1 Pressurized Pipes

1.1 Water Distribution Systems

A water supply system or water supply network is a system of engineered hydrologic and hydraulic components which provide water supply. The system typically is comprised of

1. A drainage basin capturing surface water or a groundwater basin (both are hydrologic components).
2. A raw water collection point where the water accumulates, such as a lake, a river, or groundwater from an underground aquifer. Untreated drinking water may be transferred using uncovered ground-level aqueducts, covered tunnels or underground water pipes (Lake Allen Henry water is transported in large-diameter conduit to the treatment facility South of town.).
3. Water purification facilities. The raw water is treated to inactivate pathogens, improve color, taste, and remove other regulated constituents. Treated water is then transferred using water pipes (usually underground) to storage facilities or directly to customers.
4. Water storage facilities such as reservoirs, water tanks, or water towers. Smaller water systems may store the water in cisterns or pressure vessels.
5. Additional water pressurizing components such as pumping stations may need to be situated at the outlet of underground or above ground reservoirs or cisterns (this is called "boost" pumping).
6. A pipe network for distribution of water to the consumers.

Once treated, disinfectant (chlorine, chloramine, H_2O_2+UV, ozone, chlorine-dioxide, etc.) is added to the water and it is distributed by the local supply network. Today, water supply systems are typically constructed of plastic, ferrous, or concrete circular pipe. However, other "pipe" shapes and material may be used, such as square or rectangular concrete boxes, arched brick pipe, or wood. Near the end point, the network of pipes through which the water is delivered is often referred to as the water mains.

The energy that the system needs to deliver the water is called head. That energy is transferred to the water, therefore becoming water head, in a number of ways: by a pump, by gravity feed from a water source (such as a water tower) at a higher elevation, or by compressed air. In small domestic systems, the water may be pressurized by a pressure vessel.

These systems are usually owned and maintained by local governments, such as cities, or other public entities, but are occasionally operated by a commercial enterprise (privatization). Water supply networks are part of the master planning of communities, counties, and municipalities. Their planning and design requires the expertise of city planners and civil engineers, who must consider many factors, such as location, current demand, future growth, leakage, pressure, pipe size, pressure loss, fire fighting flows, etc. — using pipe network analysis and other tools.

As water passes through the distribution system, the water quality can degrade by chemical reactions and biological processes. Corrosion of metal pipe materials in the distribution system can cause the release of metals into the water with undesirable aesthetic and health effects. Release of iron from unlined iron pipes can result in customer reports of "red water" at the tap . Release of copper from copper pipes can result in customer reports of "blue water" and/or a metallic taste. Release of lead can occur from the solder used to join copper pipe together or from brass fixtures. Copper and lead levels at the consumer's tap are regulated to protect consumer health.

Utilities will often adjust the chemistry of the water before distribution to minimize its corrosiveness. The simplest adjustment involves control of pH and alkalinity to produce a water that tends to passivate corrosion by depositing a layer of calcium carbonate. Corrosion inhibitors are often added to reduce release of metals into the water. Common corrosion inhibitors added to the water are phosphates and silicates.

Maintenance of a biologically safe drinking water is another goal in water distribution. Typically, a disinfectant is added to the water as it leaves the treatment plant. Booster stations can be placed within the distribution system to ensure that all areas of the distribution system have adequate sustained levels of disinfection.

Like electric power lines, roads, and microwave radio networks, water systems may have a loop or branch network topology, or a combination of both. A network evolves so that if one section of water distribution main fails or needs repair, that section can be isolated without disrupting all users on the network. Isolation is achieved by valves.

Most systems are divided into zones. Factors determining the extent or size of a zone can include hydraulics, telemetry systems, history, and population density. Sometimes systems are designed for a specific area then are modified to accommodate development. Terrain affects hydraulics. While each zone may operate as a stand-alone system, there is usually some arrangement to interconnect zones in order to manage equipment failures or system failures.

The remainder of this chapter presents the hydraulics, trenching, and materials considerations used in pressurized water systems.

1.2 Energy Equation

The design of a pressurized conduit involves selecting diameter and materials to satisfy hydraulic requirements at the lowest life-cycle cost. Most buyers of engineering services are "first-cost" buyers, so lowest life-cycle usually means lowest initial capital cost.

Equation 1 is the one-dimensional steady flow form of the energy equation typically applied for pressurized conduit hydraulics.

$$\frac{p_1}{\epsilon g} + \epsilon_1 \frac{V_1^2}{2g} + z_1 + h_p = \frac{p_2}{\epsilon g} + \epsilon_2 \frac{V_2^2}{2g} + z_2 + h_t + h_l \tag{1}$$

where $\frac{p}{\epsilon g}$ is the pressure head at a location, $\epsilon \frac{V^2}{2g}$ is the velocity head at a location, z is the elevation, h_p is the added head from a pump, h_t is the added head extracted by a turbine, and h_l is the head loss between sections 1 and 2. Figure 1 is a sketch that illustrates the various components in Equation 1.

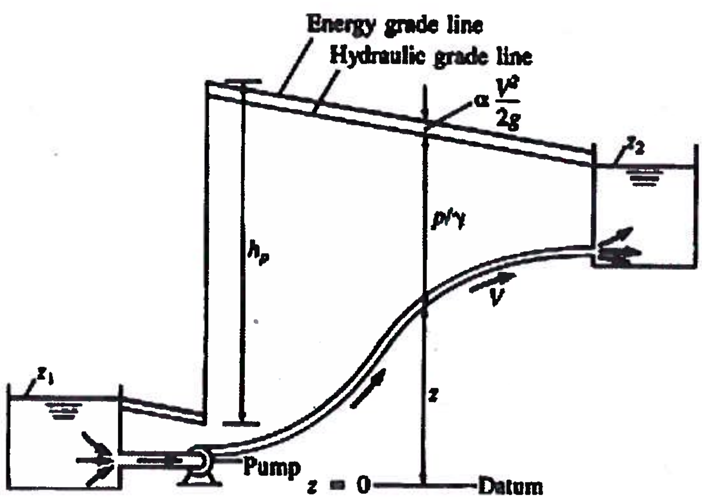

Figure 5-1 Definition sketch for terms in the energy equation

Figure 1: Definition sketch for energy equation

1.2.1 Velocity Head

The velocity in $\epsilon \frac{V^2}{2g}$ is the mean section velocity and is the ratio of discharge to flow area. The kinetic energy correction coefficient is

$$\epsilon = \frac{\int_A u^3 dA}{V^3 A} \tag{2}$$

where u is the point velocity in the cross section (usually measured relative to the centerline or the pipe wall; axial symmetry is assumed). Generally values of ϵ are 2.0 if the flow is laminar, and approach unity (1.0) for turbulent flow. In most water distribution systems the flow is usually turbulent so ϵ is assumed to be unity and the velocity head is simply $\frac{V^2}{2g}$.

1.2.2 Added Head — Pumps

The head supplied by a pump is related to the mechanical power supplied to the flow. Equation 3 is the relationship of mechanical power to added pump head.

$$\epsilon P = Q \epsilon g h_p \tag{3}$$

where the power supplied to the motor is P and the "wire-to-water" efficiency is ϵ.

1.2.3 Added Head — Turbines

The head recovered by a turbine is also an "added head" but appears on the loss side of the equation. Equation 4 is the power that can be recovered by a turbine (again using the concept of "water-to-wire" efficiency is

$$P = \epsilon Q \epsilon g h_t \tag{4}$$

1.3 Head Loss

Head loss in straight pipes is caused by resistance of the pipe wall on the liquid. In laminar flow ($Re_d < 2000$) the head loss is explained entirely by liquid viscosity, and the loss is proportional to the mean section velocity. In turbulent flow the loss is caused by the dissipation of the turbulent component of kinetic energy, and the loss is a super-linear function of velocity as well as the pipe roughness. These relationships for pipes are typically summarized by the friction factor concept and the Moody chart.

1.3.1 Head Loss using Darcy-Weisbach Model

The Darcy-Weisbach head loss model is used in civil engineering practice (as well as other disciplines). The model relates fluid properties (viscosity, density), flow and geometric properties (velocity, area), and pipe material properties (roughness, diameter) to a friction factor that is then applied in a quadratic drag formula. Equation 5 is the Darcy-Weisbach formula for pipe loss.

$$h_f = f\frac{L}{D}\frac{V^2}{2g} \tag{5}$$

where h_f is the head loss for a length of pipe L, D is the diameter, V is the mean section velocity, g is the constant of gravitational acceleration.

Equation 6 is the Darcy-Weisbach head loss formula in its often more convenient discharge form.

$$h_f = 8fL\frac{Q^2}{\epsilon^2 g D^5} \tag{6}$$

The friction factor f is a function of Reynolds number Re_d and pipe roughness ratio $\frac{\epsilon}{D}$. The relation of f, Re_d, and $\frac{\epsilon}{D}$ is plotted in Figure 2 which is called the Moody chart (or Moody-Stanton diagram)(CITE SOURCE). The diagram is a graphical representation of the analysis of thousands of experiments over the last century that established the functional relations represented by the various curves on the chart.

Typical problems using the Moody chart fall into three categories.

1. Estimate the head loss in a pipe h_f given the discharge, diameter, and material properties.

MOODY 1947

2. Estimate the discharge in a pipe Q given the available head loss, diameter, and material properties.

3. Estimate the diameter of a pipe D given the available head loss, discharge, and material properties.

These three types of problems are the subject of the next three examples.

Material	e (ft)	e (mm)
Riveted steel	0.003–0.03	0.9–9.0
Concrete	0.001–0.01	0.3–3.0
Cast iron	0.00085	0.25
Galvanized iron	0.0005	0.15
Commercial steel or wrought iron	0.00015	0.046
Drawn tubing	0.000005	0.0015

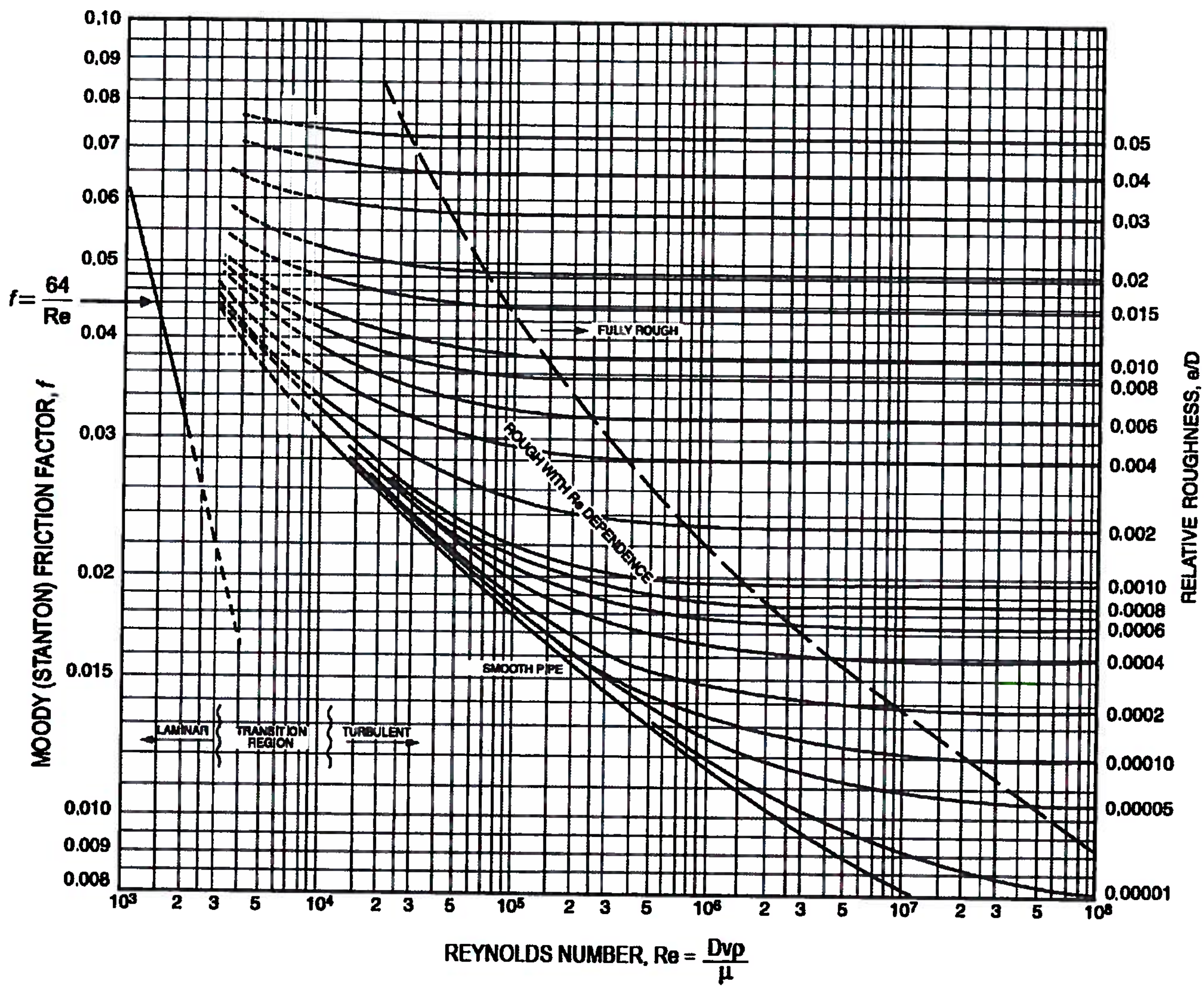

Figure 2: Moody-Stanton Diagram (from CITE NCEES).

Find h_f given Q, D, ϵ This kind of problem is relatively straightforward. The engineer computes Re_d from the discharge Q and the pipe diameter D. Then computes the roughness ratio from the tabulated ϵ for the pipe material. The friction factor, f, is then recovered directly from the Moody chart.

Example Oil with specific gravity 0.9, viscosity 0.00003 ft^2/sec flows in a 2000-foot long, 6-inch diameter, cast-iron pipe at a flow rate of 1.0 cubic-feet-per-second. The pipe slopes upward at an angle of 5^o in the direction of flow. Estimate the head loss in the pipe. Estimate the pressure drop in the pipe.

Solution Figure 3 is a sketch of the situation.

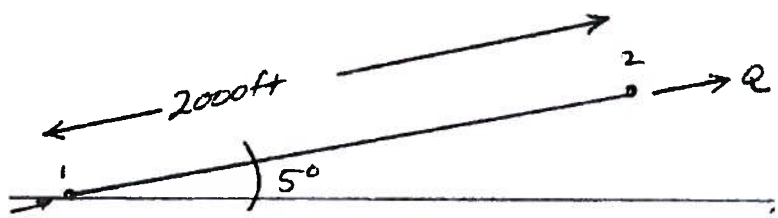

Figure 3: Sketch for Example

Equation 8 is the energy equation for the situation. The velocity terms are absent because they are equal, the added pump head and removed turbine head are absent because these devices are absent. All that remains is the pressure, elevation, and head loss terms.

$$\frac{p_1}{\epsilon g} + z_1 = \frac{p_2}{\epsilon g} + z_2 + h_l \tag{7}$$

Rearranging equation to isolate the head loss will be of value when we try to find the pressure drop.

$$(\frac{p_1}{\epsilon g} - \frac{p_2}{\epsilon g}) + (z_1 - z_2) = h_l \tag{8}$$

The first term in parenthesis is the pressure drop (rise), and the second term is the elevation drop (rise).

The head loss is evaluated using the Darcy-Weisbach head loss model. First we compute Re_d

$$Re_d = \frac{V\ D}{\epsilon} = \frac{4\ (1cfs)\ (0.5ft)}{\epsilon\ (0.5ft)^2\ (0.00003\ sq.ft/sec)} \approx 84,822 \tag{9}$$

The Reynolds number is greater than 10,000 therefore we conclude the flow is turbulent.

The roughness height is ϵ=0.00085 from the table on the Moody chart (in this document), so the roughness ratio is

$$\frac{\epsilon}{D} = \frac{0.00085}{0.5} \approx 0.0017 \tag{10}$$

Material	e (ft)	e (mm)
Riveted steel	0.003–0.03	0.9–9.0
Concrete	0.001–0.01	0.3–3.0
Cast iron	0.00085	0.25
Galvanized iron	0.0005	0.15
Commercial steel or wrought iron	0.00015	0.046
Drawn tubing	0.000005	0.0015

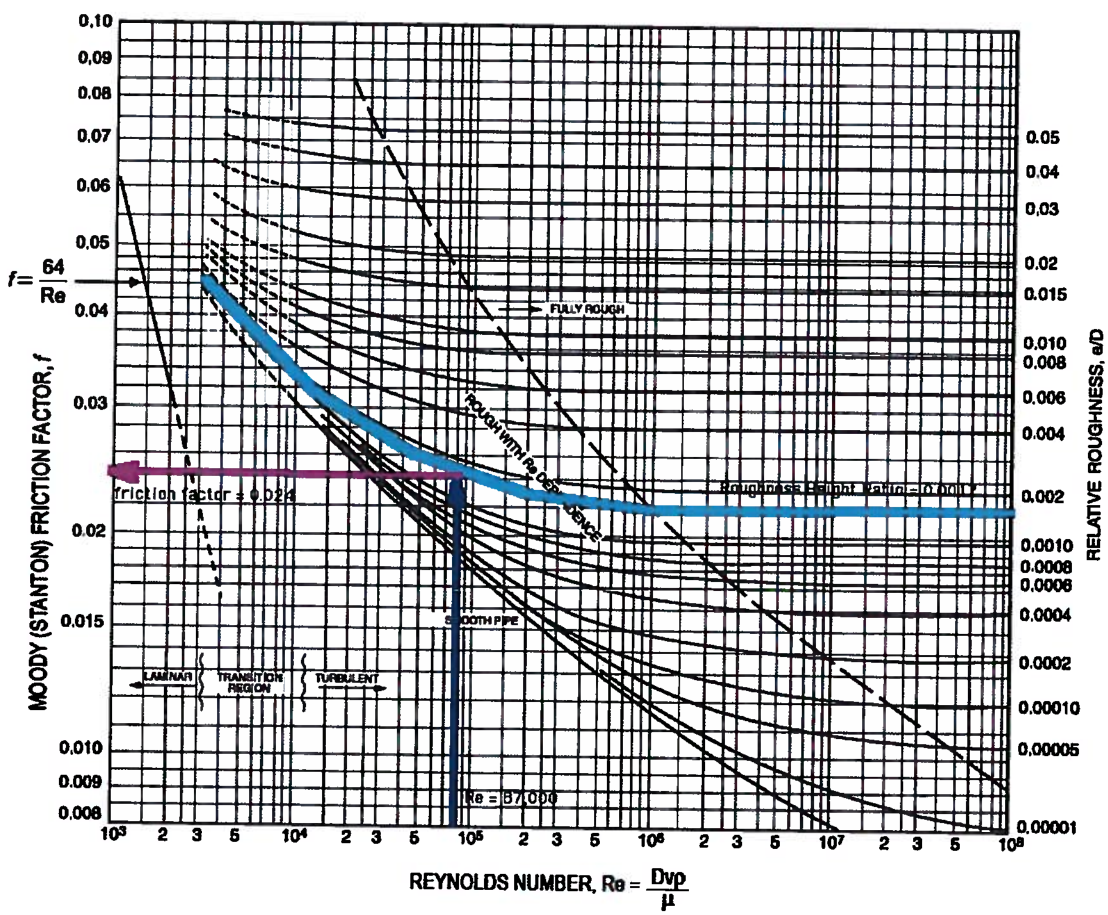

Figure 4: Moody-Stanton Diagram annotated with Example 1 components.

Figure 4 is the Moody chart with the roughness ratio shown as the light blue (cyan) curve, the reynolds number as the black line, and the recovered friction factor (f=0.024) from the magenta line.

To complete the analysis, we then use the Darcy-Weisbach equation for estimate the head loss as

$$h_l = 8fL\frac{Q^2}{\epsilon^2 gD^5} = 8(0.024)(2000ft)\frac{(1cfs)^2}{\epsilon^2(32.2ft/s^2)(0.5ft)^5} \approx 38.6ft \tag{11}$$

Now to compute the pressure drop, we simply account for the elevation change and what remains must be pressure. First the change in elevation is about $2000sin5^o \approx 175ft$. The change in pressure is therefore

$$\Delta p = \epsilon g(h_l + (z_2 - z_1)) = (38.6ft + 175ft)(62.4)(0.9) \approx 11,999lb/ft^2 = 83psi \tag{12}$$

Thus the oil pressure must be at least 83 psi greater at the lower elevation than the upper elevation for the oil to flow up the pipe.

Find Q given h_f, D, ϵ This type of problem requires iteration if using the Moody chart, but it usually converges in two attempts. The alternative is to use one of the explicit equations in a later section. The engineer computes the Then computes the roughness ratio from the tabulated ϵ for the pipe material. Then makes a guess as to the flow rate, uses that guess to compute a Reynolds number, and look up a friction factor and compute the head loss. If the computed value is too large, then the flow rate is reduced; if too small then increased. The trial-and-error process is greatly helped by using a spreadsheet to record the various computations.

Example An 80-foot horizontal, 1/2-inch diameter wrought iron pipe has an observed head loss of 40 feet. Estimate the discharge in the pipe.

Solution Apply Darcy-Weisbach directly — the pipe is horizontal so the energy equation is quite boring,

$$h_l = \frac{\Delta p}{\epsilon g} = 40ft \tag{13}$$

First compute the roughness height ratio — it will be needed to look up friction factors.

$$\frac{\epsilon}{D} = \frac{0.00015ft}{0.5i/12ft} \approx 0.0036 \tag{14}$$

Then construct a table of computations as shown in Table 2. Increase (decrease) the flow rate until the computed head loss is about the same as the required head loss. The moody chart is used the same way as in the previous example. The engineer will need to exercise some judgement of when to stop, because as one gets close to the specified head loss, the ability to read changes in f diminishes.

Table 1: Computation table for Estimating Q from head loss and material properties.

Q_{guess}	Re_d	f	$h_{l\ guess}$
0.001	2.83×10^3	0.036	≈ 0.57
0.005	1.41×10^4	0.032	≈ 12.7
0.008	2.26×10^4	0.031	≈ 31.6
0.009	2.25×10^4	0.030	≈ 37.9

The result in this example is that the pipe discharge is about 0.009 cfs. **Find D given Q, h_f, ϵ** The last kind of case is finding (design) the diameter required to move a specified volume of water given a specified working head and pipe material. In this kind of problem, the engineer must guess a diameter, then compute Re_d based on the flow rate and the diameter. The engineer must also compute $\frac{\epsilon}{D}$. Then the engineer enters the Moody chart with these two values (guesses), reads the friction factor and computed the head loss. If the head loss from the guess is too large, then the diameter is increased, too small then decreased. Upon convergence, the next larger commercially available diameter is selected for practical application.

Example An 600 foot wrought-iron pipe is to carry water at 20°C at a discharge of 3 CFS. The pipe drops 60 feet in the direction of flow and the desired pressure drop is 6 feet of head. What diameter pipe will function under these conditions?

Solution Figure 5 is a sketch of the situation.

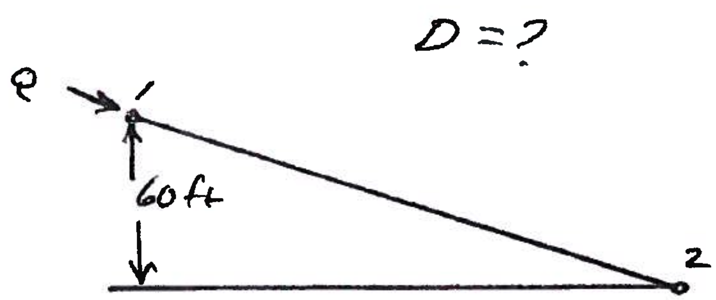

Figure 5: Sketch for Example

The energy equation for this situation is

$$(\frac{p_1}{\epsilon g} - \frac{p_2}{\epsilon g}) + (z_1 - z_2) = h_l \tag{15}$$

The elevation change is given as 60 feet and the pressure drop is given as 6 feet (that is the pressure is greater at location 1 by 6 feet than location 2). Thus the Darcy-Weisbach head loss equation is

$$h_l = 8fL\frac{Q^2}{\epsilon^2 g D^5} \approx 66ft \tag{16}$$

As in the prior example, a computation table is useful. The sixth column is a computational trick to make a hand calculations faster. The term $\frac{h_l}{f}$ is evaluated by taking the Darcy-Weisbach equation and dividing out the friction factor (i.e. $\frac{h_l}{f} = 8L\frac{Q^2}{\epsilon^2 g D^5}$)

Table 2: Computation table for Estimating D from head loss, discharge and material properties.

D_{guess}	Re_d	$\frac{\epsilon}{D}$	f	$\frac{h_l}{f}$	h_l
0.25	1.41×10^6	0.0006	0.018	1.39×10^5	≈ 2500
0.50	7.06×10^5	0.0003	0.016	4.35×10^3	≈ 69.6
0.51	6.92×10^5	0.00029	0.016	3.94×10^3	≈ 63.0

The result after three tries is that the diameter is between 6-7 inches, commercially available 7 inch iron pipe exists[1], so this size could be specified in such a situation.

Explicit Equations for h_f, Q, and D

An alternative to the Moody chart are explicit equations based on regression models of the data represented by the Moody chart. These equations are certainly useful in programming solutions to common pipe-flow design problems.

Friction Factor Formulas

Equation 17 is the formula for friction factor for laminar flow ($Re_d < 2000$).

$$f = \frac{64}{Re_d} \tag{17}$$

Equation 18 is the formula for friction factor for transitional to fully rough flow for the ranges of Re_d and roughness ratio shown (CITE SOURCE).

COLEBROOK-WHITE

$$f = \frac{0.25}{[log_{10}(\frac{\frac{k_e}{D}}{3.7} + \frac{5.74}{Re_d^{0.9}})]^2} \tag{18}$$

valid for : 4,000 < Re_d <100,000,000 and 0.00001 < $\frac{\epsilon}{D}$ < 0.002.

Discharge Formula

[1]7-inch pipe is uncommon, but is reported on NPS tables; so the pipe is commercially available somewhere.

Combining Equation 18 and Equation 6, then rearranging to isolate the discharge Q produces an explicit formula for estimating discharge from head loss and material properties. Equation 19 is such an explicit formula (~~CITE SOURCE~~).
SWAMEE-JAIN

$$Q = -2.22D^{5/2} \times \sqrt{gh_f/L} \times [log_{10}(\frac{\epsilon}{3.7D} + \frac{1.78\epsilon}{D^{3/2}\sqrt{gh_f/L}})] \tag{19}$$

Diameter Formula A formula for diameter is also available. Equation 20 is a formula to estimate the required pipe diameter for a particular discharge, head loss, and roughness (~~CITE SOURCE~~).

SWAMEE-JAIN / STREETER WYLIE ← THE COYOTE? BEEP-BEEP

$$D = 0.66[\epsilon^{1.25} \times (\frac{LQ^2}{gh_f})^{4.75} + \epsilon Q^{9.4} \times (\frac{L}{gh_f})^{5.2}]^{0.04} \tag{20}$$

1.3.2 Head Loss using Hazen-Williams Model ← WATER ONLY !!!

The Hazen-Williams head loss model is another common model in civil engineering practice. It is an empirical model valid only for water, and is not for use with other liquids. It appears in the Texas Administrative Code and has been used for water distribution systems design for at least a century.

Equation 21 is the formula that relates pipe velocity to head loss.

$$V = 1.381\ C_h\ R^{0.63}\ S^{0.54} \tag{21}$$

where, V is the mean section velocity in feet per second, C_h is the Hazen-WIlliams loss coefficient (tabulated), R is the hydraulic radius in feet, and $S = h_f/L$ is the slope of the energy grade line (head loss per unit length)

If Equation 21 is rearranged, a formal head loss equation results, as in Equation 22 for circular pipes of diameter D in feet.

$$h_f = 3.02\ L\ D^{-1.167}(\frac{V}{C_h})^{1.85} \tag{22}$$

More useful is the head loss in discharge form for circular pipes with discharge Q is cubic feet per second.

$$h_f = 3.02\ L\ D^{-1.167}(\frac{4Q}{\epsilon D^2 C_h})^{1.85} \tag{23}$$

The loss coefficients are tabulated in many places and are usually based on material type (cement, steel, etc.) and an estimate of age. Table 3 is one such tabulation[2], and is a rather extensive list. The model is intended for pipes in sizes from 2-inches to 6-feet; outside these ranges the model may not be applicable.

Table 3: Hazen-Williams Coefficients for Different Materials.

Material	C_h	Material	C_h
ABS - Acrylonite Butadiene Styrene	130	Aluminum	130 - 150
Asbestos Cement	140	Asphalt Lining	130 - 140
Brass	130 - 140	Brick sewer	90 - 100
Cast-Iron - new unlined (CIP)	130	Cast-Iron 10 years old	107 - 113
Cast-Iron 20 years old	89 - 100	Cast-Iron 30 years old	75 - 90
Cast-Iron 40 years old	64-83	Cast-Iron, asphalt coated	100
Cast-Iron, cement lined	140	Cast-Iron, bituminous lined	140
Cast-Iron, wrought plain	100	Cast-Iron, seal-coated	120
Cement lining	130 - 140	Concrete	100 - 140
Concrete lined, steel forms	140	Concrete lined, wooden forms	120
Concrete, old	100 - 110	Copper	130 - 140
Corrugated Metal	60	Ductile Iron Pipe (DIP)	140
Ductile Iron, cement lined	120	Fiber	140
Fiber Glass Pipe - FRP	150	Galvanized iron	120
Glass	130	Lead	130 - 140
Metal Pipes - Very to extremely smooth	130 - 140	Plastic	130 - 150
Polyethylene, PE, PEH	140	Polyvinyl chloride, PVC, CPVC	150
Smooth Pipes	140	Steel new unlined	140 - 150
Steel, corrugated	60	Steel, welded and seamless	100
Steel, interior riveted, no projecting rivets	110	Steel, projecting girth and horizontal rivets	100
Steel, vitrified, spiral-riveted	90 - 110	Steel, welded and seamless	100
Tin	130	Vitrified Clay	110
Wrought iron, plain	100	Wooden or Masonry Pipe - Smooth	120
Wood Stave	110 - 120		

Example Estimate the head loss in a 72-inch, 10,000-foot steel pipe carrying water at 200 CFS using the Hazen-Williams formula.

Solution Using Table 3 an estimate of the C_h is 100. Next substitute into the HW formula as

$$h_f = 3.02\ (10{,}000ft)\ (6ft)^{-1.167}\left(\frac{4(200cfs)}{\epsilon\,(6ft)^2 100}\right)^{1.85} \approx 28ft \qquad (24)$$

[2]Adapted from `http://www.engineeringtoolbox.com/hazen-williams-coefficients-d_798.html`.

1.4 Head Losses in Bends and Fittings — (aka Minor Losses)

In addition to head loss in the conduit, other losses are created by inlets, outlets, transitions, and other connections in the system. In fact such losses can be used to measure discharge (think of the orifice plate in the fluids laboratory). The fittings create additional turbulence that generates heat and produces the head loss.

Equation 25 is the typical loss model

$$h_{minor} = K\frac{V^2}{2g} \tag{25}$$

where K is called a minor loss coefficient, and is tabulated (e.g. Table 4) for various kinds of fittings.

Table 4: Minor Loss Coefficients for Different Fittings

Fitting Type	K
Tee, Flanged, Line Flow	0.2
Tee, Threaded, Line Flow	0.9
Tee, Flanged, Branched Flow	1.0
Tee, Threaded , Branch Flow	2.0
Union, Threaded	0.08
Elbow, Flanged Regular 90^o	0.3
Elbow, Threaded Regular 90^o	1.5
Elbow, Threaded Regular 45^o	0.4
Elbow, Flanged Long Radius 90^o	0.2
Elbow, Threaded Long Radius 90^o	0.7
Elbow, Flanged Long Radius 45^o	0.2
Return Bend, Flanged 180^o	0.2
Return Bend, Threaded 180^o	1.5
Globe Valve, Fully Open	10
Angle Valve, Fully Open	2
Gate Valve, Fully Open	0.15
Gate Valve, 1/4 Closed	0.26
Gate Valve, 1/2 Closed	2.1
Gate Valve, 3/4 Closed	17
Swing Check Valve, Forward Flow	2
Ball Valve, Fully Open	0.05
Ball Valve, 1/3 Closed	5.5
Ball Valve, 2/3 Closed	200
Diaphragm Valve, Open	2.3
Diaphragm Valve, Half Open	4.3
Diaphragm Valve, 1/4 Open	21
Water meter	7

NEED TO CITE SOURCE — I BET I TOOK FROM INTERNET

The use is straightforward, and multiple fittings are summed in the loss term in the energy equation.

Example What is the pressure drop across a valve with nominal diameter of 8 cm, a loss coefficient of 3.2, and a flow rate of 0.04 m^3/sec?

Solution First write the minor loss equation, solve for head loss.

$$h_l = K\frac{V^2}{2g} = (3.2)\frac{(\frac{4*0.04}{\epsilon\,(0.08)^2})^2}{2(9.8)} \approx 10.3m \tag{26}$$

Then convert the head loss into a pressure drop from

$$\epsilon g \approx h_l = \Delta p = 9800N/m^3 \approx 10.3m = 101,321Pa \approx 101kPa \tag{27}$$

1.4.1 Hydraulic and Energy Grade Lines

The terms of Equation 1 have dimensions of length and this result provides a useful physical relationship. The sum of pressure and elevation head (static head) is a length that liquid would rise in a piezometer attached to the system at a particular location. The locus of all such points in a hydraulic system (visualize piezometers every few feet) is called the hydraulic grade line (HGL). In an open conduit, the water surface is the hydraulic grade line.

The total head includes the static head and the velocity head. The locus of these points is called the energy grade line (EGL). Engineers from time to time find the ability to sketch HGL and EGL useful to locate potential trouble spots in a hydraulic system.

Hints for drawing HGL and EGL sketches are listed as follows:

1. The EGL is above the HGL by a distance equal to the velocity head at a location. If the velocity is zero, or small, as in a reservoir, the HGL and EGL will coincide with the liquid surface (e.g. Figure 6).
2. Head loss requires the EGL to slope downward in the direction of flow. The only exception is when a pump adds energy (and pressure) to the flow. In this instance an abrupt rise in the EGL occurs from the upstream side (suction) of the pump to the downstream side (discharge).
3. When energy is removed from the system as in a turbine, the EGL and HGL will drop abruptly (e.g. Figure 6).
4. An expansion can be used to gradually convert velocity head to pressure head, a sudden expansion is much less efficient and wastes energy (e.g. Figure 6).
5. In a pipe where the pressure is zero, the HGL is coincident with the water surface in the system because $p/\epsilon = 0$ at these points. This hint is useful for finding the HGL in a system such as the outlet of a pipe where liquid discharges to the atmosphere, or at the upstream end where the pressure is zero in a reservoir.

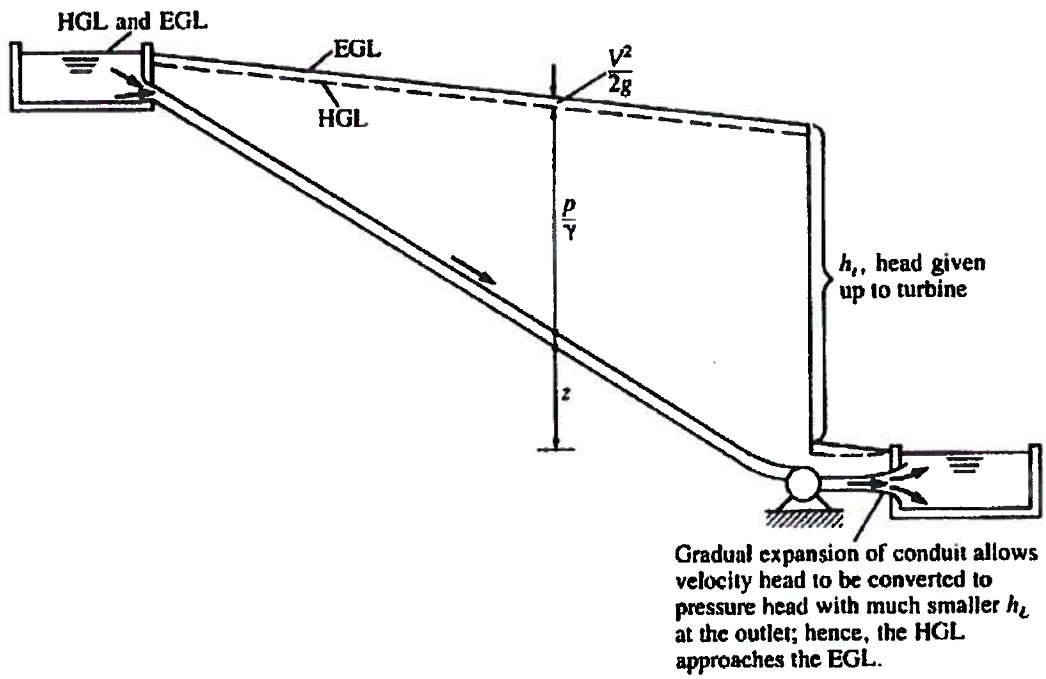

Figure 6: HGL and EGL and energy loss in a turbine system.

6. Steady flow in a pipe of constant cross section and material properties (roughness) requires the head loss per unit length be some constant; thus the slope of the EGL and HGL will be constant along that section of pipe.

7. When flow passes to a pipe of a different cross section or material property, the velocity will change and the distance between the EGL and HGL will change. Furthermore, the slope of the EGL will change because the head loss per unit length will be larger in the conduit with the greater velocity.

8. If the HGL falls below the elevation of the pipe, then the pressure head is negative, as depicted in Figure 7.

   If the negative head of the water is less than the vapor pressure head of the water (about -34 feet at STP), cavitation will occur. Cavitation is undesirable in engineered systems[3], causing increased head loss, structural damage from vibrations and pitting of the conduit wall. Similarily undesirable is when the pressure decreases to the vapor pressure and stays that low a large vapor cavity forms. When the liquid rejoins with a system pressure rise a huge dynamic pressure is formed as the vapor cavity collapses

[3]Except a sonicator,which uses cavitation to impart energy into a sample — however such devices are not common in civil engineering processes.

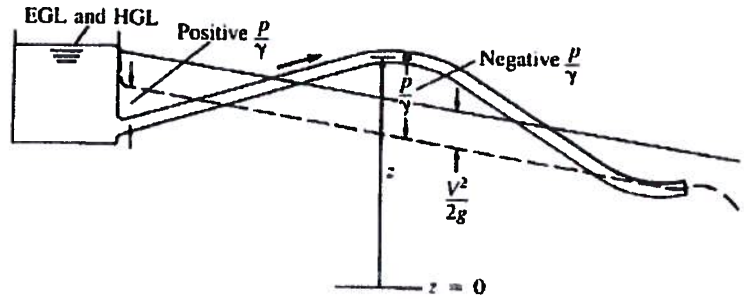

Figure 7: HGL and EGL in a negative pressure system.

(water hammer) and can rupture the pipe. If the pipe is thin walled, the negative pressure can cause the pipe itself to collapse (pinch). The engineer needs to be cautious in specifying sustained or high negative pressure in a system[4].

1.5 Head-Discharge Relations for Pumps and Turbines

Example
A water supply system draws from a river at an elevation of 800-feet and delivers the water to a storage reservoir at elevation 820-feet. The supply pipeline is a 1000-foot long, 10-inch diameter, cast iron pipe. Minor losses, entrance, and exit losses are neglected. A single pump with the pump characteristic curve in Figure 8 is used to fill the reservoir.

If friction loses are calculated using the Darcy-Weisbach equation with a friction factor of $f = 0.02$ estimate the head loss in the 1000-foot force main for a discharge of 1500 gallons-per minute.

Solution

Example
The system characteristics for the water supply above are listed in Table 5.

2.If friction loses are calculated using the Darcy-Weisbach equation with a friction factor of $f = 0.02$, what is the operating discharge for the pump under the system characteristics provided, and the electric power required in kilowatts?

Solution

[4]There will be times when negative pressure is intentional, such as in a high-vaccum system, the warning about negative pressure is for routine pipe systems.

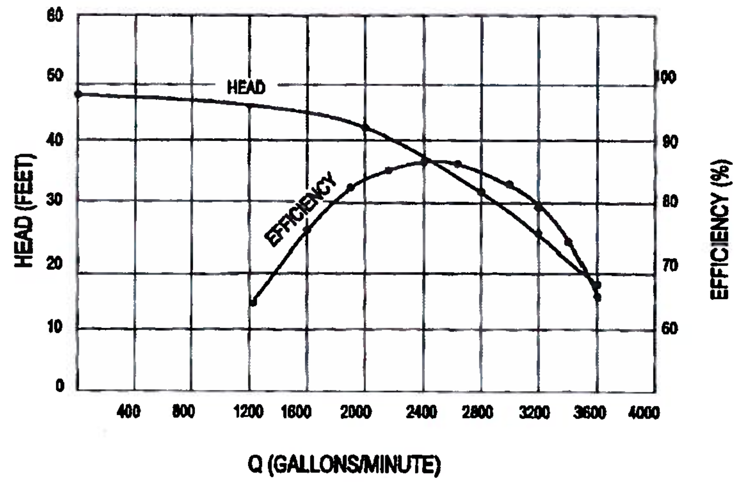

Figure 8: Pump characteristic curve

Table 5: Pumped-Storage System Performance Characteristics.

Discharge (gpm)	System Loss (feet)	Pumping Head (feet)
1,000	6.2	47
1,500	14.0	45
2,000	24.9	44
2,500	39.0	34
3,000	52.6	28

1.6 Non-circular conduits

The Darcy-Weisbach head loss equation is shape independent, although to this point in the discussion circular cross section is assumed. Non-circular conduits are examined using the hydraulic-radius concept which is the ratio of flow area to wetted perimeter.

$$R_h = \frac{A}{P_w} \tag{28}$$

For a circular pipe the result is

$$R_h = \frac{\frac{\epsilon D^2}{4}}{\epsilon D} = \frac{D}{4} \tag{29}$$

The hydraulic radius appears in the Hazen-William's formula as well as Manning's formula, both of which are head loss models used in hydraulic engineering. In the Hazen-William's equation above the hydraulic radius was used to render the loss equation in terms of pipe diameter. If the conduit is of some other shape, then the hydraulic radius is used directly in the head loss computation.

1.6.1 Manning's head loss model

Another head loss model in use is Manning's equation applied to a conduit.

$$V = \frac{1.49}{n} R_h^{2/3} S^{1/2} \tag{30}$$

Rearranged in terms of head loss the equation is

$$h_f = L \frac{n^2 V^2}{2.22 R^{4/3}} \tag{31}$$

The use of Manning's equation in this form is observed in storm sewer design, and large diameter pipelines. In Texas the Hazen-Williams formula appears in the Texas Administrative code and various municipal design manuals and is probably the default model in common use in small diameter (less than 6 feet) distribution systems.

The actual model selected is computationally (and hydraulically) irrelevant, all three return about the same head loss for identical conditions, so the model selection becomes one of convenience and statute. If the problem involves liquid other than water, then the Darcy-Weisbach model is the most appropriate; neither Manning's nor Hazen-Williams capture specific fluid properties such a density or viscosity.