$$F = m\frac{dv}{dt} = \rho Q \Delta v = \rho Q(v_2 \rightarrow v_1) = (\gamma/g)Q(v_2 \rightarrow v_1) \quad (3\text{-}8)$$

where F is the sum (resultant) of all forces acting, ρ is mass density, Q is flow rate or discharge, the arrow sign indicates vectorial subtraction (change of velocity), γ is specific weight, and g is acceleration due to gravity.

A force acting on a free jet to deflect it is applied by the curved vane in Figure 3-3. Vectorial subtraction is made by changing the sign of vector $\rho Q v_1$ then adding it vectorially (as depicted in Figure 3-3b or 3-3c) to obtain F. The reaction of the jet against the vane is equal and opposite.

The momentum equation is needed to find the required strength of tie-downs, anchors, and thrust blocks to restrain piping at elbows, tees, etc. An example of the use of Equation 3-8 is given in Section 3-8.

3-2. Friction Losses in Piping

The first well-known formula for flow in pipes was proposed by deChezy. The deChezy friction coefficient was given by a complicated equation developed by Kutter. These formulas are no longer in common use. The Hazen–Williams (H–W) formula has been used in the United States for 90 yr. It is simple and easy to use, it has been verified by many field observations for common sizes of pipes at conventional flow rates, and its use is even mandated in the Ten-State Standards [1]. It has, however, some serious limitations. (See the next subsection, Hazen–Williams Equation.)

The Manning equation (Section 3-5) is somewhat similar to the H–W formula and is subject to the same limitations. It is widely used in the United States for open channel flow, such as pipes that are partly full. Sometimes it is used for full pipes, but for that application it has no advantage over the H–W formula.

The Colebrook–White equation is more accurate than the H–W formula and is applicable to a wider range of flow, pipe size, and temperature. It is widely used in the United Kingdom and elsewhere in Europe.

The Darcy–Weisbach equation is the only rational formula, and it is applicable to turbulent, laminar, or transitional flow, all sizes of pipe, and any incompressible Newtonian fluid at any temperature. It has not been popular because, being an implicit equation, it must be solved by successive trials. It was therefore inconvenient to use, but now, modern computers (even programmable pocket calculators) can be used to solve the equation in seconds.

In this text, only the H–W, Manning, and Darcy–Weisbach equations are discussed. Benedict [2] has discussed formulas for pipe flow extensively.

Hazen–Williams Equation and a Warning

The Hazen–Williams (H–W) equation, developed from extensive reviews of data on pipes installed all over the world, was made public in 1905 [3]. The appeal of the equation is due partly to its simplicity and ease of use, partly to the source of the data (real pipes in the field—not just laboratory pipes), and, by now, to a tradition of nearly a century of use and a blind faith in the results. Unfortunately, the formula is irrational; it is valid only for water at or near room temperature and flowing at conventional velocities; the flow regime must be in the transition zone (see Figure B-1); the C factor varies with pipe size; and 92% of the pipes studied were smaller than 1500 mm (90 in.) in diameter. These disadvantages seem to be generally ignored, but errors can be appreciable (up to 40%) for pipes less than 200 mm (8 in.) and larger than, say, 1500 mm (60 in.), for very cold or hot water, and for unusually high or low velocities. In field tests of a municipal water system only five years

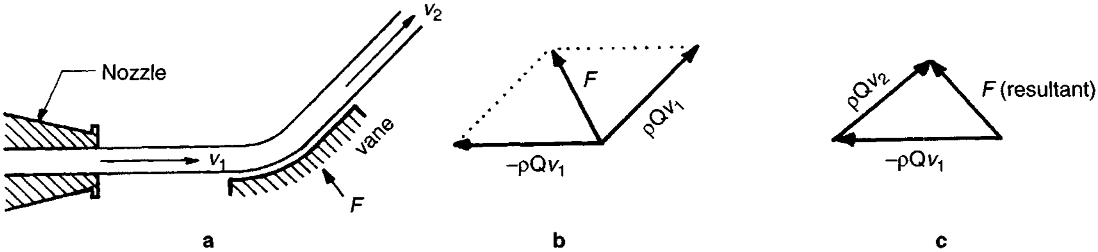

Figure 3-3. Impulse momentum. (a) Schematic diagram; (b) vector diagram; (c) equivalent vector diagram.

old, Bombardelli and Garcia [4] found the C value was only 91 for a 2250-mm (90-in.) pipe and 103 for a 1800-mm (72-in.) pipe, in contrast to the value of 120 used for design and thought to be conservative for good masonry. The low values were caused by deposits in the form of small scales several mm thick covering the inside surface. One long transmission main develops slimes that gradually reduce the C value from about 135 to 110. After a concentrated slug of chlorine is introduced, the C reverts to about 135 again. The errors in applying *any* formula for friction loss can be substantial and the consequences serious even for fairly new pipe. Consequently, prudent engineers use a *range* of coefficients to define a probable region of losses that may be encountered during the expected service life of the system.

The original form of the Hazen–Williams equation was developed in U.S. units. In SI units, the equation is

$$v = 0.849CR^{0.63}S^{0.54} \tag{3-9a}$$

where v is velocity in meters per second, C is a coefficient ranging from about 80 for very rough pipes to 150 for smooth pipes, R is the hydraulic radius in meters, and S is the friction headloss per unit length or slope of the energy grade line in meters per meter. The hydraulic radius is defined as the water cross-sectional area divided by the wetted perimeter. For full pipes, R reduces to $D/4$ where D is the ID.

In U.S. customary units, the equation is

$$v = 1.318CR^{0.63}S^{0.54} \tag{3-9b}$$

where v is in feet per second, R is in feet, and S is in feet per foot.

Friction headloss is expressed more conveniently as the gradient, h_f, in meters per 1000 m (or feet per 1000 ft) instead of S. Velocity can also be expressed as flow rate, Q, divided by water cross-sectional area, A. Substituting and rearranging Equation 3-9 yields another, somewhat more convenient form. In SI units,

$$h_f = \left[10{,}700\left(\frac{Q}{C}\right)^{1.85}\right]D^{-4.87} = \left(\frac{151Q}{CD^{2.63}}\right)^{1.85} \tag{3-10a}$$

where h_f is meters per 1000 m, Q is cubic meters per second, and D is pipe diameter in meters. Values of C are given in Table B-5 (Appendix B).

Equation 3-10b, expressed in U.S. customary units, is

$$h_f = \left[10{,}500\left(\frac{Q}{C}\right)^{1.85}\right]D^{-4.87} = \left(\frac{149Q}{CD^{2.63}}\right)^{1.85} \tag{3-10b}$$

where h_f is feet per 1000 ft, Q is gallons per minute, D is pipe diameter in inches, and C, again, is given in Table B-5 (Appendix B).

See Subsection "Friction Coefficients" for a discussion of the H–W C factor and Subsection "Warning" for reliance on answers that may be in error.

Darcy–Weisbach Equation

The equation for circular pipes is

$$h = f\frac{L}{D}\frac{v^2}{2g} \tag{3-11}$$

where h is the friction headloss in meters (feet), f is a coefficient of friction (dimensionless), L is the length of pipe in meters (feet), D is the inside pipe diameter in meters (feet), v is the velocity in meters per second (feet per second), and g is the acceleration of gravity, 9.81 m/s^2 (32.2 ft/s^2). The advantages of the Darcy–Weisbach equation are as follows:

- It is based on fundamentals.
- It is dimensionally consistent.
- It is useful for any fluid (oil, gas, brine, and sludges).
- It can be derived analytically in the laminar flow region.
- It is useful in the transition region between laminar flow and fully developed turbulent flow.
- The friction factor variation is well documented.

The disadvantage of the equation is that the coefficient f depends not only on roughness but also on Reynolds number, a variable that is expressed as

$$\boldsymbol{R} = \frac{vD}{\boldsymbol{\nu}} \tag{3-12}$$

where $\boldsymbol{R}$ is Reynolds number (dimensionless), v is velocity in meters per second (feet per second), D is the pipe ID in meters (feet), and $\boldsymbol{\nu}$ is kinematic viscosity in square meters per second (square feet per second) as given in Appendix A, Tables A-8 and A-9.

Determination of *f*

In the laminar flow region where $\boldsymbol{R}$ is less than 2000, f equals $64/\boldsymbol{R}$ and is independent of roughness. Between

Reynolds numbers of 2000 and about 4000, flow is unstable and may fluctuate between laminar and turbulent flow, so f is somewhat indeterminate. When R is very large (greater than about 10^5), the flow is fully turbulent and f depends only on roughness. In the transition zone between turbulent and laminar flow, both roughness and R affect f, which can be calculated from a semi-analytical expression developed by Colebrook [5]:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{R\sqrt{f}}\right) \tag{3-13}$$

where ε is the absolute roughness in millimeters (or inches or feet) and D is the inside diameter in millimeters (or inches or feet), so that ε/D is dimensionless. The Moody diagram, Figure B-1 (Appendix B), was developed from Equation 3-13 [6]. Note that the curves are asymptotic to the smooth-pipe curve (at the left). To the right, curves calculated from the Colebrook (also called Colebrook–White) equation are indistinguishable from the horizontal lines for fully developed turbulent flow given in Prandtl [7]. The probable variation of f for commercial pipe is about $\pm 10\%$, but this variation is masked by the uncertainty of quantifying the surface roughness.

An explicit, empirical equation for f was developed by Swamee and Jain [8]:

$$f = \frac{0.25}{\left[\log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{5.74}{R^{0.9}}\right)\right]^2} \tag{3-14}$$

The value of f calculated from Equation 3-14 differs from f calculated from the Colebrook equation by less than 1%.

Friction headloss can be determined from the Darcy–Weisbach equation in a number of ways:

- Use one of the Appendix tables (B-1 to B-4) to find the appropriate pipe size. Compute R, find f from the Moody diagram, and compute an accurate value of h from the Darcy–Weisbach equation. Because f changes only a little for large changes of R, no second trial is needed. Compare the h so obtained with the value in Tables B-1 to B-4 for an independent check.
- Program Colebrook's Equation 3-13 to find f as an iterative subroutine for solving Equation 3-11 with a computer. Once programmed (a simple task even for a hand-held, card-programmable calculator), any pipe problem can be solved in a few seconds.
- Use the Swamee–Jain expression for f in the Darcy–Weisbach equation. Equation 3-14 could even be used as a first approximation for iteration of Equation 3-13.
- Refer to the extensive tables of flow by Ackers [9].
- Program the Moody diagram on a computer by assuming it to consist of a family of short, straight lines [10].
- Guess the pipe size and thus estimate v, calculate R, find f from the Moody diagram, and compute h from the Darcy–Weisbach formula. Revise v and D, if necessary, and recompute.

Other Pipe Formulas

There are many formulas for flow in pipes, but none is easier to use than the Hazen–Williams, and none is more accurate or universally applicable than the Darcy–Weisbach supplemented by the Moody diagram or the Colebrook equation. The limitation of the accuracy of all pipe formulas lies in the estimation of the proper coefficient of friction, a value that cannot be physically measured and, hence, is subject to large error (see Subsection "Friction Coefficients").

Comparison of f and C

The Darcy–Weisbach friction factor can be compared to the Hazen–Williams C factor by solving both equations for the slope of the hydraulic grade line and equating the two slopes. Rearranging the terms gives, in SI units,

$$f = \left(\frac{1}{C^{1.85}}\right)\left(\frac{134}{v^{0.15}D^{0.167}}\right) \tag{3-15a}$$

where v is in meters per second and D is in meters. In U.S. customary units, the relationship is

$$f = \left(\frac{1}{C^{1.85}}\right)\left(\frac{194}{v^{0.15}D^{0.167}}\right) \tag{3-15b}$$

where v is in feet per second and D is in feet. For any given pipe and velocity, the relation between ε/D and C can be found by calculating f from Equation 3-15 and entering the Moody diagram with R and f to find ε/D.

Friction Coefficients—Warning

The major weakness of any headloss formula is the uncertainty in selecting the correct friction coefficient. The proper friction factor for new pipe is uncertain because of the variation in roughness of the pipe walls, quality of installation, effect of slight angular offsets in laying the pipe, and water quality. For example, the H–W C factor should be reduced by 5 units for pipe laid in hilly regions due to the angular deflection at joints.

Anticipating the friction factor after years of service is doubly difficult due to changes caused by corrosion, deposition of minerals or grease, or attachment of bacterial slimes. Estimation of the friction coefficient merits judicious attention.

A century ago, unlined cast-iron water pipe (or cast iron with the then-common but short-lived bituminous linings) did indeed become coated with tubercles and, thus, became very rough in a few years. But the modern use of cement mortar or plastic linings for ductile iron and steel pipe has eliminated the devastating effect of rust and tuberculation on friction. Plastic pipe remains very smooth unless foreign matter collects on the walls. Chemical precipitates (from water treatment) and bacterial slime in water pipes and grease or debris deposits in sewers can greatly increase the interior pipe roughness independently of the pipe material. This subject is addressed in more detail below.

Hazen–Williams C Factor

The basis of the Hazen–Williams C factor in Equation 3-9 has resulted in some confusion. The factor is a function not only of the smoothness of the pipe wall, but also of the difference between the actual ID of the pipe and the nominal pipe size. The calculation of C from field data is, by custom, based on the nominal diameter of the pipe. One could scarcely do otherwise, because finding the ID of a buried pipe is somewhat difficult and costly. Physical measurement at one point does not guarantee the ID at other points, so the best method is the use of tracers to measure the true average diameter. (See Section 3-9.) The use of nominal (not true average) diameters leads to strange conclusions. For example, the C value of an uncoated, new Class 50 ductile iron pipe 300 mm (12 in.) in diameter is typically given as 130. A Class 56 pipe carries 94% as much water, so its C value should be 122, but such a listing is unlikely to be found. The ratio of actual to nominal diameter accounts for the difference between the published C values for ductile iron pipe (DIP) and steel pipe with its smaller bore when both are lined with cement mortar. The confusion over the proper C value to use is worsened because the nominal diameter of steel pipe 300 mm (12 in.) and smaller is the ID, whereas for larger pipe, the nominal diameter is the OD. To permit reasonably accurate estimation of friction losses, the C value ought to be selected for the type of lining, thus allowing the true ID to be applied to the Hazen–Williams equation.

Matters are not improved by the apparent increase of C with diameter. According to AWWA Manual M11 [11], the average value of C for pipe with smooth interior linings can be approximated as $C = 140 + 0.17d$, where d is inside pipe diameter in inches. After a long term of lining deterioration, slime buildup, etc., $C = 130 + 0.16d$. However, above a diameter of about 900 or 1200 mm (36 or 48 in.), there is little increase in C values according to Gros [12], who has had many years of experience in measuring C values in the field. The values of C listed in the first part of Table B-5 reflect this experience.

In addition to the discussion above, there are other limitations on the value of C. Values of C less than 100 are only applicable for velocities reasonably close to 1 m/s (3 ft/s). At other velocities, the coefficients are somewhat in error. For water pipes, Lamont [13] advises the following:

- C values of 140 to 150 are suitable for smooth (or lined) pipes larger than 300 mm (12 in.).
- For smaller smooth pipes, C varies from 130 to 140 depending on diameter.
- C values from 100 to 150 are applicable in the transitional zone (between laminar and turbulent flow), but the scale effect for different diameters is not included in the formula.
- The formula is unsuitable and, hence, not recommended for old, rough, or tuberculated pipes with C values below 100.
- Force mains for wastewater can become coated with grease and C values may vary down to 120 or less for severe grease deposition.

Linings

Before 1950, it was common to line steel and cast-iron pipe with hot coal-tar dip, which provided poor protection and allowed C values to drop from 130 for new pipe to 100 or less for pipe in service for 20 yr or more [14]. The modern use of cement mortar or plastic linings makes pipe very smooth, prevents corrosion and tuberculation, and maintains its smoothness indefinitely. In field measurements [15] made all over the United States on new water pipe with diameters of 100 to 750 mm (4 to 30 in.) lined with cement mortar, the values of C varied from 134 to 151 (median = 149, average = 144). For 150- to 900-mm (6- to 36-in.) pipe in service for 12 to 39 yr, C varied from 125 to 151 (median = 139, average = 140)—a decrease of only about 5 units.

Shop lining applied to DIP is usually one layer of cement mortar centrifugally cast with minimum thicknesses varying from 1.6 mm ($\frac{1}{16}$ in.) for small pipe to 3.2 mm ($\frac{1}{8}$ in.) for large pipe and given a thin asphaltic seal coat to control curing per ANSI/AWWA C104/A21.4. Optionally, a double thickness can be specified. The thicknesses of actual linings may vary considerably from those specified. These linings are so thin that many engineers specify double thickness to ensure adequate coverage, eliminate the danger of pinholes, and provide greater integrity. Shop linings applied to steel pipe can be coal-tar, enamel, thin plastic, or thick cement mortar varying from 6 to 13 mm ($\frac{1}{4}$ to $\frac{1}{2}$ in.) per AWWA C205. Cement mortar lining for steel pipe is customarily three to four times as thick as for DIP. See Table 4-6.

Field-applied cement-mortar linings, according to Table 4-7, can vary from 3 to 13 mm ($\frac{1}{8}$ to $\frac{1}{2}$ in.). Considering all the possibilities for pipe thickness and for shop and field linings, inside diameters can vary substantially. Designers should determine the metal IDs from manufacturers' catalogs and industry standards such as AWWA and ASME. Determine the probable net ID and the probable range of friction coefficients carefully. For final design, trust no table, but calculate the flow by formula. If the pipe is larger than about 600 mm (24 in.) or smaller than about 75 mm (3 in.), or if the temperature is less than about 10°C (50°F) or more than about 30°C (86°F), do not trust the Hazen–Williams formula. Use the Darcy–Weisbach formula instead.

Deposition in Pipes

Water treatment often creates deposits that greatly increase friction in pipes. In one pipeline, lime incrustation reduced the measured value of *C* to only 80 downstream from the treatment plant. Pipe can, however, be cleaned and relined with cement mortar in situ and restored to nearly its original smoothness. Under some circumstances, deposits of bacterial slime in water pipes can change the smoothest pipe (whatever the material) into very rough pipe. Fortunately, chlorination destroys the slime and restores the former smoothness. In New York, for example, the *C* factor for a 1800-mm (72-in.) water main 7.7 km (4.8 mi) long drops from 140 to 120 about twice per year and is chlorinated to restore the *C* value to 140. Another example is a 1050-mm (42-in.) cement-lined steel cylinder prestressed concrete transmission main 48 km (30 mi) long. It develops a slime layer only about 3 mm ($\frac{1}{8}$ in.) thick every five years, but the thin slime is sufficient to decrease the *C* value from 140 to 100. A massive dose of chlorine restores its former smoothness. Instead of massive doses of chlorine at long intervals, however, the maintenance of a free chlorine residual of about 0.5 mg/L or a stronger (2 to 3 mg/L) dose for two hours twice per week in a southern California pipeline has been reported to maintain the original capacity. As bacteria do not develop immunity to chlorine, experimentation with doses, contact time, and time intervals between doses offers an opportunity to achieve overall economy [16]. Biofouling is far more prevalent than most people realize, so chlorination facilities must be added for pipelines subject to slime buildup. The coefficient of friction should be determined when a new pipeline is first put into service to establish an irrefutable reference point for future cleaning needs and for evaluating cleaning procedures.

Sewers often become fouled with grease, and grease from industries (such as commercial laundries, slaughterhouses, or locomotive repair shops) can reduce the diameter of wastewater pipes by one-third or more. Their original size and smoothness can be restored, however, by cleaning the pipe in place. To prevent excessive buildup of grease, include pig launching and recovery stations (see Section 4-9).

The headloss in pumping station piping is usually small (about 2 m or 5 ft) and is largely related to valve and fitting losses (see Tables B-6 and B-7), so the selection of a *C* value for piping within the pumping station is of minor importance. If the static lift is the major part of the TDH and the transmission or force main is short, say 150 m (500 ft) or less, the *C* value is of minor importance.

Long Force Mains

Friction coefficients for long force or transmission mains must be established with great care. Using the Hazen–Williams formula can lead to serious errors, particularly for (1) large pipes, (2) high velocities, or (3) water temperature that differs from 15°C (60°F) by more than about 11°C (20°F). For such situations, use the Darcy–Weisbach equation. If the energy loss is a vital design consideration, search the literature for tests on similar conduits instead of attempting to use the Moody diagram for the Darcy–Weisbach equation.

Pump and Impeller Selection

To base pump operating points on station curves drawn for an unrealistic roughness is a serious blunder. If some jurisdiction requires the use of some specific value of roughness deemed by the designer to be too great (for example, a C value of 120, as specified in the Ten-State Standards), use that value only to find the size of the pipe. Select the pump and its impeller for a rational envelope of curves that include the maximum and minimum limit of possible roughness, for example, $150 > C > 120$. By choosing a pump that can accommodate impellers of a substantial range of diameters, the pump can be modified to operate at or near its best efficiency point (BEP) for any curve within the envelope. However, assuming an excessively rough pipe can be disastrous. One pumping station featured several sets of two pumps in series to develop the head calculated for a single C value of 100. To keep the pumps from vibrating, the operators partly closed a downstream valve. A better solution would have been to bypass the tandem pump and achieve a savings of \$100,000 per year in electric power.

It is wise to use a calibrated pressure gauge in measuring the total dynamic head (TDH) during the start-up procedure so that the impeller trim can, if necessary, be refined with confidence.

3-3. Pipe Tables

So many materials, pipe diameters, wall thicknesses, and liner thicknesses can be used for pumping stations, yard piping, and transmission or force mains that complete tables of flow and headloss would have to be extensive indeed. Because interpolation between tabular values is onerous, calculating the flow and headloss with the Hazen–Williams formula is much quicker. Tables, however, can be used advantageously to find the proper size of pipe quickly, to approximate the friction headloss, and to provide an independent check on a solution by formula.

The purposes of the pipe tables in Appendix B (Tables B-1 to B-4) are the following:

- For a quick, preliminary determination of pipe size, flow rate, and headloss for a moderate friction coefficient ($C = 120$) and velocity (2 m/s in Tables B-1 and B-3 and 5 ft/s in Tables B-2 and B-4);
- For finding the available sizes and weights of the thinnest (and most common) pipes used within pumping stations;
- For a quick, rough check of flow or headloss found by other means; and
- For providing useful data for both ductile iron pipe (DIP) and steel in both SI and U.S. customary units.

For final design, for different conditions, and for piping outside of the pumping station, calculate flow and headloss with the Darcy–Weisbach formula and consult the tables to check for blunders.

Example 3-1
Designing Pipe with the Pipe Tables

Problem: Select the pipe for a water pumping station with a 15-km- (9.3-mi)-long transmission main. Maximum flow is $0.4\,\mathrm{m^3/s}$ (6360 gal/min or $14.1\,\mathrm{ft^3/s}$).

Solution: One choice for the pumping station is DIP lined with cement mortar and sized for a velocity of about 2.5 m/s (8.2 ft/s), which is high enough to minimize the size and cost of valves and other fittings and low enough to prevent cavitation and excessive headloss.

Using Table B-1 for SI units (or Table B-2 for U.S. customary units),

SI Units

Pipe size for v = 2 m/s: 500 mm

$$\frac{v_{\text{desired}}}{v_{\text{Table B-1}}} = \frac{2.5\ \mathrm{m/s}}{2\,\mathrm{m/s}} = 1.25$$

$$\text{Area required} = \frac{0.213\,\mathrm{m^2}}{1.25} = 0.17\,\mathrm{m^2}$$

$$v = Q/A = 0.4/0.172 = 2.33\,\mathrm{m/s}$$

U.S. Customary Units

Pipe size for v = 5 ft/s: 24 in.

$$\frac{v_{\text{desired}}}{v_{\text{Table B-2}}} = \frac{8.2}{5} = 1.64$$

$$\text{Area required} = \frac{3.32\,\mathrm{ft^2}}{1.64} = 2.02\,\mathrm{ft^2}$$

$$v = Q/A = 14.1/1.85 = 7.78\,\mathrm{ft/s}$$

SI Units

Choose 450-mm pipe: $A = 0.172\,\text{m}^2$

Friction headloss: use Equation 3-10a and $C = 120$

$$h_f = 10{,}700\left(\frac{0.4}{120}\right)^{1.85}(0.468)^{-4.87}$$

U.S. Customary Units

Choose 18-in. pipe: $A = 1.85\,\text{ft}^2$

Friction headloss: use Equation 3-10b and $C = 120$

$$h_f = 10{,}500\left(\frac{6360}{120}\right)^{1.85}(18.4)^{-4.87}$$

Always check such calculations with the pipe table. Note that headloss is a function of Q or v to the 1.85 power. Hence,

SI Units:

$$h_f = 11.3\,m/1000\,m$$

$$h_{f_{\text{actual}}} = h_{f_{\text{table}}}\left(\frac{Q_{\text{actual}}}{Q_{\text{table}}}\right)^{1.85}$$

$$= 8.5\left(\frac{0.4}{0.344}\right)^{1.85}$$

$$= 11.2\,\text{m}/1000\,\text{m}$$

U.S. Customary Units:

$$h_f = 11.3\,ft/1000\,ft$$

$$h_{f_{\text{actual}}} = h_{f_{\text{table}}}\left(\frac{Q_{\text{actual}}}{Q_{\text{table}}}\right)^{1.85}$$

$$= 5.1\left(\frac{6360}{4160}\right)^{1.85}$$

$$= 11.2\,\text{ft}/1000\,\text{ft}$$

Entrance, fitting, and valve losses must be added (see Section 3-4).

At $C = 145$, the friction headloss is 8.4 m/1000 m, which, in the short length of pipe in a pumping station, would only be about 60 mm (0.2 ft). At 11.3 m/1000 m, the loss in head would be only about 40 mm (0.1 ft) more, which is insignificant.

For the transmission main, a velocity of about 2 m/s (6 ft/s) seems likely to be economical when the cost of pipe, valves and fittings, water hammer control methods and devices, installation, and energy are analyzed for, say, a 20-yr period. Using Table B-1 or B-2, a 500-mm (20-in.) pipe would fit the conditions. But flanged joints are not needed for the transmission main, where mechanical or push-on joints allow Class 50 DIP to be used. By referring to the DIPRA handbook [17], the wall thickness is 9.1 mm (0.36 in.). Let us assume the cement mortar is to be double thickness with negligible tolerance. The OD values in Tables B-1 and B-2 are correct for all classes of DIP, so

SI Units:

$$\text{ID} = 549 - 2(9.1 + 2 \times 2.38)$$

$$= 521\,\text{mm}$$

$$h_f = 10{,}700\left(\frac{0.4}{120}\right)^{1.85}(0.521)^{-4.87}$$

$$= 6.69\,\text{m}/1000\,\text{m}$$

Or, use Table B-1,

$$\text{True velocity} = \frac{0.4\,\text{m}^3/\text{s}}{0.213\,\text{m}^2} = 1.88\,\text{m/s}$$

$$h_f = 7.5\left(\frac{1.88}{2}\right)^{1.85} = 6.69\,\text{m}/1000\,\text{m}$$

Good check.

U.S. Customary Units:

$$\text{ID} = 21.60 - 2[0.36 + 2(3/32)]$$

$$= 20.5\,\text{in.}$$

$$h_f = 10{,}500\left(\frac{6360}{120}\right)^{1.85}(20.5)^{-4.87}$$

$$= 6.65\,\text{ft}/1000\,\text{ft}$$

Or, use Table B-2,

$$\text{True velocity} = \frac{14.1\,\text{ft}^3/\text{s}}{2.29\,\text{ft}^2} = 6.16\,\text{ft}$$

$$h_f = 4.5\left(\frac{6.16}{5}\right)^{1.85} = 6.62\,\text{ff}/1000\,\text{ft}$$

Good check.

For 15 km (9.3 miles) of pipe, the total headloss at $C = 120$ is $6.69 \times 15 = 100\,\text{m}$ (330 ft) versus 70.5 m (231 ft) at $C = 145$. The difference in headloss and energy use is important and worthy of careful study. Check by using the Darcy–Weisbach formula; also consider the maximum and minimum water temperatures.