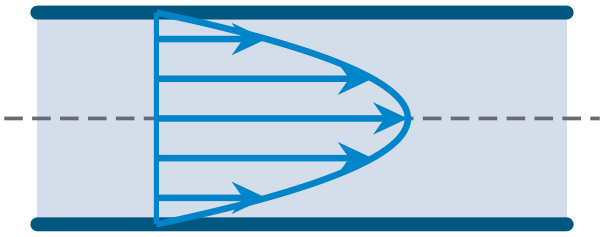
FLUID MECHANICS 1

PROBLEM BOOK

SAMPLE PAGES

7 chapters · 152 problems · step-by-step solutions



Ertan Sinan Şahin

ertansinansahin.com

How to use this book

- Each chapter opens with a reminder box summarizing the definitions and formulas the problems rely on.
- Difficulty: ★☆☆ basic ★★☆ intermediate ★★★ advanced. Each chapter has a few multiple-choice concept questions; its last problem is an exam-style mixed problem combining several topics.
- The dotted area below each problem is for your own work. Solve first; if stuck, go back to the reminder box and the lecture notes, and look at the solution last.
- All solutions are at the end of the book. The Solution → link next to a problem takes you to its solution, and ← Problem takes you back. Short answers are in the **ANSWER** box.
- **Shared chapters:** Chapters 6–7 (dimensional analysis, internal flow) also appear in *Fluid Mechanics 2*, for schools whose second course begins with dimensional analysis and pipe flow.
- **Midterm and final:** In one-semester courses the midterm usually covers fluid properties, fluid statics, and the Bernoulli equation (Chapters 1–4); the final adds momentum analysis, dimensional analysis, and pipe flow (Chapters 5–7). This book covers one-semester courses in civil, environmental, chemical, and food engineering as well as one-semester mechanical engineering courses. Two-semester courses also need *Fluid Mechanics 2* for the second term. Choose the chapters to study according to your own course syllabus.

Contents

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CHAPTER 2

PRESSURE AND FLUID STATICS

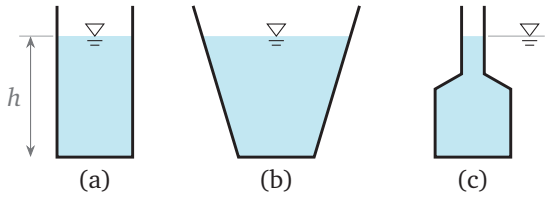
gage pressure	$P_{\text{gage}} = P - P_{\text{atm}}$	buoyant force	$F_B = \rho_f \, g \, V_{\text{sub}}$
variation with depth	$P_2 = P_1 + \rho g \, (z_1 - z_2)$	metacentric height	$\overline{GM} = \overline{KB} + \dfrac{I_0}{V_{\text{sub}}} - \overline{KG}$
plane surface	$F_R = (P_0 + \rho g h_C) A$	linear acceleration	$\tan\theta = \dfrac{a_x}{g + a_z}$
center of pressure ($P_0 = 0$, gage)	$y_P = y_C + \dfrac{I_{xx,C}}{y_C A}$	surface in rotation	$z_s = h_0 - \dfrac{\omega^2}{4g}\left(R^2 - 2r^2\right)$
curved surface	$F_H = F_{\text{proj}}, \;\; F_V = \rho g V_{\text{above}}$	pressure in rotation	$P = P_0 + \frac{1}{2}\rho \, \omega^2 r^2 - \rho g z$

Unless stated otherwise, the density of water is $\rho = 1000$ kg/m^3, the specific gravity of mercury is $SG = 13.6$, the gravitational acceleration is $g = 9.81$ m/s^2, and the atmospheric pressure is $P_{\text{atm}} = 101.3$ kPa. The hydrostatic pressure difference of gases is neglected compared with that of liquids. Pressures are explicitly stated as *gage* or *absolute*; if atmospheric pressure acts on both sides of a surface, it cancels in the force calculation. h is the depth measured downward from the free surface; z is positive upward. In the figures, water and aqueous liquids are drawn in light cyan, oil in light yellow, mercury and liquid metals in gray, and pressure and force in red; the interface between two liquids is a thin black line.

Pressure and its variation with depth

2.1 ★☆☆ Solution →

The three vessels in the figure have equal base areas and are all filled with water to the same height h. Vessel (b) widens upward, and vessel (c) has a narrow neck. The weights of the vessels themselves are equal. Which of the following is correct?



A) The base pressure is largest in vessel (b), which contains the most water.

B) Both the base pressures and the water forces on the bases are equal in the three vessels.

C) The base pressures are equal, but the force on the base is largest in vessel (b).

D) If the vessels are placed on a scale one after the other, the scale shows the same reading for all three.

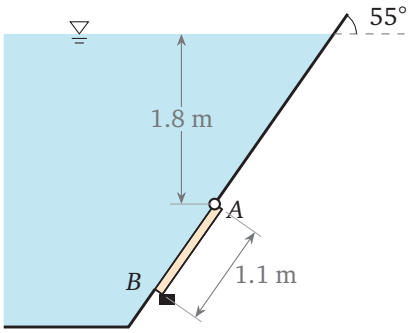
E) The base pressure is largest in vessel (c) because the water is squeezed in the narrow neck.

Forces on plane surfaces

2.10

★★☆ Solution →

The side wall of a rainwater cistern makes an angle of 55° with the horizontal. A rectangular cleanout gate in the wall is 1.1 m long along the slope and 1.4 m wide. The gate can open outward about hinge A at its top edge and is held closed by a latch at its bottom edge B. Hinge A is 1.8 m below the water surface. The outer face of the gate is open to the atmosphere; neglect the weight of the gate.



a. Find the hydrostatic force on the gate.

b. Find the distance of the center of pressure from the hinge along the slope.

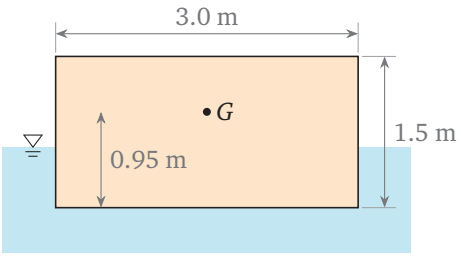
c. Find the force the latch exerts on the gate (perpendicular to the gate).

Buoyancy and stability

2.18

★★★ Solution →

The floating pumping station used on a dam reservoir is a pontoon in the shape of a rectangular prism: length 7.5 m, width 3.0 m, height 1.5 m. The mass of the pontoon with its equipment is 8.1 t and its center of gravity G is 0.95 m above the bottom. The reservoir water is fresh water.



a. Find the draft of the pontoon and its metacentric height for rolling about the longitudinal axis. Is the pontoon stable?

b. A 2.5 t pump unit is to be placed on the deck at the middle of the pontoon. If the metacentric height is required to remain at least 0.5 m, how high above the deck can the center of gravity of the unit be at most?

CHAPTER 4

MASS, BERNOULLI, AND ENERGY EQUATIONS

conservation of mass $\dfrac{dm_{KH}}{dt} = \sum \dot{m}_{\text{in}} - \sum \dot{m}_{\text{out}}$

flow rate $\dot{m} = \rho VA, \quad \dot{V} = Q = VA$

Bernoulli (steady, incompressible, frictionless, along a streamline) $\dfrac{P}{\rho} + \dfrac{V^2}{2} + gz = \text{constant}$

stagnation pressure $P_0 = P + \frac{1}{2}\rho V^2$

flow meter $Q = C_d A_2 \sqrt{\dfrac{2\,\Delta P}{\rho\,(1-\beta^4)}}, \quad \beta = \dfrac{d}{D}$

HGL and EGL $\text{HGL} = \dfrac{P}{\rho g} + z, \quad \text{EGL} = \text{HGL} + \alpha \dfrac{V^2}{2g}$

energy equation $\dfrac{P_1}{\rho g} + \alpha_1 \dfrac{V_1^2}{2g} + z_1 + h_{\text{pump}} = \dfrac{P_2}{\rho g} + \alpha_2 \dfrac{V_2^2}{2g} + z_2 + h_{\text{turbine}} + h_L$

kinetic energy correction factor $\alpha = \dfrac{1}{A}\displaystyle\int_A \left(\frac{u}{V}\right)^3 dA$

power and efficiency $\dot{W} = \rho g Q h, \quad \eta = \dfrac{\dot{W}_{\text{out}}}{\dot{W}_{\text{in}}}$

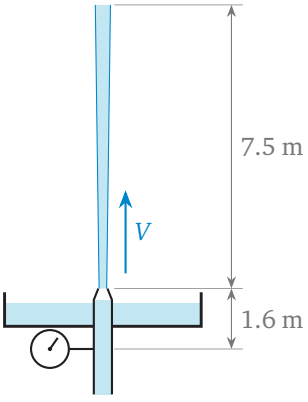
Unless stated otherwise, take the density of water as $\rho = 1000\ \text{kg/m}^3$, the specific gravity of mercury as $SG = 13.6$, the gravitational acceleration as $g = 9.81\ \text{m/s}^2$, and atmospheric pressure as $P_{\text{atm}} = 101.3\ \text{kPa}$; for air, $R = 0.287\ \text{kJ/(kg}\cdot\text{K)}$. Pressures are explicitly stated as *gage* or *absolute*; on surfaces open to the atmosphere and in free jets the gage pressure is zero. z is positive upward. The velocity of the free surface of a large tank is neglected. The Bernoulli equation is valid only for steady, incompressible, frictionless flow and along a streamline; where there is a loss, a pump, or a turbine, the energy equation is used. Unless stated otherwise, $\alpha = 1$.

Bernoulli equation: static, dynamic, and stagnation pressure

4.8

★☆☆ Solution →

At the center of an ornamental pool in a city square, a water jet from a vertically upward-facing nozzle must rise 7.5 m above the nozzle, and its flow rate must be 7.0 L/s. The inside diameter of the vertical pipe feeding the nozzle is 80 mm; a pressure gage is connected to the pipe 1.6 m below the nozzle exit. The head loss between the gage and the nozzle exit is 0.8 m. Neglect air resistance on the jet.



a. Find the nozzle exit velocity and the nozzle diameter.

b. Find the gage pressure that the gage must read.

c. Find the jet diameter 5 m above the nozzle. Why does the jet widen?

CHAPTER 7

INTERNAL FLOW

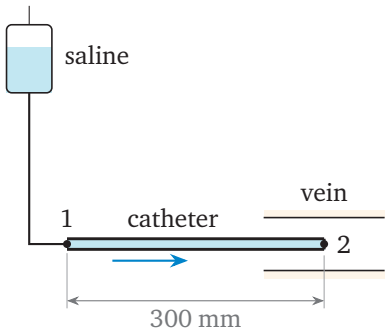
Reynolds number	$Re = \dfrac{\rho V D}{\mu},\ D_h = \dfrac{4A_c}{p}$	Colebrook	$\dfrac{1}{\sqrt{f}} = -2.0\log\left(\dfrac{\varepsilon/D}{3.7} + \dfrac{2.51}{Re\sqrt{f}}\right)$
head loss	$h_L = \left(f\dfrac{L}{D} + \Sigma K_L\right)\dfrac{V^2}{2g}$	Haaland	$\dfrac{1}{\sqrt{f}} \cong -1.8\log\left[\left(\dfrac{\varepsilon/D}{3.7}\right)^{1.11} + \dfrac{6.9}{Re}\right]$
laminar ($Re \lesssim 2300$)	$f = \dfrac{64}{Re},\ \dot{V} = \dfrac{\pi\,\Delta P\,D^4}{128\,\mu L}$	operating point	$h_{\text{pump}}(\dot{V}) = h_{\text{system}}(\dot{V})$
flow meter ($\beta = d/D$)	$\dot{V} = C_d A_0\sqrt{\dfrac{2\,\Delta P}{\rho\,(1-\beta^4)}}$		
energy equation	$\dfrac{P_1}{\rho g} + \alpha_1\dfrac{V_1^2}{2g} + z_1 + h_{\text{pump}} = \dfrac{P_2}{\rho g} + \alpha_2\dfrac{V_2^2}{2g} + z_2 + h_L$		

Unless stated otherwise, take $\rho = 1000$ kg/m^3 and $\mu = 1.00 \times 10^{-3}$ Pa · s for water; $\rho = 1.2$ kg/m^3 and $\mu = 1.8 \times 10^{-5}$ Pa · s for air; $g = 9.81$ m/s^2 and $P_{\text{atm}} = 101.3$ kPa. The flow is steady and incompressible; pipes are circular in cross section and the flow is fully developed. The flow regime is checked with the Reynolds number in every problem ($Re \gtrsim 4000$ is turbulent). In turbulent flow f is found from the relation specified in the problem (log is base 10), and $\alpha = 1$ is taken. In series pipes the flow rate is the same and the head losses add; in parallel pipes the head loss is the same in every branch and the flow rates add. In figures, oil and fuel are drawn light yellow; in single-line schematics the pipe is a thick black line.

Laminar flow in pipes

7.4 ★☆☆ Solution →

Physiological saline is administered to a patient through one lumen of a central venous catheter. The lumen has an inside diameter of 1.2 mm and a length of 300 mm. The pressure at the catheter inlet (1) is 9.0 kPa and at its tip inside the vein (2) is 1.2 kPa (both gage). The saline has a density of 1005 kg/m^3 and a viscosity of 1.02×10^{-3} Pa · s; the catheter is taken to be horizontal.



a. Assuming fully developed laminar flow, find the flow rate in mL/min.

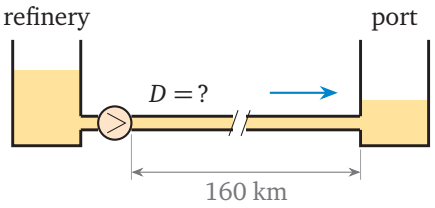
b. Check the assumption with the Reynolds number. What fraction of the catheter is the laminar entry length ($L_h \approx 0.05\,Re\,D$)?

c. If the same flow rate is to be delivered through a lumen with an inside diameter of 0.9 mm, what must the pressure difference be?

Turbulent flow and the friction factor

7.9

★★★ Solution →



Diesel fuel will be pumped from a refinery to a storage facility at a port through a horizontal steel pipeline 160 km long ($\varepsilon = 0.045$ mm) at a flow rate of 0.09 m^3/s. The diesel has a density of 840 kg/m^3 and a kinematic viscosity of 3.0×10^{-6} m^2/s. The design criterion is that the frictional pressure drop must not exceed 45 kPa per kilometer. Find f with the Haaland equation; neglect minor losses.

a. Find the smallest inside diameter required.

b. Select the appropriate pipe from inside diameters of 250, 300, and 350 mm; find the pressure drop per kilometer in the selected pipe.

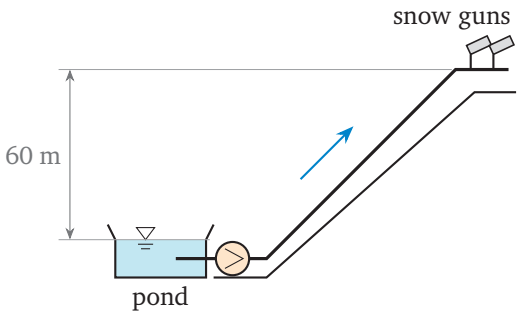
c. If each pumping station can provide a pressure rise of at most 6 MPa, how many stations does the line need? What is the total power the pumps deliver to the fluid?

Piping systems with pumps; operating point

7.20

★★☆ Solution →

In a ski resort, water is pumped from a pond to snow guns on the slope for artificial snow production. The inlet of the distribution line feeding the guns is 60 m above the pond surface, and a pressure of 600 kPa (gage) is required there. The main pipe is steel ($\varepsilon = 0.045$ mm) with an inside diameter of 150 mm and a length of 1.4 km; the sum of the minor loss coefficients is $\Sigma K_L = 8$. The water is at 2°C: $\mu = 1.67 \times 10^{-3}$ Pa · s. The head–flow-rate curve of the pump is given by $h_{\text{pump}} = 200 - 1.2 \times 10^4 \dot{V}^2$ (h in meters, $\dot{V}$ in m^3/s). Include the kinetic energy at the inlet of the distribution line; find f with the Haaland equation.



a. Write the equation of the system curve and find the operating point (flow rate and pump head).

b. If the pump efficiency at the operating point is 0.74, what is the shaft power?

c. If each snow gun uses 8 L/s of water, at most how many guns can be operated at the same time at full pressure?

SOLUTIONS

2 PRESSURE AND FLUID STATICS

2.1

← Problem

In a liquid at rest, pressure depends only on depth: at the base of all three vessels $P_{\text{gage}} = \rho g h$. Since the base areas are equal, the force on the base, $F = \rho g h A$, is also the same in all three. **B** is correct.

- (A) and (E): Pressure does not depend on the shape of the vessel or the amount of liquid; water is treated as incompressible.
- (C): If pressure and area are equal, the force is equal too.
- (D): A scale reads not the force on the base but the total weight of the vessel and water. The inclined walls carry the weight of the extra water in vessel (b); in (c), the water at the shoulder pushes the vessel upward. The readings are largest for (b) and smallest for (c). This is the *hydrostatic paradox*.

ANSWER B

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2.10

← Problem

The y axis lies in the plane of the gate and is measured downward from the line where the plane of the water surface intersects it. Atmospheric pressure is present on both faces; gage pressure is used.

a. Positions y of the hinge and the centroid:

$$y_A = \frac{1.8}{\sin 55^\circ} = 2.197 \text{ m},$$

$$y_C = 2.197 + 0.55 = 2.747 \text{ m},$$

$$h_C = y_C \sin 55^\circ = 2.251 \text{ m},$$

$$A = (1.1)(1.4) = 1.54 \text{ m}^2.$$

$$F_R = (1000)(9.81)(2.251)(1.54) = 34.0 \text{ kN}.$$

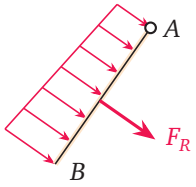
b. Center of pressure:

$$I_{xx,C} = \frac{(1.4)(1.1)^3}{12} = 0.1553 \text{ m}^4,$$

$$y_P - y_C = \frac{0.1553}{(2.747)(1.54)} = 0.0367 \text{ m}.$$

$$s = 0.55 + 0.0367 = 0.5867 \approx 0.587 \text{ m} \quad \text{(from hinge)}.$$

In the shift of y_P, the distance y_C (measured from the surface) is used, not the 0.55 m distance to the hinge.



c. Moment about A (weight neglected; the latch force acts at B, perpendicular to the gate):

$$F_B(1.1) = F_R(0.5867),$$

$$F_B = \frac{(34.0)(0.5867)}{1.1} = 18.13 \approx 18.1 \text{ kN}.$$

The latch carries slightly more than half of the total force because the center of pressure is slightly below the middle of the gate.

ANSWER a. 34.0 kN b. 0.587 m c. 18.1 kN

2.18

← Problem

K is the bottom (keel) point, B is the centroid of the submerged volume (center of buoyancy), and M is the metacenter. For a rectangular-section pontoon, $\overline{KB} = T/2$ and $\overline{BM} = I_0/V_{\text{sub}}$; I_0 is the second moment of the waterplane area about the longitudinal axis.

a. Draft and metacentric height:

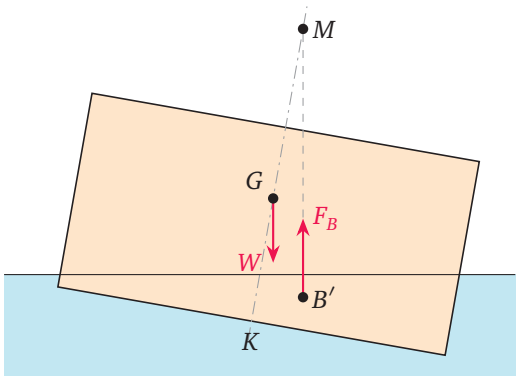
$$T = \frac{8100}{(1000)(7.5)(3.0)} = 0.360 \text{ m}, \quad \overline{KB} = 0.18 \text{ m}.$$

$$I_0 = \frac{(7.5)(3.0)^3}{12} = 16.875 \text{ m}^4, \quad V_{\text{sub}} = 8.1 \text{ m}^3,$$

$$\overline{BM} = \frac{16.875}{8.1} = 2.083 \text{ m}.$$

$$\overline{GM} = 0.18 + 2.083 - 0.95 = 1.313 \approx 1.31 \text{ m} > 0.$$

Although G is above B, M is above G: the pontoon is stable. In a wide, shallow pontoon, the large second moment of the waterplane area provides stability.



b. New mass 10.6 t:

$$T' = \frac{10\,600}{(1000)(22.5)} = 0.4711 \text{ m}, \quad \overline{KB}' = 0.2356 \text{ m},$$

$$\overline{BM}' = \frac{16.875}{10.6} = 1.5920 \text{ m}, \quad \overline{KM}' = 1.8276 \text{ m}.$$

For $\overline{GM}' \geq 0.5$, $\overline{KG}' \leq 1.3276$ m. If the center of gravity of the unit is at height z above the bottom,

$$\overline{KG}' = \frac{(8.1)(0.95) + 2.5z}{10.6} \leq 1.3276,$$

$$7.695 + 2.5z \leq 14.073 \Rightarrow z \leq 2.551 \text{ m}.$$

$$z - 1.5 = 1.051 \approx 1.05 \text{ m} \text{ (above the deck)}.$$

The load both raises G and increases the draft, reducing $\overline{BM}$; both effects reduce stability.

ANSWER a. $T = 0.360$ m, $\overline{GM} = 1.31$ m, stable b. at most 1.05 m above the deck

4 MASS, BERNOULLI, AND ENERGY EQUATIONS

4.8

← Problem

The flow is steady and incompressible. There is no friction in the jet (air resistance is neglected); the pressure is atmospheric everywhere, so the Bernoulli equation is valid along a streamline from the nozzle exit to the top of the jet. Between the gage and the nozzle there is a loss, so the energy equation is used there.

a. Between the nozzle exit (2) and the top of the jet ($V = 0$):

$$V_2 = \sqrt{2(9.81)(7.5)} = 12.13 \approx 12.1 \text{ m/s},$$

$$A_2 = \frac{7.0 \times 10^{-3}}{12.13} = 5.771 \times 10^{-4} \text{ m}^2,$$

$$d_2 = \sqrt{\frac{4A_2}{\pi}} = 0.02711 \text{ m} \approx 27.1 \text{ mm}.$$

b. Between the gage point (1) and the nozzle exit ($\alpha = 1$), using the velocity $V_1 = 7.0 \times 10^{-3}/(5.0265 \times 10^{-3}) = 1.393$ m/s:

$$\frac{P_{1,\text{gage}}}{\rho g} = (z_2 - z_1) + \frac{V_2^2 - V_1^2}{2g} + h_L,$$

$$\frac{P_{1,\text{gage}}}{\rho g} = 1.6 + \frac{147.15 - 1.939}{19.62} + 0.8,$$

$$\frac{P_{1,\text{gage}}}{\rho g} = 1.6 + 7.401 + 0.8 = 9.801 \text{ m},$$

$$P_{1,\text{gage}} = (9810)(9.801) = 96.15 \approx 96.2 \text{ kPa}.$$

Without the loss, 88.3 kPa would suffice; the 0.8 m loss in the pipe increases the required pressure by about 8 kPa.

c. Velocity at a height of 5 m and the diameter from continuity:

$$V = \sqrt{147.15 - 2(9.81)(5)} = \sqrt{49.05} = 7.004 \text{ m/s},$$

$$d = 27.11\sqrt{\frac{12.13}{7.004}} = 35.68 \approx 35.7 \text{ mm}.$$

As it rises the water slows down; since the flow rate is constant, VA must remain constant and the cross section grows.

ANSWER a. 12.1 m/s, $d = 27.1$ mm b. 96.2 kPa (gage) c. 35.7 mm

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7 INTERNAL FLOW

7.4

← Problem

The catheter is horizontal; the pressure difference $\Delta P = 9.0 - 1.2 = 7.8$ kPa only overcomes friction.

a. D^4 in the Hagen–Poiseuille relation:

$$(1.2\times10^{-3})^4 = 2.074\times10^{-12}\ \text{m}^4,$$

$$\dot V = \frac{\pi(7800)(2.074\times10^{-12})}{128\,(1.02\times10^{-3})(0.30)},$$

$$\dot V = \frac{5.082\times10^{-8}}{0.03917} = 1.297\times10^{-6}\ \text{m}^3/\text{s}.$$

That is, 1.297 mL/s = 77.8 mL/min.

b. Average velocity and Reynolds number:

$$V = \frac{4(1.297\times10^{-6})}{\pi(1.2\times10^{-3})^2} = 1.147\ \text{m/s},$$

$$Re = \frac{(1005)(1.147)(1.2\times10^{-3})}{1.02\times10^{-3}} = 1356 \approx 1360.$$

$Re < 2300$: the flow is laminar and the relation is valid. Entry length:

$$L_h = 0.05(1356)(1.2\times10^{-3}) = 0.0814\ \text{m},$$

about 27% of the catheter. Since the wall shear stress is larger in the entrance region, the actual flow rate is slightly smaller than the value found; the fully developed assumption is approximate here.

c. At the same flow rate, $\Delta P \propto D^{-4}$:

$$\Delta P' = 7.8\left(\frac{1.2}{0.9}\right)^4 = 7.8(3.160) = 24.65 \approx 24.7\ \text{kPa}.$$

The average velocity increases by a factor of $(1.2/0.9)^2$; the Reynolds number, on the other hand, is inversely proportional to D:

$$Re' = 1356\left(\frac{1.2}{0.9}\right) = 1808 < 2300,$$

the flow is still laminar and the relation is valid. A 25% reduction in diameter increases the pressure difference by a factor of 3.16. For thin catheters the height of the saline bag is not enough; an infusion pump is used.

ANSWER a. 77.8 mL/min b. $Re = 1360$, laminar; $L_h = 0.0814$ m (about 27%) c. 24.7 kPa

7.9

← Problem

The pressure drop per kilometer is related to the diameter by writing $V = 4\dot V/(\pi D^2)$:

$$\frac{\Delta P}{L} = \frac{f}{D}\frac{\rho V^2}{2} = \frac{8 f \rho \dot V^2}{\pi^2 D^5}.$$

a. For $\Delta P/L = 45$ Pa/m:

$$D = \left(\frac{8\rho\dot V^2}{\pi^2(45)}f\right)^{1/5} = (0.1226\,f)^{1/5}.$$

f depends on the diameter, so an iterative solution is used: the guess $f = 0.016$ gives $D = 0.2874$ m. At this diameter $V = 1.387$ m/s, $Re = VD/\nu = 1.33\times10^5$, $\varepsilon/D = 1.57\times10^{-4}$, and Haaland gives $f = 0.01765$. With the new f, $D = 0.2931$ m, $Re = 1.30\times10^5$, $f = 0.01770$; one more step:

$$D = [(0.1226)(0.01770)]^{1/5} = 0.2933\ \text{m}.$$

The flow is turbulent ($Re \approx 1.3\times10^5$). The smallest diameter is 0.293 m.

b. 250 mm is not enough; 300 mm is selected:

$$V = \frac{4(0.09)}{\pi(0.30)^2} = 1.273\ \text{m/s}, \quad Re = 1.27\times10^5.$$

$\varepsilon/D = 1.5\times10^{-4}$; inside the logarithm in Haaland, $1.333\times10^{-5} + 5.419\times10^{-5} = 6.752\times10^{-5}$:

$$\frac{1}{\sqrt f} = -1.8\log\left(6.752\times10^{-5}\right) = 7.507,$$

$$f = 0.01774.$$

$$\frac{\Delta P}{L} = \frac{0.01774}{0.30}(680.9) = 40.26\ \text{Pa/m} \approx 40.3\ \text{kPa/km}$$

($\rho V^2/2 = 680.9$ Pa); the criterion is satisfied.

c. Total pressure drop of the line:

$$\Delta P = (40.26)(160) = 6442\ \text{kPa} = 6.44\ \text{MPa}.$$

This exceeds the 6 MPa limit of one station; **2 stations** are needed (about 3.2 MPa each). Total power:

$$\dot W = \dot V \Delta P = (0.09)(6.442\times10^6) = 580\ \text{kW}.$$

A 350 mm pipe would cut the pressure drop by about half (as D^{-5}) and a single station would suffice; the choice is a trade-off between the cost of the pipe and the cost of pumping stations and energy.

ANSWER a. $D_{\min} = 0.293$ m b. 300 mm; 40.3 kPa/km c. 6.44 MPa, 2 stations; 580 kW

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7.20 ← Problem

The energy equation is written between the pond surface (1) and the distribution line inlet (2):

$$h_{\text{pump}} = (z_2 - z_1) + \frac{P_2}{\rho g} + \left(1 + f\frac{L}{D} + \Sigma K_L\right)\frac{V^2}{2g}.$$

a. Static head $60 + 600\,000/[(1000)(9.81)] = 121.2$ m. With $V = \dot{V}/A$ ($2gA^2 = 6.127 \times 10^{-3}$ m^5/s^2):

$$h_{\text{system}} = 121.2 + \frac{1 + 9333f + 8}{6.127 \times 10^{-3}}\dot{V}^2.$$

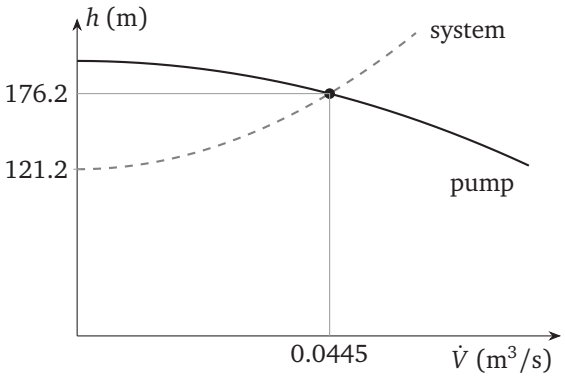
f depends on the flow rate; with the guess $f = 0.017$ the coefficient is 2.737×10^4. Equating with the pump curve,

$$\dot{V} = \sqrt{\frac{200 - 121.2}{1.2 \times 10^4 + 2.737 \times 10^4}} = 0.0447 \text{ m}^3/\text{s}.$$

At this flow rate $V = 2.53$ m/s, $Re = 2.27 \times 10^5$ (turbulent), and Haaland gives $f = 0.01726$. The coefficient becomes $2.776 \times 10^4 \approx 2.78 \times 10^4$ and the new flow rate is 0.0445 m^3/s; one more step changes nothing ($Re = 2.26 \times 10^5$, $f = 0.01727$). Operating point:

$$\dot{V} = 0.0445 \text{ m}^3/\text{s} = 44.5 \text{ L/s},$$

$$h = 200 - 1.2 \times 10^4 (0.0445)^2 = 176.2 \approx 176 \text{ m}.$$



b. Shaft power:

$$\dot{W}_{\text{shaft}} = \frac{\rho g \dot{V} h}{\eta} = \frac{(1000)(9.81)(0.0445)(176.2)}{0.74},$$

$$\dot{W}_{\text{shaft}} = 104 \text{ kW}.$$

c. $0.0445/0.008 = 5.56$: at most **5 guns** can operate at full pressure. If a sixth gun is opened, the flow demand exceeds the operating point; the pump head drops and the pressure at the guns falls below 600 kPa.

ANSWER a. $h_{\text{sys}} = 121.2 + 2.78 \times 10^4\,\dot{V}^2$; $\dot{V} = 44.5$ L/s, $h = 176$ m b. 104 kW c. 5 guns

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- 7 chapters and 152 problems, all with step-by-step solutions.
- A reminder box at the start of each chapter, summarizing the relations the problems rely on.
- Basic, intermediate and advanced problems, each with a dotted area for your own work.
- One-click links from each problem to its solution and back.



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