly used for flow measurement. The flow dynamics are complex, influenced by head (H), weir height (P), turbulence, and nappe ventilation.

- **Simplified Flow Rate Equation (Rectangular Weir):** $q = Cw * (2/3) * \sqrt{2g} * H^{3/2}$
  - **q:** Flow rate per unit width
  - **Cw:** Weir coefficient

- **H:** Head on the weir
- **Rehbock's Empirical Formula for Cw:** For well-ventilated, sharp-crested rectangular weirs, the coefficient can be estimated:
  - $C_w = 0.602 + 0.08(H/P) + 1/(900H)$

## 5.3 Outlet Structures for Stormwater Management

Modern stormwater management relies on engineered outlet structures to control runoff and mitigate flooding.

- **Surface Extended Detention Basin:** These basins use a multi-stage outlet control structure to manage different storm events. Components include a forebay, a low-flow channel, and an outlet structure with orifices at different elevations for water quality storms, 2-year, 10-year, and 100-year events, as well as an emergency spillway.
- **Bioretention Systems:** These systems use soil and vegetation to treat stormwater. They often incorporate an overflow structure, which also serves as the outlet for managing water quantity during larger flood control storms.
- **Case Example:** A bioretention system at Rutgers University Busch Campus demonstrates a practical application, featuring two inlet pipes and a single concrete outlet structure to manage runoff from a parking lot.