Optimum design of pulp stock pipelines

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Because power costs will continue to increase, the design engineer should consider power costs as well as capital costs on any project.

Since power costs will continue to increase, perhaps even at an accelerated rate in the future, the design engineer must consider power costs as well as capital costs on any project. Optimum pipe design is based on the least sum of fixed costs and power costs. In many installations, pipe friction is responsible for a sizable portion of pumping power costs. The engineer must also consider proper design for nonplugging operation.

The method presented here allows the engineer to select a pipe size from friction loss curves on which optimum flows and nonplugging flows are shown. The method applies to stocks of all consistencies and can be extended to any stock for which pipeline friction parameters are known. The curves presented at the end of this paper are for consistencies of 1.5–6.0%.

Where local material, labor, and power costs vary considerably from the costs used here, the engineer can nevertheless use the curves to make an initial selection for pipe size. Then he can calculate actual costs for the size selected and for the size on either side of the one selected.

Curves for friction loss for a long-fibered kraft pulp, dried and reslurried, illustrate the method. Bodenheimer's work (*1*) was used to determine critical plugging velocities. Sheldon's method (*2*) was used to find optimum pipe diameters based on fixed costs (as a percentage of installed capital cost) and pumping energy costs.

A recent estimate of capital costs was used for material and labor costs for Schedule 5, 304-L stainless steel pipe in sizes of 3, 4, 6, 8, 10, 12, 14, 16, and 18 in. These estimates are given in **Table I**. Duffy's method (*3*) was used to plot friction loss curves for these pipe sizes.

Theory

In the following analysis, the first equation for each pair is in English units, and the second equation is given for SI units. The analyses of material and labor costs for nine pipe sizes gave the following equations:

$$C_M/100\ \text{ft} = 548.40\ e^{0.194\ D} \qquad (1a)$$

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I. Capital costs for T304L stainless steel pipe, Schedule 5, including fittings, hand valves and hangers

Nominal pipe size, in.	*Inside diam. in.*	*Material costs, $/linear ft.*	*Labor costs, $/linear ft.*
3	3.334	10.38	34.64
4	4.334	12.12	38.03
6	6.407	19.80	48.58
8	8.407	28.05	55.36
10	10.532	42.35	73.66
12	12.500	58.30	82.96
16	15.750	136.40	110.64
18	17.720	159.50	124.49

Material costs are multiplied by 1.10 for overhead and profit. Labor costs at $16/man·hour are multiplied by 1.45 for overhead and profit.

$$C_M/100\ \text{m} = 1799.30\ e^{0.0076\ D} \qquad (1b)$$

$$C_L/100\ \text{ft} = 2639.00\ e^{0.090\ D} \qquad (2a)$$

$$C_L/100\ \text{m} = 8658.56\ e^{0.0035\ D} \qquad (2b)$$

where

C_M = materials cost, including fittings, flanges, and valves

C_L = labor cost

D = inside pipe diameter, in. or mm

e = 2.718.

Sheldon found that his cost equations were a power function, whereas these equations are exponential. Also, Sheldon used installation labor as a fixed ratio of material costs, whereas the labor cost figures used here are not a fixed ratio of material costs for all diameters. [For a more detailed discussion, see Sheldon (*2*) or Laskey (*4*).]

The equation for pumping power per 100 ft. of pipe is

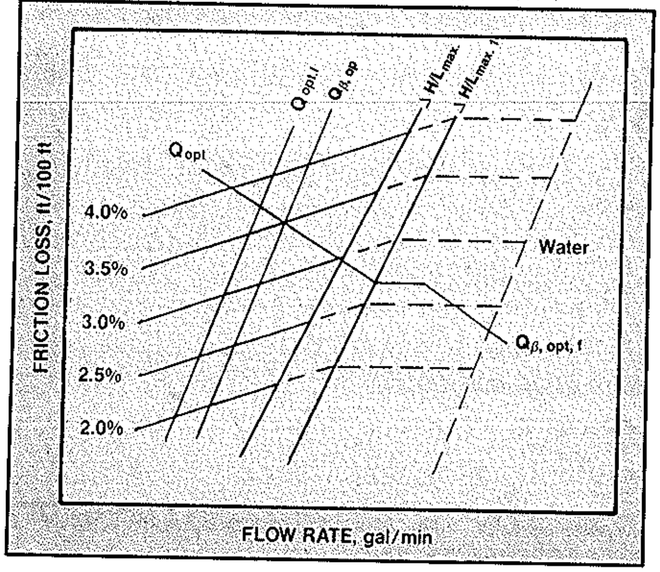
$$P = Q\,(\Delta H/100)/\,3960E \qquad (3a)$$

where

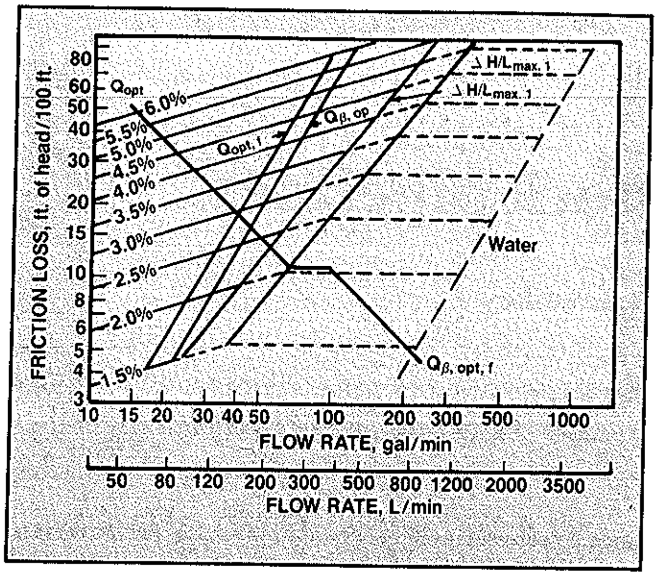
P = power in brake horsepower, or bhp

Q = flow rate, gal/min

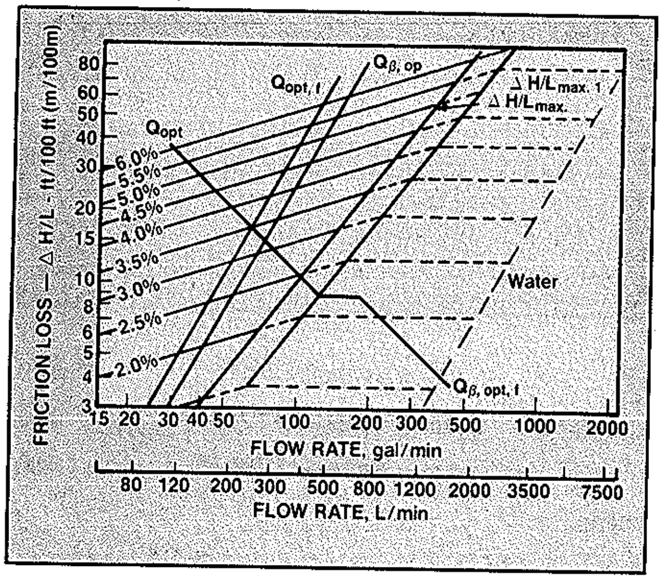
1. Friction curves with optimum flow lines and Bodenheimer's lines (a: friction loss. b: friction loss corrected according to Eq. 12)



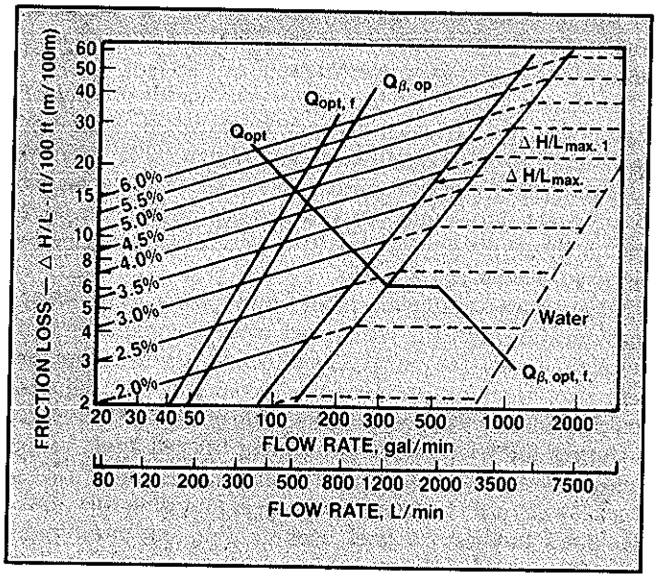
2. Friction loss curves for kraft pulp with an average fiber length of 3.334 in. (85mm)



3. Friction loss curves for kraft pulp with an average fiber length of 4.334 in. (110mm)



4. Friction loss curves for kraft pulp with an average fiber lengfth of 6.407 in. (163mm)



ΔH = drop in header pressure, ft of head

E = efficiency of pump and motor as a decimal.

For pumping power per 100 m of pipe, the equation is

$$P = Q\,(\Delta H/100)/\,6126\,E \tag{3b}$$

where Q is in L/min and P is in kilowatts.

Using electric power costs of \$0.06/kW·h is equivalent to \$0.0448/bhp-h. Thus, the power cost, C_P, can be given as follows:

$$C_P = 0.0448 \times 8760\,Q\,(\Delta\,H/100)/\,3960\,E \tag{4a}$$

$$C_P = 0.060 \times 8760\,Q\,(\Delta\,H/100)/\,6126\,E \tag{4b}$$

where

C_p = bhp power cost per 100 ft and KW power cost per 100 m, respectively

8760 = total possible operating hours per year

Q = flow rate, gal/min and L/min, respectively.

Grouping constants and assuming $E = 0.60$ for pump and motor gives:

$$C_P = 0.1652 \times Q\,(\Delta\,H/100) \tag{5a}$$

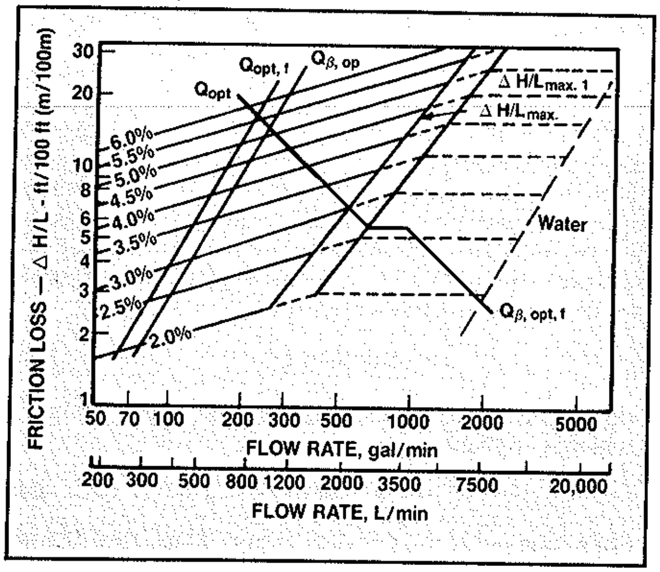
$$C_P = 0.1431\,Q\,(\Delta H/100) \tag{5b}$$

Using metric terms, Sheldon gives power costs by:

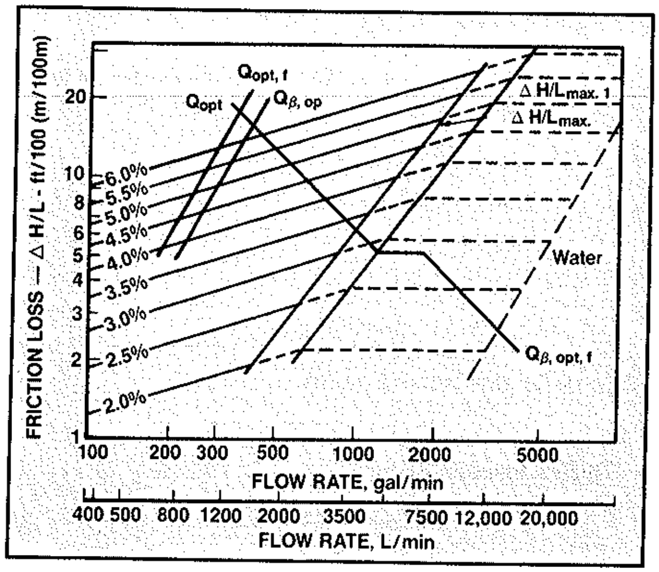
$$C_P = 0.00981\,(\Delta H/len)\rho Q\,K_e\,N_h/E \tag{6}$$

where

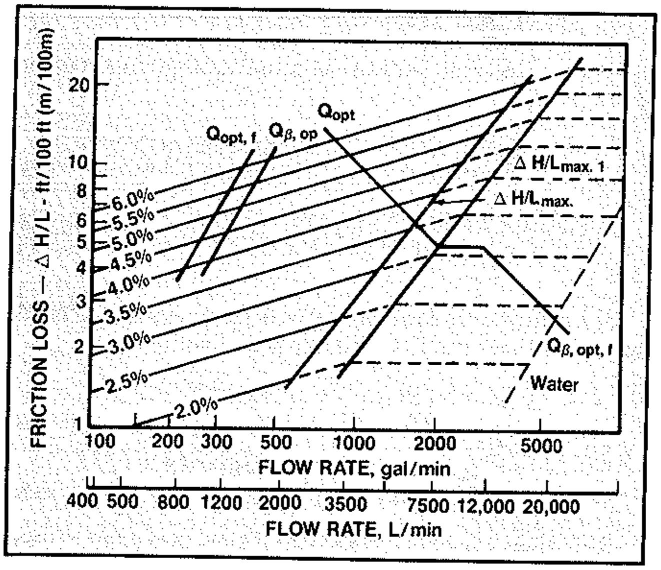
5. Friction loss curves for kraft pulp with an average fiber length of 8.407 in. (214mm)



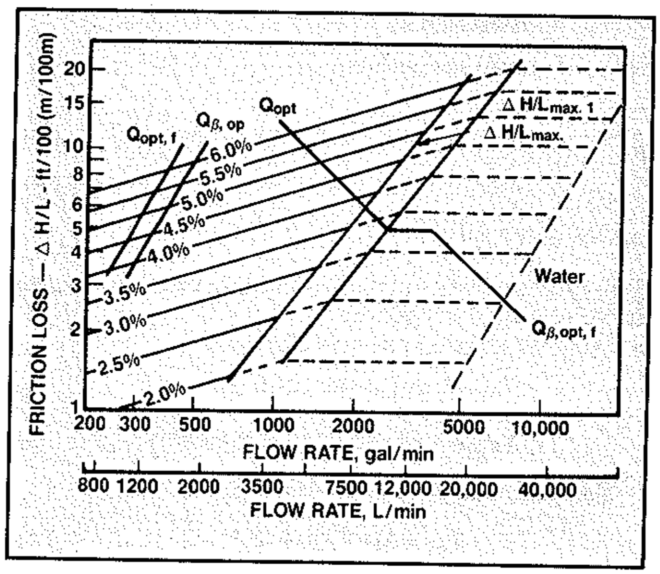
6. Friction loss curves for kraft pulp with an average fiber length of 10.532 in. (318mm)



7. Friction loss curves for kraft pulp with an average fiber length of 12.50 in. (318mm)



8. Friction loss curves for kraft pulp with an average fiber length of 13.75 in. (349mm)



len	=	piping length
ρ	=	stock density, kg/m^3
Q	=	flow rate, m^3/s
K_e	=	cost of electric power, \$/(kW-h)
N_h	=	number of operating hours per year
E	=	efficiency of pump and motor $\Delta H/len$ = friction loss, m/100 m of pipe.

Pipe material and labor costs are multiplied by linear feet of pipe/100 ft or by linear meters of pipe/100 m. The power costs, however, should be based on total equivalent feet/100 ft or on total equivalent meters/100 m. Total equivalent length includes the effect of fittings and valves. The length of pipe was increased by 5% for an average number of fittings and then by 40% for friction loss at the control valve. The factor 0.1652 in Eq. 5 becomes

$$0.1652 \times 1.05 \times 1.40 = .243$$

This gives the cost of power in English units as

$$C_P = 0.243 \times Q\,(\Delta H/100) \tag{7a}$$

It gives the cost of power in SI units as

$$C_P = 0.2103\,Q\,(\Delta H/100) \tag{7b}$$

In this way, all costs can be based on the linear feet or linear meters of pipe.

In cases where an optimum pipe size falls between two diameters, costs for each diameter should be calculated using power costs from Eq. 5, multiplying by the appropriate factor for pipe fittings and pressures drops across control valves.

For Duffy's formula for pulp stock friction loss, a correction factor F is introduced:

$$F = F_1 \times F_2$$

where these factors are as follows for long-fibered kraft, dried, and reslurried:

F_1 = temperature correction factor
= $1.528 - (0.00556 \times {}^\circ F)$
= 0.972 for 100°F

F_2 = pipe roughness factor
= 1.25 for stainless steel pipe.

Solving for this factor gives us

$$F = 0.972 \times 1.25 = 1.215$$

Duffy's formula, then, is

$$\Delta H/len = F\,K\,V^{\alpha}\,C^{\beta}\,D^{\gamma} \tag{8}$$

where parameters are as follows for long-fibered kraft, dried, and reslurried:

K = 9.40 for English units and 1036 for SI units

C = consistency, %

D = inside pipe diameter

α = 0.31

β = 1.81

γ = −1.34

$\Delta H/len$ = friction loss.

Other factors for the amount of beating and design safety factor are equal to 1.00.

Using these parameters, we derive:

$$\Delta H/len = 11.42\,V^{0.31} \times C^{1.81} \times D^{-1.34} \tag{9a}$$

$$\Delta H/len = 1258.74\,V^{0.31} \times C^{1.81} \times D^{-1.34} \tag{9b}$$

The maximum velocity for Eq. 9 is:

$$V_{max} = K_1\,C^{\sigma} = 0.49\,C^{1.80} \tag{10a}$$

$$V_{max} = 0.15C^{1.80} \tag{10b}$$

for PVC pipe. K_1 will be smaller for stainless steel pipe; therefore, we have used:

$$V_{max} = 0.44\,C^{1.80} \tag{11a}$$

$$V_{max} = 0.135\,C^{1.80} \tag{11b}$$

Also, for friction above V_{max} (the velocity where friction levels off and actually decreases), we have used:

$$\text{friction loss} = 1.15\Delta H/\,L_{max} \tag{12}$$

This is one of the methods proposed by Duffy for use in the drag reduction portion of a friction loss curve.

For the general formula for fixed cost plus power cost, using fixed cost as 20% of installed pipe cost and combining Eqs. 1, 2, 7, 8, we obtain the following general formula for total cost, which is good for any stock:

$$C_t = (109.68\,e^{0.194\,D}\ 527.80\,e^{0.090\,D})\,0.243\,Q\,F\,K\,V^{\alpha}\,C^{\beta}\,D^{\gamma} \tag{13a}$$

$$C_t = (359.86\,e^{0.0076\,D}\ 1731.71\,e^{0.0035\,D}/)\ 0.2103\,Q\,F\,K\,V^{\alpha}\,C^{\beta}\,D^{\gamma} \tag{13b}$$

For a specified flow rate, fixed cost will increase with pipe diameter, and friction power cost will decrease. Thus, there is an optimum economic pipe size for any flow rate, which is derived by setting the first derivative with respect to D in Eq. 13 equal to zero. Before this is done, we must substitute Q for V in Eq. 13, since the friction loss curves are friction loss vs. flow rate, or Q.

$$V = Q\,(0.4085/\,D^2) \tag{14a}$$

where V is in ft/s, Q is in gal/min, and D is in. When V is in m/s, we have

$$V = Q\,(21.231/D^2) \tag{14b}$$

where Q is in L/min, and D is in mm. Thus, Eqs. 13a and 13b become

$$C_l = (109.68\,e^{0.194\,D} + 527.80\,e^{0.090\,D}) + (0.243 \times 0.4085^{\alpha} \times Q^{(1+\alpha)}\,F\,K\,C^{\beta})\,D^{\gamma+2\alpha} \tag{15a}$$

$$C_l = (359.86\,e^{0.0076\,D} + 1731.71\,e^{0.0035\,D}) + (0.2103 \times 21.231^{\alpha}\,Q^{1+\alpha}\,F\,K\,C^{\beta})\,D^{(\gamma-2\alpha)} \tag{15b}$$

Setting the first derivative equal to zero with respect to D gives:

$$C_l = (0.194 \times 109.68\,e^{0.194\,D} + 0.090 + 527.80\,e^{0.090\,D}) + (\gamma - 2^{\alpha}) \times (0.243 \times 0.4085^{\alpha} \times Q^{(1+\alpha)} F\,K\,C^{\beta})\,D^{(\gamma-2\alpha-1)} = 0 \tag{16a}$$

$$C_l = (0.0076 \times 359.86\,e^{0.0076\,D}\ 0.0035 \times 1731.71\,e^{0.0035\,D}) + (\gamma - 2^{\alpha}) \times (0.2103 \times 21.231^{\alpha}\ \mathrm{x}\ Q^{1+\alpha}\,F\,K\,C^{\beta})\,D^{(\gamma-2\alpha-1)} = 0 \tag{16b}$$

Substituting these parameters gives an equation for the optimum flow rate, Q_{opt}, for any pipe size:

$$Q_{opt} = (21.278\,e^{0.194\,D} + 47.502\,e^{0.090\,D})^{0.763} \times (D^{2.260}/C^{1.382})/2.946 \tag{17a}$$

$$Q_{opt} = (2.735\,e^{0.0076\,D} + 6.061\,e^{0.0035\,D})^{0.763} \times (D^{2.260}/C^{1.382})/242.87 \tag{17b}$$

Equations 17a and 17b are valid down to the flat portion of the friction curves. At that point, the power portion of Eq. 15 changes:

$$V_{max} = K_f \times C^{\sigma} \tag{18}$$

K_f = cost of power in the flat portion.

Using Eq. 18 and drawing from Eq. 12 for the corrected value of friction loss, the expression for C_p is as follows:

$$C_p = 0.243\,Q\,1.15\,F\,K\,K_f^{\alpha}\,C^{\sigma\alpha+\beta}\,D^{\gamma} \tag{19a}$$

$$C_p = 0.2103\,Q\,1.15\,F\,K\,K_f^{\alpha}\,C^{\sigma\alpha+\beta}\,D^{\gamma} \tag{19b}$$

Substituting Eqs. 19a and 19b into the second part of Eqs. 15a and 15b and setting the first derivative with respect to D equal to zero, we get the following general equations for the optimum flow rate $Q_{opt,2}$ in the flat part of the friction curves:

$$Q_{opt,f} = (/21.278e^{194D} + 47.502\,e^{0.090\,D})(\,D^{2.340}/\,C^{2.368})/3.310 \tag{20a}$$

Problem 1

Design a pipe for 100 tons/day at 6.0% consistency.

$$Q = (100 \times 16.7)/6.0 = 278.3 \text{ gal/min} = 1054 \text{ L/min}$$

For a pipe size of 10 in., the friction loss is 12.4 ft/100 ft of pipe, which falls to the left of the plugging with a velocity that is too low. For a pipe size of 8 in., the friction loss is 17.5 ft/100 ft of pipe, and a velocity that is too low. For a pipe size of 6 in., the friction loss is 33.0 ft/100 ft of pipe, and the velocity is satisfactory for nonplugging flow.

The pipe will be 6 in. Because of high friction loss, this is not an economic size, but it is required for a nonplugging velocity.

Problem 2

During a machine break, 220 tons/day of kraft stock at 4.0% consistency is to be pumped from a couch pit to a storage tank. The pipe is 500 ft long. It has fifteen 90°, long-radius elbows, one knife gate valve, and a level control valve. The static head is zero.

$$220 \times 16.7/4.0 = 919 \text{ gal/min} = 3480 \text{ L/min.}$$

For a pipe size of 10 in., the friction loss is 8.7 ft/100 ft, which falls to the right of the economic line. On the other hand, for a pipe size of 12 in., the friction loss is 6.2 ft/100 ft, which falls to the left of the economic line.

Table II shows the results of running the actual cost comparison. The smaller size is the economic size. If the 12-in. pipe had been the economic size and the total annual costs were close, the engineer might decide to use the 10-in. pipe based on lower capital costs.

II. Cost comparison

	10-in.	*12-in.*
Pipe length, linear ft	500	500
Fifteen 90° elbows, ft	23	30
Knife gate valve (open)	...	...
Total equiv. ft/100 ft of pipe	5.23	5.30
Total friction loss, ft	45.5	32.9
Control valve loss,[a] ft	18.2	13.2
Total pumping head, ft	63.7	46.1
Power cost[b]	9,700	7,000
Fixed cost[c]	11,100	14,300
Total annual cost	20,800	21,300

[a]40% loss. [b]Power cost = 0.1652 × 919 × total head.
[c]Fixed cost is taken from Eq. 13a.

$$Q_{opt,f} = (/2.735\, e^{0.0076\, D} + 6.061\, e^{0.0035\, D})(D^{2.340}/C^{2.368})/219.26 \quad (20b)$$

Figure 1 shows how Q_{opt} and $Q_{opt,2}$ look on a family of friction loss curves.

For the best economic design flow, we should follow close to the lines for Q_{opt} and $Q_{opt,f}$. However, we should also consider the flows which may be too small and give rise to plugging conditions in a pipeline.

Bodenheimer (*1*) produced critical shear lines on typical stock friction curves of friction loss vs. flow rate. He gives a formula for a critical pseudo-Reynold's number which can be reduced to:

$$\text{Reynold's number} = V\,D = 0.139\,F\,C^{1.22} \quad (21)$$

where

V = velocity, ft/s

D = pipe diameter, ft

F = a factor for pulp type

C = oven-dry consistency, %.

Figure 1 also shows Bodenheimer's lines for $F = 1.0$ (at $Q_{B,opt}$) and and $F = 0.80$ (at $Q_{B,opt,2}$).

In the best design, the flow rate should follow just to the right of $Q_{B,opt}$ for this stock until the economic line $Q_{B,opt,f}$ is reached at $C = 3.5$. Then it should follow close to Q_{opt} and $Q_{opt,f}$. Bodenheimer's F value varies for different types of pulp stock.

Results

Friction loss curves are presented in **Figures 2–8** for pipe sizes of 3–14 in. For each pipe size, critical plugging consistencies and consistencies where the stock acts like water can be read from the curves.

In most cases, the region to the left of V_{max} will be used. For cases where there is a wide range of flows in the pipe, the size should be selected for nonplug flow at the smallest flow rate. Then it is possible that at maximum flow will be in the $Q_{opt,f}$ region.

Conclusions

Using these equations presented, mill engineers can draw the critical plugging velocity lines and optimum flow lines on their set of friction loss curves, provided the parameters for Eq. 8 are known.

Optimum pipe sizing will become more important as power costs increase. Since plugging flows will determine pipe size in smaller diameters and high consistencies, more experimental work in the area of plug flow for various pulp stocks is warranted.

Literature cited

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