Briefing on Core Principles of Hydraulics

Executive Summary

This briefing synthesizes the fundamental principles of hydraulics, focusing on:

- **Pressurized pipe flow**
- **Pump systems**
- **Open channel flow**
- **Outlet and flow control structures**

Two primary hydraulic flow regimes dominate engineering practice:

1. **Pressurized Pipe Flow**
   Energy loss is governed by:
   - Friction along pipe walls
   - Local losses from fittings and transitions
2. **Open Channel Flow**
   Characterized by a **free surface** exposed to atmospheric pressure and typically analyzed using **Manning's Equation**.

Key Takeaways

- The **Moody Diagram** is essential for determining friction factors in pipe flow based on Reynolds number and relative roughness.
- Local losses are quantified using standardized loss coefficients (K values).
- Pump power is proportional to flow rate and dynamic head.
- Manning's Equation governs gravity-driven systems such as storm sewers.
- Outlet structures (orifices, weirs, culverts) regulate discharge using established hydraulic relationships and empirical coefficients.

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1. Pressurized Pipe Flow

Pressurized pipe flow occurs in closed conduits without a free surface. Flow is driven by pressure gradients.

The primary analytical challenge is evaluating **energy losses**, which fall into two categories:

1.1 Head Loss Components

1. Frictional Head Loss (hf)

Loss caused by shear stress between fluid and pipe wall along the pipe length.

2. Local Head Loss (hL)

Loss caused by fittings and disruptions such as:

- Valves
- Bends
- Contractions
- Expansions
- Entrances and exits

1.2 Frictional Loss and the Moody Diagram

The **Moody Diagram** determines the Darcy friction factor (f) as a function of:

- Reynolds number (Re)
- Relative roughness (ε/d)

Reynolds Number

$$Re = \frac{\rho V d}{\mu}$$

Where:

- ρ = fluid density
- V = mean velocity
- d = pipe diameter
- μ = dynamic viscosity

Friction Factor Definition

$$f = \frac{2d}{\rho V^2 l}\Delta P$$

Flow Regimes

Laminar Flow (Re < ~2000)

- Smooth, orderly motion
- Independent of roughness

$$f = \frac{64}{Re}$$

Transition Region

- Unstable and unpredictable

Fully Turbulent Flow

- Chaotic motion
- Friction factor depends primarily on relative roughness

1.3 Typical Pipe Roughness Values

Material	ε (mm)
Concrete, coarse	0.25
Concrete, smooth	0.025
Drawn tubing	0.0025
Glass / Plastic	0.0025
Cast iron	0.15
Steel, rusted	0.5
Old sewers	3.0
Old water mains	1.0

1.4 Local (Minor) Losses

Local head loss:

$$h_L = K\frac{V^2}{2g}$$

Where:

- K = loss coefficient
- V = velocity at reference section

Typical K Values

- Sharp-edged entrance: 0.50
- Well-rounded entrance: 0.03
- 90° miter bend (no vanes): 1.1
- 90° elbow: 0.9
- Gate valve (wide open): 0.2
- Globe valve (wide open): 10.0

Local losses can dominate in short piping systems.

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2. Pump Flow and Power

Pumps add mechanical energy to overcome:

- Elevation changes
- Friction losses
- Pressure differences

2.1 Pump Power Equation

$$P = \frac{\gamma Q H}{\eta \cdot 1000}$$

Where:

- P = power (kW)
- γ = specific weight of water (9,810 N/m³)
- Q = flow rate (m³/s)
- H = dynamic head (m)
- η = efficiency

2.2 Illustrative Example

Given:

- Q = 0.15 m³/s
- Suction: 250 mm Hg vacuum
- Discharge pressure: 275 kPa

Converted Pressures

- Discharge head = 28.1 m
- Suction head = –3.4 m

Velocities

- Suction (200 mm pipe): 4.77 m/s
- Discharge (150 mm pipe): 8.48 m/s

Pump Head

$$H = 37.0 \text{ m}$$

Power (η = 1)

$$P = 54.4 \text{ kW}$$

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3. Open Channel Flow

Open channel flow differs fundamentally from pipe flow:

- It has a **free surface**
- Flow is driven by gravity

3.1 Manning's Equation (Uniform Flow)

Metric Form

$$V = \frac{1}{n} R^{2/3} S^{1/2}$$

$$Q = \frac{1}{n} A R^{2/3} S^{1/2}$$

Where:

- n = Manning's roughness coefficient
- A = cross-sectional area
- R = hydraulic radius (A/P)
- S = slope

3.2 Channel Geometry

Rectangle

- $A = by$
- $P = b + 2y$

Trapezoid

- $A = (b + xy)y$
- $P = b + 2y\sqrt{(1+x^2)}$

Circular (Partially Full)

- $A = (1/8)(\varphi - \sin\varphi)D^2$
- $P = \frac{1}{2}\varphi D$

3.3 Typical Manning's n Values

Surface	n
Concrete (trowel finish)	0.013
Concrete (unfinished)	0.017
Earth channel	0.027
Natural stream, clean	0.030
Weedy channel	0.070
Dense brush floodplain	0.100

4. Storm Sewer Design

Storm sewers operate primarily under gravity flow.

4.1 Design Criteria

- Flow type: Open channel (near full pipe)

- Design depth: $h \leq D$
- Minimum velocity: > 2 ft/s (avoid deposition)
- Maximum velocity: < 10 ft/s (avoid scour)

4.2 Example: Concrete Pipe

Given:

- $Q = 15$ ft³/s
- $S = 0.005$
- $n = 0.013$

For full pipe:

- $A = (\pi/4)D^2$
- $R = D/4$

Result

Required diameter:

$$D = 2 \text{ ft}$$

Velocity:

$$V = 4.78 \text{ ft/s}$$

Within acceptable limits.

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5. Outlet Flow and Control Structures

Outlet structures regulate discharge from:

- Detention basins
- Culverts
- Stormwater systems

5.1 Orifice Flow

$$Q = CA\sqrt{2gh}$$

Where:

- C = discharge coefficient
- A = area
- h = head

Typical Coefficients

Type	C
Sharp-edged	0.61
Rounded	0.98
Short tube	0.80
Borda	0.51

5.2 Weir Flow

Rectangular weir (unit width):

$$q = C_w \frac{2}{3}\sqrt{2g}H^{3/2}$$

Rehbock Formula

$$C_w = 0.602 + 0.08(H/P) + \frac{1}{900H}$$

5.3 Stormwater Outlet Applications

Surface Extended Detention Basin

- Multi-stage outlet structure
- Orifices at different elevations

- Emergency spillway

Designed for:

- Water quality storm
- 2-year storm
- 10-year storm
- 100-year storm

Bioretention Systems

- Soil and vegetation treatment
- Overflow structure for larger events

Example: Rutgers University Busch Campus

- Two inlet pipes
- Single concrete outlet structure
- Parking lot runoff management

Final Conceptual Summary

Hydraulics fundamentally involves:

- **Energy accounting** (pipe flow and pumps)
- **Gravity-driven resistance relationships** (open channels)
- **Flow regulation mechanisms** (orifices, weirs, culverts)

Across all systems, engineers balance:

- Head
- Velocity
- Roughness
- Geometry
- Energy losses

These principles form the analytical backbone of water resources and stormwater engineering design.