TREATMENT PLANT HYDRAULICS FOR ENVIRONMENTAL ENGINEERS

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PREFACE

The design of water and wastewater treatment plants involves both *process design* and *hydraulic design*. Each of these segments of design must be performed correctly if the treatment plant is to function properly and provide the desired degree of treatment. Most engineering courses are structured to emphasize process mechanisms and control variables and thus prepare students to perform *process design*. In addition, many textbooks are available to which engineers can turn for information on this subject.

Unfortunately, the *hydraulic design* of water and wastewater treatment plants is largely ignored in most engineering curricula. Undergraduate courses in fluid mechanics and hydraulics emphasize fundamentals and introduce problems on pipe flow, pumps, and open channel flow. Environmental engineering courses may address the hydraulics of a particular process, such as a rapid sand filter, but usually do not consider overall plant hydraulics. Consequently, many graduates are not familiar with the hydraulic design of treatment plants and, since hydraulic design is normally not included in engineering course work, textbooks specifically intended to provide guidance on the subject are not currently available.

The authors feel that a need exists for a book that brings together the information required for the *hydraulic design* of water and wastewater treatment facilities. This book was written in an attempt to help satisfy that need. The reader is assumed to have at least an elementary background in the principles of fluid mechanics. It is also assumed that the reader has an acquaintance with the utilization of digital computers to solve scientific problems.

The first five chapters provide a review of hydraulic fundamentals, emphasizing components and situations commonly encountered in treatment plant design. Chapter 6 presents a step-by-step example of the hydraulic design of an activated sludge treatment plant. The example does not attempt to optimize plant hydraulics and, in fact, an effort is made to introduce a variety of components and conditions that may not be found in a typical treatment plant. The example is intended to illustrate the importance of hydraulic control points in plant design and to show the reader the manner in which various units must operate compatibly to provide the desired flow profile. Once these concepts are understood, the reader should be able to adapt them to any plant configuration or processes dictated by a particular situation.

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FLOW IN PIPES

The purpose of this chapter is to review briefly the hydraulic fundamentals required to solve problems related to the flow of water in pipes. It is appropriate to begin with a discussion of the types of flow a design engineer is likely to encounter. The two fundamental types of fluid flow are known as laminar and turbulent. *Laminar flow* is characterized by fluid particles that move in straight lines or parallel layers, whereas *turbulent flow* is characterized by random movement of fluid particles (see Fig. 1-1). According to Brater and King (1976), the greater energy loss in turbulent flow is probably the most important practical difference between laminar and turbulent flow.

On the basis of discharge, a flow may be classified as steady or unsteady. In *steady flow*, the discharge and depth at a particular cross section do not vary with time. The flow is *unsteady* when the discharge or depth at a particular point varies with time. A steady or unsteady flow may be described as spatially variable, uniform, or nonuniform. *Spatially variable flow* (a subclassification of nonuniform flow) occurs when the discharge varies along a specified reach or length of channel. *Uniform flow* occurs when the cross-sectional area of the fluid remains constant along a specified reach of channel, while *nonuniform flow* arises when the cross-sectional area of the fluid varies along a specified length of channel (see Fig. 1-2).

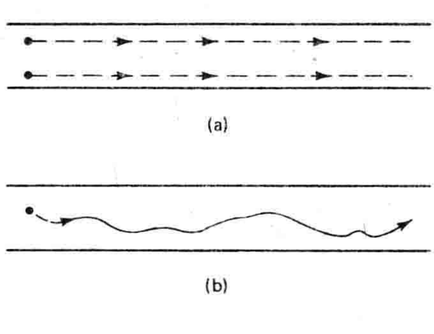


FIGURE 1-1 *(a) Laminar flow; (b) turbulent flow.*

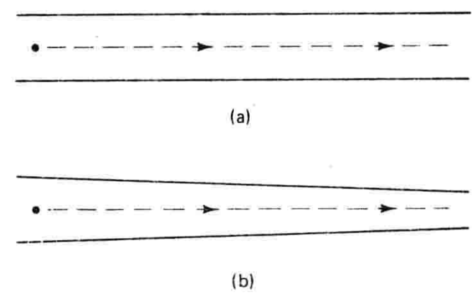


FIGURE 1-2 (a) Uniform flow; (b) nonuniform flow.

1.1 CONSERVATION LAWS

The conservation laws of mass, momentum, and energy are the three fundamental concepts used in the solution of problems related to fluid flow. The simplified equations derived from the conservation principles of mass, energy, and momentum are commonly called the continuity equation, the Bernoulli equation, and the linear momentum equation, respectively.

Conservation of Mass

According to the Law of Conservation of Mass, material is neither created nor destroyed. Hence, any mass of material that enters a system must either accumulate in the system or leave the system. This fundamental statement is expressed by Eq. (1-1).

$$\begin{bmatrix}\text{Accumulation}\\ \text{of mass in}\\ \text{the system}\end{bmatrix} = \begin{bmatrix}\text{total mass of}\\ \text{material that has}\\ \text{entered system}\end{bmatrix} - \begin{bmatrix}\text{total mass of}\\ \text{material that has}\\ \text{entered system}\end{bmatrix} \qquad \textbf{(1-1)}$$

The majority of the systems encountered in hydraulic design are continuous flow systems. For this case Eq. (1-1) has the form

$$\begin{bmatrix}\text{Rate of accumulation}\\ \text{of mass in the}\\ \text{system}\end{bmatrix} = \begin{bmatrix}\text{total rate of}\\ \text{mass flow}\\ \text{into system}\end{bmatrix} - \begin{bmatrix}\text{total rate of}\\ \text{mass flow out}\\ \text{of the system}\end{bmatrix} \qquad \textbf{(1-2)}$$

This situation is illustrated schematically in Fig. 1-3. In this figure Q represents the volumetric flow rate (i.e., volume of fluid flowing per unit time). A mathematical relationship that describes the situation presented in Fig. 1-3 is

$$\rho_{\text{basin}}\left[\frac{\Delta \forall}{\Delta t}\right] = \rho_{\text{in}}Q_{\text{in}} - \rho_{\text{out}}Q_{\text{out}} \qquad \textbf{(1-3)}$$

where ρ represents the mean fluid density and $\forall$ represents volume within control.

In a case where there is no storage (such as a pipe flowing full) Eq. (1-3) reduces

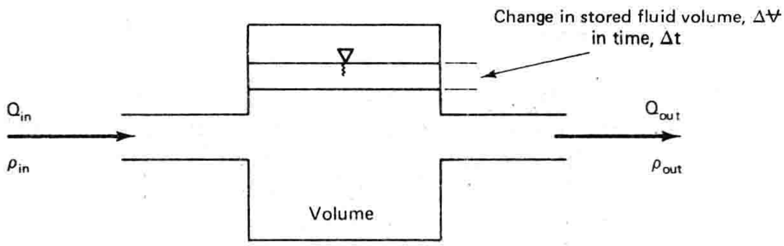


FIGURE 1-3 *Schematic representation of conservation of mass.*

to the form

$$0 = \rho_{\text{in}} Q_{\text{in}} - \rho_{\text{out}} Q_{\text{out}} \tag{1-4}$$

or for incompressible fluids

$$Q_{\text{in}} = Q_{\text{out}} \tag{1-5}$$

Note: ρ may not be constant even for incompressible fluids. However, most wastewaters are considered to have a constant density.

The volumetric flow rate may be expressed in terms of velocity and area as

$$Q = AV \tag{1-6}$$

where Q = volumetric flow rate, length^3 time^{-1}
A = cross-sectional area of flow, length^2
V = average velocity of the flow through the section, length time^{-1}

Substituting for Q in Eq. (1-5) from Eq. (1-6) gives

$$(AV)_{\text{in}} = (AV)_{\text{out}} \tag{1-7}$$

EXAMPLE PROBLEM 1-1: A 4-in. pipe is connected to a 6-in. pipe. If the average velocity of flow in the 6-in. pipe is 20 ft/sec (fps), what is the average velocity of flow in the 4-in. pipe?

Solution: Apply Eq. (1-7) and solve for velocity in the 4-in. section.

$$V_4 = \frac{A_6 V_6}{A_4}$$

$$= \frac{[\pi(6/12)^2/4](20)}{[\pi(4/12)^2/4]}$$

$$V_4 = \mathbf{45\ fps}$$

Conservation of Energy

In most hydraulic problems encountered by environmental engineers, two forms of energy are important. These are kinetic and potential energy. The kinetic energy of a mass, m, moving with a velocity, V, is given by $mV^2/2$. Two types of potential energy are of interest. The first type is related to the height of the mass above an arbitrary datum (elevation), Z, and the acceleration due to gravity, g, and is given by mgZ. The second type of potential energy is due to the pressure, p, of the flowing fluid and is given by pm/ρ. These different types of energy may be summed to give an expression for total energy.

$$E_T = \frac{mV^2}{2} + mgZ + \frac{pm}{\rho} \tag{1-8}$$

Equation (1-8) is more useful when expressed on a total energy per unit mass of fluid basis. This can be accomplished by dividing Eq. (1-8) by mass of fluid.

$$\frac{E_T}{m} = \frac{V^2}{2} + gZ + \frac{p}{\rho} \tag{1-9}$$

This equation assumes one-dimensional flow where the velocity is constant at a cross section. When nonuniform velocity profiles are considered, the velocity head term must be multiplied by the kinetic energy correction factor.

The Law of Conservation of Energy is a statement of the First Law of Thermodynamics, which says that energy cannot be created or destroyed but can be transformed from one form to another. Consider the pipe section presented in Fig. 1-4. As fluid flows between sections 1 and 2, fluid friction will convert some of the useful energy into heat energy. Hence, when writing a flow energy balance between sections 1 and 2, the energy loss due to friction must be accounted for.

$$\frac{(E_T)_1}{m} = \frac{(E_T)_2}{m} + \frac{(E_T)_L}{m} \tag{1-10}$$

where $(E_T)_L/m$ represents the useful energy loss due to friction per unit mass of fluid. Substituting for the energy terms in Eq. (1-10) from Eq. (1-9) gives

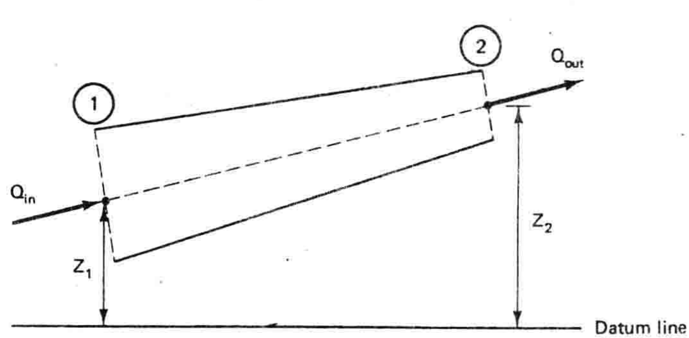


FIGURE 1-4 Flow section for the development of the Bernoulli equation.

$$\frac{V_1^2}{2} + gZ_1 + \frac{p_1}{\rho} = \frac{V_2^2}{2} + gZ_2 + \frac{p_2}{\rho} + \frac{(E_T)_L}{m} \tag{1-11}$$

If mechanical energy is added to or taken from the fluid over the section of interest, this must be accounted for in the energy balance equation. In this regard, a pump adds mechanical energy to the system, while a turbine extracts mechanical energy from the system.

The Bernoulli equation is obtained by dividing each term in Eq. (1-11) by the acceleration of gravity so that each term will have the dimension of length

$$\frac{V_1^2}{2g} + Z_1 + \frac{p_1}{\gamma} = \frac{V_2^2}{2g} + Z_2 + \frac{p_2}{\gamma} + h_L \tag{1-12}$$

where γ represents the specific weight of the fluid (i.e., $g\rho$) and h_L represents the energy loss per unit mass of fluid due to friction. Because each term in Eq. (1-12) has the units of length, each term is referred to as a type of head. *Velocity head* is the designation given to the $V^2/2g$ term, whereas the Z term is called *elevation head,* the p/γ term is called *pressure head,* and the h_L term is called *head loss.*

The sum of the velocity head, the elevation head, and the pressure head is referred to as the *total head,* whereas the sum of only the pressure head and the elevation head is called the *piezometric head.* Piezometric head represents the height to which fluid would rise in a pipe with one of its ends inserted into the flow field perpendicular to the direction of flow. The hydraulic grade line (HGL) is a line that shows how the piezometric head varies over a particular reach of the system of interest, whereas the energy grade line (EGL) indicates the variation in the total head over the reach of interest. The hydraulic grade line and the energy grade line are illustrated for a particular flow system in Fig. 1-5. The difference in elevation between the EGL and the HGL is the velocity head, $V^2/2g$.

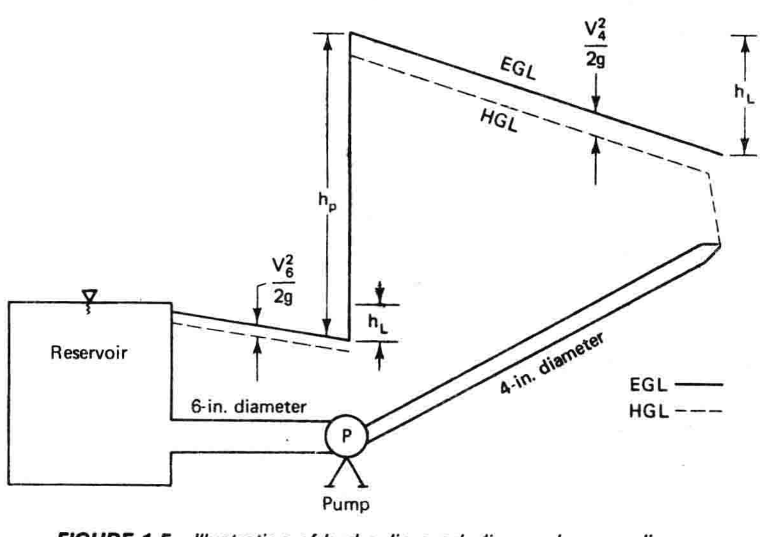


FIGURE 1-5 *Illustration of hydraulic grade line and energy line.*

Equation (1-12) may also be applied to open channel flow problems, so long as points 1 and 2 are taken along the same streamline (e.g. along the water surface).

EXAMPLE PROBLEM 1-2: Calculate the head loss due to friction and other factors in the piping system shown below. The pipe is 12 in. in diameter and 500 ft long and passes a flow of 40 cfs. The water discharges as a free jet at a point 2.

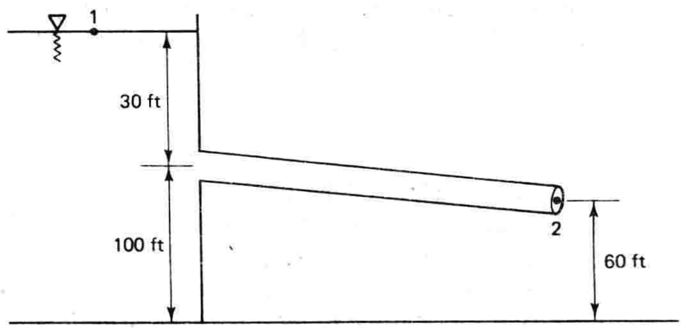


FIGURE P1-2

Solution:

1. Write the Bernoulli equation between points 1 and 2.

$$\frac{V_1^2}{2g} + \frac{p_1}{\gamma} + Z_1 = \frac{V_2^2}{2g} + \frac{p_2}{\gamma} + Z_2 + h_L$$

2. Evaluate each term in the Bernoulli equation and solve for h_L. Since both points 1 and 2 are at atmospheric pressure, the pressure head at both points is zero. Neglecting the fluid velocity in the reservoir and solving the Bernoulli equation for h_L gives

$$h_L = (Z_1 - Z_2) - \frac{V_2^2}{2g}$$

$$h_L = 70 - \frac{Q^2}{2gA^2}$$

$$= 70 - \frac{(40)^2}{64.4(\pi)^2\,(0.5)^4}$$

$$h_L = \mathbf{29.7\ ft}$$

Conservation of Momentum

Momentum is defined as the product of mass and velocity. Hence, for an incompressible fluid, the rate at which momentum is carried across a section is defined mathematically as

$$\overline{M} = \rho Q V \qquad \textbf{(1-13)}$$

where $\overline{M}$ = momentum flux at the section, mass length time^{-2}

ρ = density of fluid, mass length^{-3}

Q = volumetric flow rate, length^3 time^{-1}

V = average velocity at the section, length time^{-1}

Substituting for Q in Eq. (1-13) from Eq. (1-6) produces an alternate form of Eq. (1-13)

$$\overline{M} = \rho A V^2 \tag{1-14}$$

where A represents the cross-sectional area of flow.

The Law of Conservation of Momentum states that the sum of the external forces acting on a fluid system equals the rate of change of momentum of the system. For example, consider steady flow through the pipe bend shown in Fig. 1-6. The momentum carried across areas A_1 and A_2 in time Δt are given, respectively, by

$$M_1 = (\rho Q \Delta t)V_1 = (\rho A_1 V_1 \Delta t)V_1 \tag{1-15}$$

$$M_2 = (\rho Q \Delta t)V_2 = (\rho A_2 V_2 \Delta t)V_2 \tag{1-16}$$

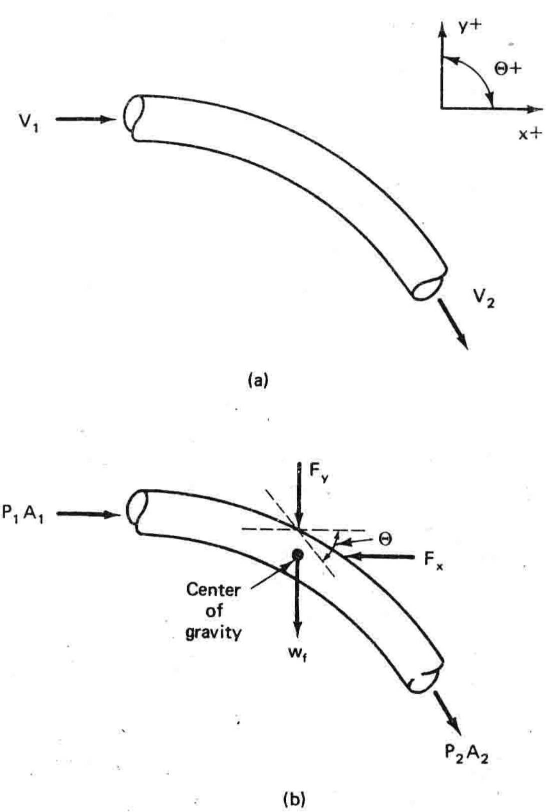


FIGURE 1-6 *Pipe bend to illustrate momentum principle.*

The change in momentum between A_1 and A_2 is, therefore,

$$\Delta M = (\rho A_2 V_2 \Delta t)V_2 - (\rho A_1 V_1 \Delta t)V_1$$

The net force acting on the fluid between A_1 and A_2 is, thus, equal to the *rate of change of momentum* between A_1 and A_2. Hence

$$\Sigma F = \frac{\Delta M}{\Delta t}$$

or

$$\Sigma F = \frac{(\rho Q \Delta t)V_2 - (\rho Q \Delta t)V_1}{\Delta t} \tag{1-17}$$

where ΣF = net force acting on the fluid between A_1 and A_2

Equation (1-17) is a vector equation. Considering the free body diagram shown in Fig. 1-6(b), it is also possible to write the component equation of Eq. (1-17) in the x and y directions as follows:

$$\Sigma F_x = \begin{bmatrix}\text{net force acting on the}\\ \text{fluid in the } x \text{ direction}\end{bmatrix} = \begin{bmatrix}\text{rate of change in momentum}\\ \text{in the } x \text{ direction}\end{bmatrix}$$

or

$$p_1A_1 - F_x - p_2A_2 \cos \Theta = \rho Q(V_2 \cos \Theta - V_1) \tag{1-18}$$

$$\Sigma F_y = \begin{bmatrix}\text{net force acting on the}\\ \text{fluid in the } y \text{ direction}\end{bmatrix} = \begin{bmatrix}\text{rate of change in momentum}\\ \text{in the } y \text{ direction}\end{bmatrix}$$

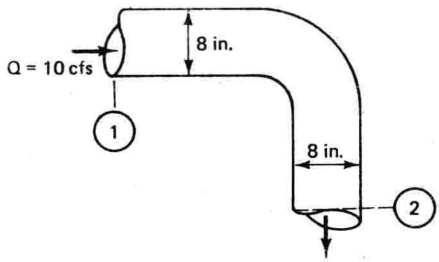
or

$$p_2A_2 \sin \Theta - W_F - F_y = -\rho Q V_2 \sin \Theta \tag{1-19}$$

where W_F is the weight of the fluid in the bend section. The negative sign on the right-hand side of Eq. (1-19) arises because the velocity component at point 2 is in the negative y direction.

For the two-dimensional case, Eqs. (1-18) and (1-19) represent the two forms of the *momentum equation*. This equation is important in many hydraulic problems. It is often employed in conjunction with the continuity equation and many times additionally with the Bernoulli equation. One of the most common applications of the momentum equation is to solve problems where a *change in velocity* or *direction* occurs.

EXAMPLE PROBLEM 1-3: An 8-in. pipeline carries a flow of 10 cubic feet per second (cfs). Compute the magnitude of the force exerted by the fluid on the pipe when the flow passes through a 90° bend. Assume the pipe is horizontal.

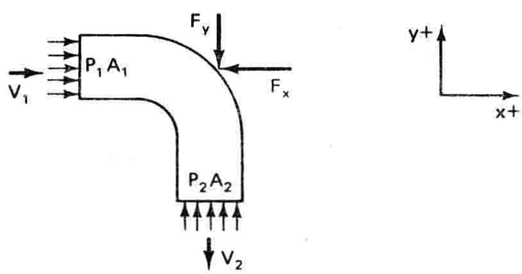


(a) **FIGURE P1-3a**

The pipe discharges into the atmosphere at point 2. Assume the head loss through the bend is given by $h_L = 0.21\ V_1^2/2g$.

Solution:

1. Construct the free body diagram of the flow section.



(b) **FIGURE P1-3b**

2. Compute the average velocity of flow through the pipeline.

$$V_1 = V_2 = \frac{Q}{A}$$

$$= \frac{3}{[\pi(8/12)^2/4]}$$

$$= \mathbf{8.6\ fps}$$

3. Write Bernoulli's equation between sections 1 and 2 and evaluate the pressure at each section.

$$\frac{V_1^2}{2g} + Z_1 + \frac{p_1}{\gamma} = \frac{V_2^2}{2g} + Z_2 + \frac{p_2}{\gamma} + h_L$$

Since the pipe is horizontal, $Z_1 = Z_2$. Because the pipe discharges into the