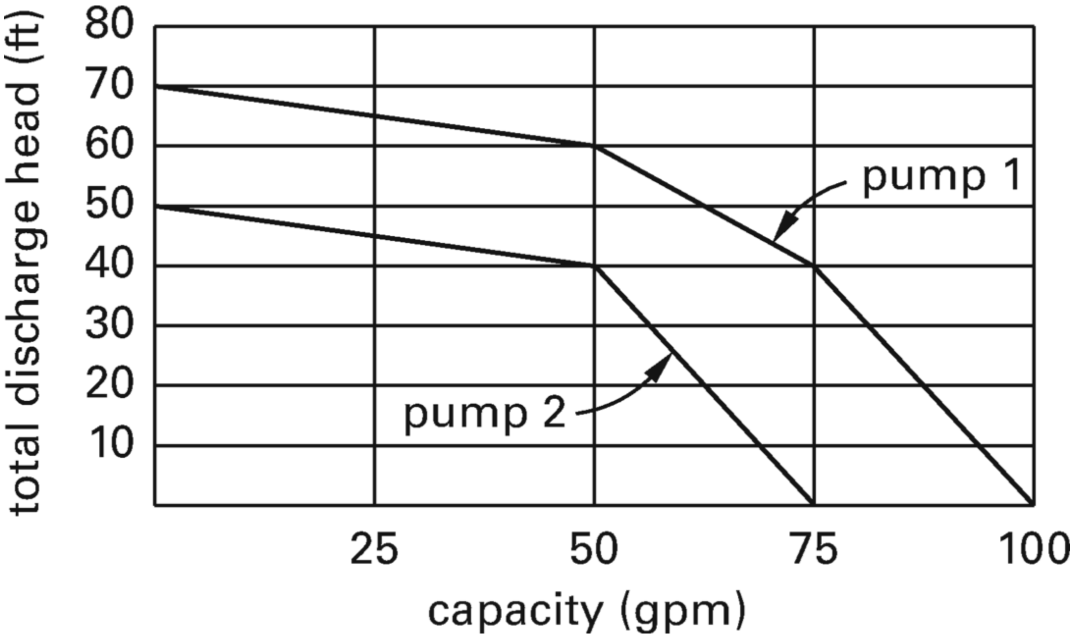
To print, please use the print page range feature within the application.

Chapter 5. Hydraulic Machines

Practice Problems

1.

Two centrifugal pumps used in a water pumping application have the characteristic curves shown. The pumps operate in parallel and discharge into a common header against a head of 40 ft. What is most nearly the discharge rate of the pumps operating in parallel?



(A)

30 gpm

(B)

50 gpm

(C)

75 gpm

(D)

130 gpm

2.

An electric motor drives a pump in a gasoline transfer network. The system and pump curves are defined by the points in the given table. The gasoline has a specific gravity of 0.7. What is most nearly the horsepower for the motor?

	volume	
head(ft)	system curve (gpm)	pump curve (gpm)
10	0	1500
20	500	1200
30	1000	1000

	volume	
head(ft)	system curve (gpm)	pump curve (gpm)
40	1200	500
50	1500	0

(A)

4.0 hp

(B)

5.3 hp

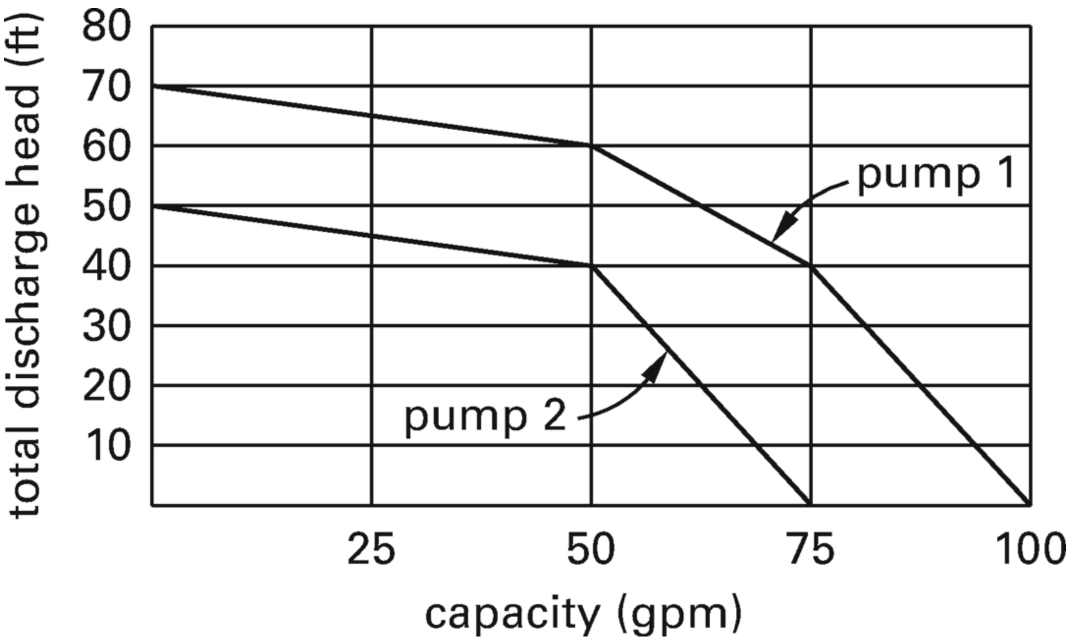
(C)

5.5 hp

(D)

7.6 hp
3.

Two centrifugal pumps used in a water pumping application have the characteristic curves shown. The pumps operate in series and have a combined discharge of 50 gpm. What is most nearly the total discharge head?



(A)

24 ft

(B)

50 ft

(C)

80 ft

(D)

100 ft

4.

2000 gal/min of 60°F thickened sludge with a specific gravity of 1.2 flows through a pump with an inlet diameter of 12 in and an outlet diameter of 8 in. The centerlines of the inlet and outlet are at the same elevation. The inlet pressure is 8 in of mercury (vacuum). A discharge pressure gauge located 4 ft above the pump discharge centerline reads 20 psig. The pump efficiency is 85%. All pipes are schedule-40. The input power of the pump is most nearly

(A)

26 hp

(B)

31 hp

(C)

37 hp

(D)

53 hp

5.

1.25 ft^3/sec (35 L/s) of 70°F (21°C) water is pumped from the bottom of a tank through 700 ft (230 m) of 4 in (102.3 mm) schedule-40 steel pipe. The line includes a 50 ft (15 m) rise in elevation, two right-angle elbows, a wide-open gate valve, and a swing check valve. All fittings and valves are regular screwed. The inlet pressure is 50 psig (345 kPa), and a working pressure of 20 psig (140 kPa) is needed at the end of the pipe. The hydraulic power for this pumping application is most nearly

(A)

16 hp (12 kW)

(B)

23 hp (17 kW)

(C)

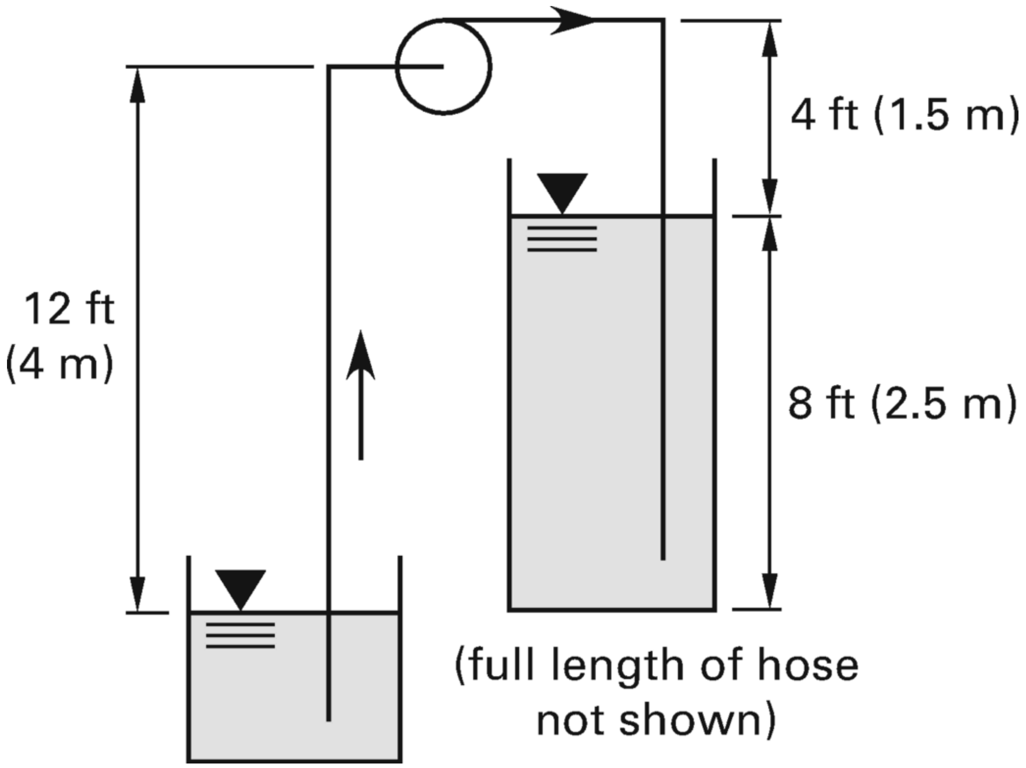
49 hp (37 kW)

(D)

66 hp (50 kW)

6.

80 gal/min (5 L/s) of 80°F (27°C) water is lifted 12 ft (4 m) vertically by a pump through a total length of 50 ft (15 m) of a 2 in (5.1 cm) diameter smooth rubber hose. The discharge end of the hose is submerged in 8 ft (2.5 m) of water as shown.



The head added by the pump is most nearly

(A)

10 ft (3.0 m)

(B)

13 ft (4.0 m)

(C)

22 ft (6.6 m)

(D)

31 ft (9.3 m)
7.

A 20 hp motor drives a centrifugal pump. The pump discharges 60°F (16°C) water at a velocity of 12 ft/sec (4 m/s) into a 6 in (15.2 cm) steel schedule-40 line. The inlet is 8 in (20.3 cm) schedule-40 steel pipe. The pump suction is 5 psig (35 kPa) below standard atmospheric pressure. The friction and fitting head loss in the system is 10 ft (3.3 m). The pump efficiency is 70%. The suction and discharge lines are at the same elevation. The maximum height above the pump inlet that water is available with that velocity at standard atmospheric pressure is most nearly

(A)

28 ft (6.9 m)

(B)

37 ft (11 m)

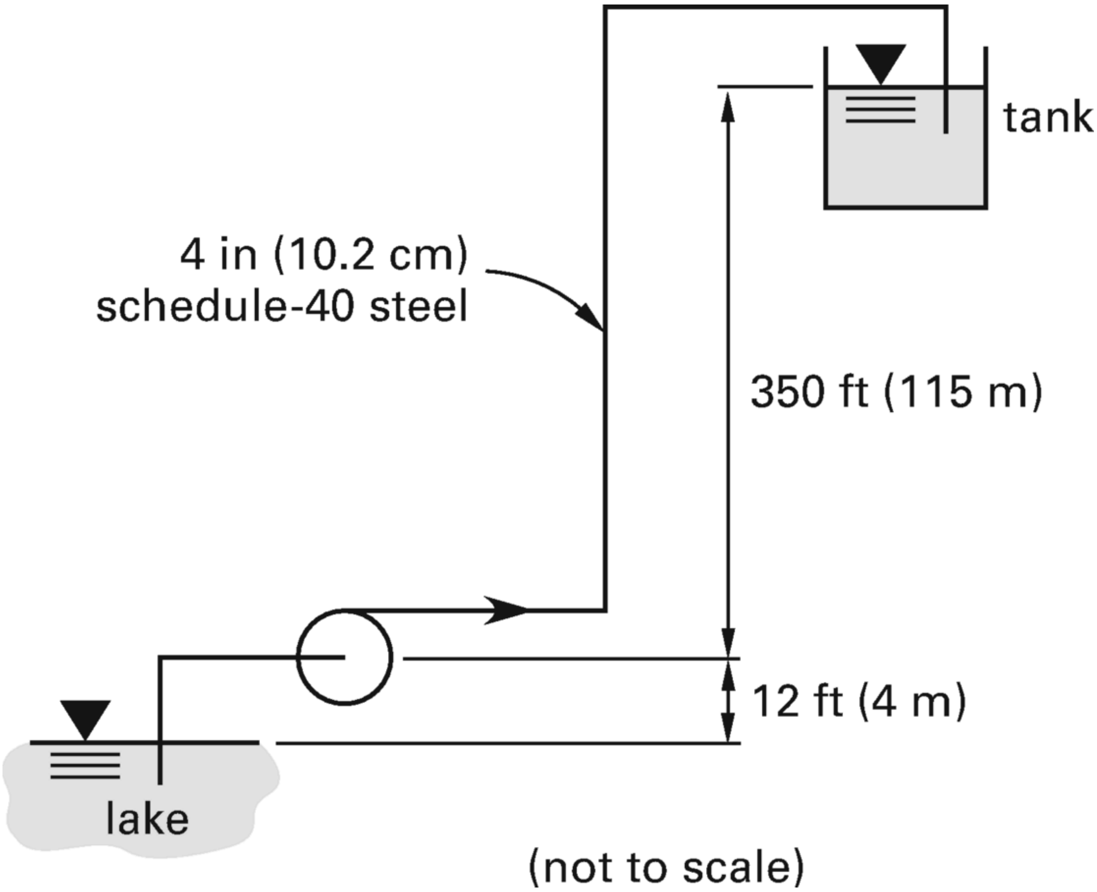
(C)

49 ft (15 m)

(D)

81 ft (25 m)
8.

An electrically driven pump is used to fill a tank on a hill from a lake below. The flow rate is 10,000 gal/hr (10.5 L/s) of 60°F (16°C) water. The atmospheric pressure is 14.7 psia (101 kPa). The pump is 12 ft (4 m) above the lake, and the tank surface level is 350 ft (115 m) above the pump. The suction and discharge lines are 4 in (10.2 cm) diameter schedule-40 steel pipe. The equivalent length of the inlet line between the lake and the pump is 300 ft (100 m). The total equivalent length between the lake and the tank is 7000 ft (2300 m), including all fittings, bends, screens, and valves. The cost of electricity is \$0.04 per kW·h. The overall efficiency of the pump and motor set is 70%.



The cost to operate the pump for one hour is most nearly

(A)

\$0.1

(B)

\$1

(C)

\$3

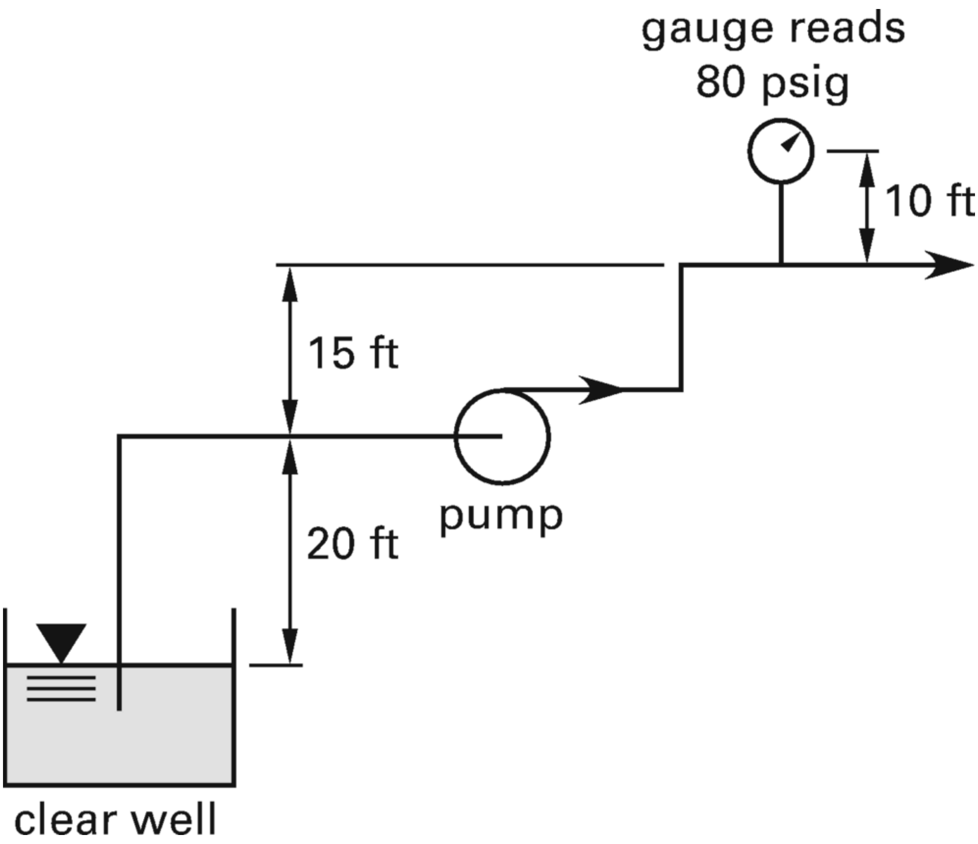
(D)

\$6

9.

A pump transfers 3.5 MGD of filtered water from the clear well of a 10 ft wide by 20 ft long rapid sand filter to a higher elevation. The pump efficiency is 85%, and the motor driving the pump has an efficiency of 90%.

Minor losses are insignificant. Refer to the illustration shown for additional information.



The required motor power is most nearly

(A)

50 hp

(B)

100 hp

(C)

150 hp

(D)

200 hp
10.

Gasoline with a specific gravity of 0.7 and kinematic viscosity of 6×10^{-6} ft^2/sec (5.6×10^{-10} m^2/s) is transferred from a tanker to a storage tank. The interior of the storage tank is maintained at atmospheric pressure by a vapor-recovery system. The free surface in the storage tank is 60 ft (20 m) above the tanker's free surface. The pipe consists of 500 ft (170 m) of 3 in (7.62 cm) schedule-40 steel pipe with six flanged elbows and two wide-open gate valves. The pump and motor both have individual efficiencies of 88%. Electricity costs $0.045 per kW·h. The pump's performance data (based on cold, clear water) are known.

flow rate (gpm (L/s))	head (ft (m))
0 (0)	127 (42)
100 (6.3)	124 (41)
200 (12)	117 (39)
300 (18)	108 (36)
400 (24)	96 (32)

flow rate (gpm (L/s))	head (ft (m))
500 (30)	80 (27)
600 (36)	55 (18)

The total cost of operating the pump for one hour is most nearly

(A)

\$0.20

(B)

\$0.80

(C)

\$1.30

(D)

\$2.70

11.

The pressure of 37 gal/min (65 L/s) of 80°F (27°C) SAE 40 oil is increased from 1 atm to 40 psig (275 kPa). The hydraulic power required is most nearly

(A)

0.45 hp (9 kW)

(B)

0.9 hp (18 kW)

(C)

1.8 hp (36 kW)

(D)

3.6 hp (72 kW)

12.

A double-suction water pump moving 300 gal/sec (1.1 kL/s) turns at 900 rpm. The pump adds 20 ft (7 m) of head to the water. The specific speed is most nearly

(A)

3000 rpm (52 rpm)

(B)

6000 rpm (100 rpm)

(C)

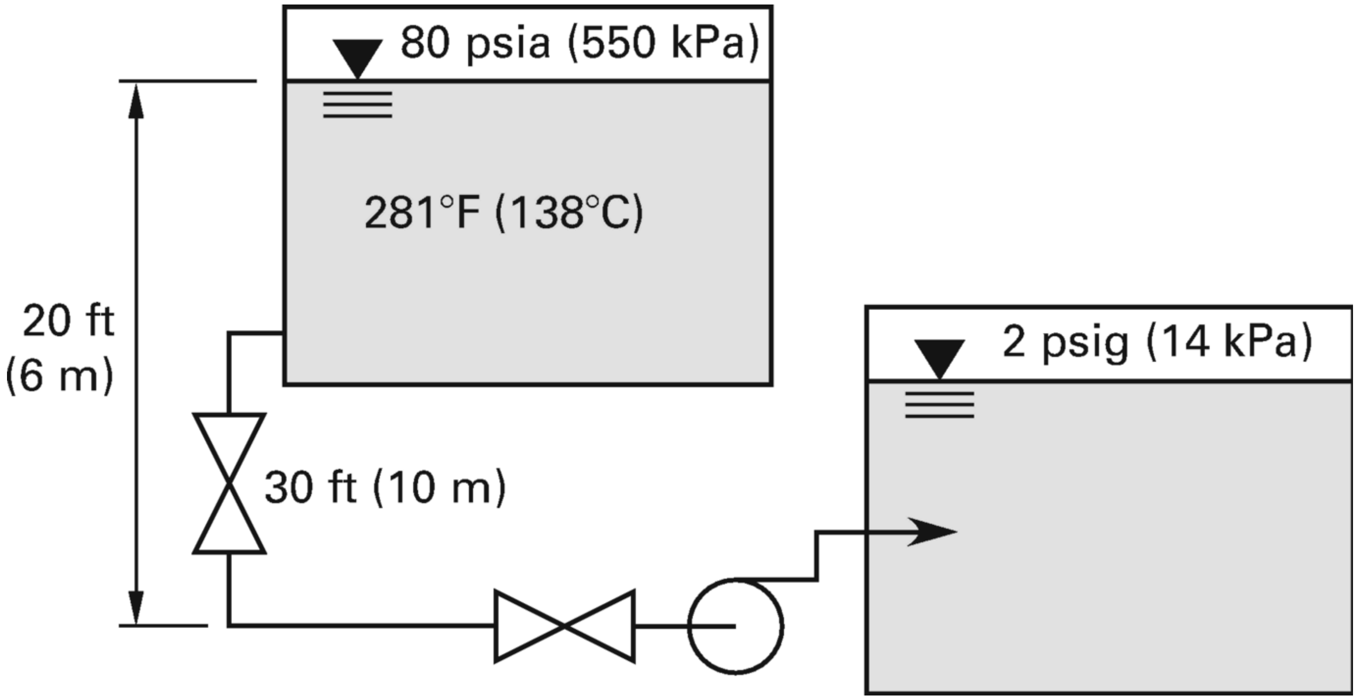
9000 rpm (160 rpm)

(D)

12,000 rpm (210 rpm)

13.

100 gal/min (6.3 L/s) of pressurized hot water at 281°F and 80 psia (138°C and 550 kPa) is drawn through 30 ft (10 m) of 1.5 in (3.81 cm) schedule-40 steel pipe into a tank pressurized to a constant 2 psig (14 kPa). The inlet and outlet are both 20 ft (6 m) below the surface of the water when the tank is full. The inlet line contains a square mouth inlet, two wide-open gate valves, and two long-radius elbows. All components are regular screwed. The pump's NPSHR is 10 ft (3 m) for this application. The kinematic viscosity of 281°F (138°C) water is 0.239×10^{-5} ft^2/sec (0.222×10^{-6} m^2/s), and the vapor pressure is 50.02 psia (3.431 bar). Will the pump cavitate?



(A)

yes; NPSHA = 4 ft (1.2 m)

(B)

yes; NPSHA = 9 ft (2.7 m)

(C)

no; NPSHA = 24 ft (7.2 m)

(D)

no; NPSHA = 68 ft (20.6 m)

14.

The velocity of the tip of a marine propeller is 4.2 times the velocity of the boat. The propeller is located 8 ft (3 m) below the surface. The temperature of the seawater is 68°F (20°C). The density of seawater is approximately 64.0 lbm/ft^3 (1024 kg/m^3), and the salt content is 2.5% by weight. The practical maximum boat velocity, as limited strictly by cavitation, is most nearly

(A)

9.1 ft/sec (2.7 m/s)

(B)

12 ft/sec (3.8 m/s)
(C)

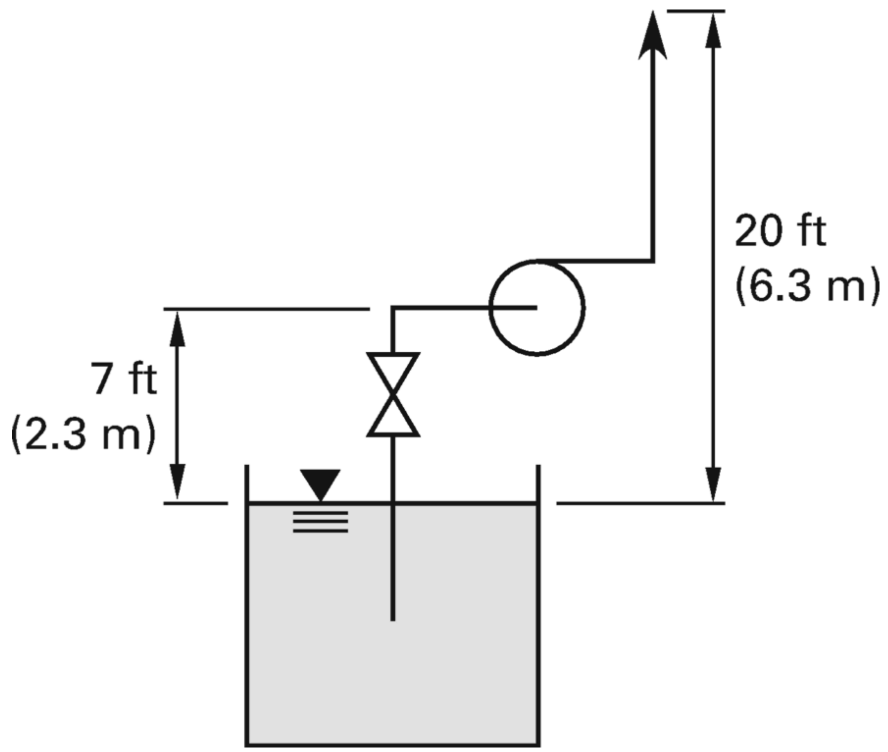
15 ft/sec (4.5 m/s)

(D)

22 ft/sec (6.6 m/s)
15.

The inlet of a centrifugal water pump is 7 ft (2.3 m) above the free surface from which it draws. The suction point is a submerged pipe. The suction line consists of 12 ft (4 m) of 2 in (5.08 cm) schedule-40 steel pipe and contains one long-radius 90° elbow and one swing check valve. The discharge line is 2 in (5.08 cm) schedule-40 steel pipe and includes two long radius elbows and an 80 ft (27 m) run. The discharge is 20 ft (6.3 m) above the free surface and is a jet to the open atmosphere. All components are regular screwed. The water temperature is 70°F (21°C). Use the following pump curve data.

flow rate (gpm (L/s))	head (ft (m))
0 (0)	110 (37)
10 (0.6)	108 (36)
20 (1.2)	105 (35)
30 (1.8)	102 (34)
40 (2.4)	98 (33)
50 (3.2)	93 (31)
60 (3.6)	87 (29)
70 (4.4)	79 (26)
80 (4.8)	66 (22)
90 (5.7)	50 (17)



The flow rate is most nearly

(A)

44 gal/min (2.9 L/s)

(B)

69 gal/min (4.5 L/s)

(C)

82 gal/min (5.5 L/s)

(D)

95 gal/min (6.2 L/s)
16.

A pump was intended to run at 1750 rpm when driven by a 0.5 hp (0.37 kW) motor. The required power rating of a motor that will turn the pump at 2000 rpm is most nearly

(A)

0.25 hp (0.19 kW)

(B)

0.45 hp (0.34 kW)

(C)

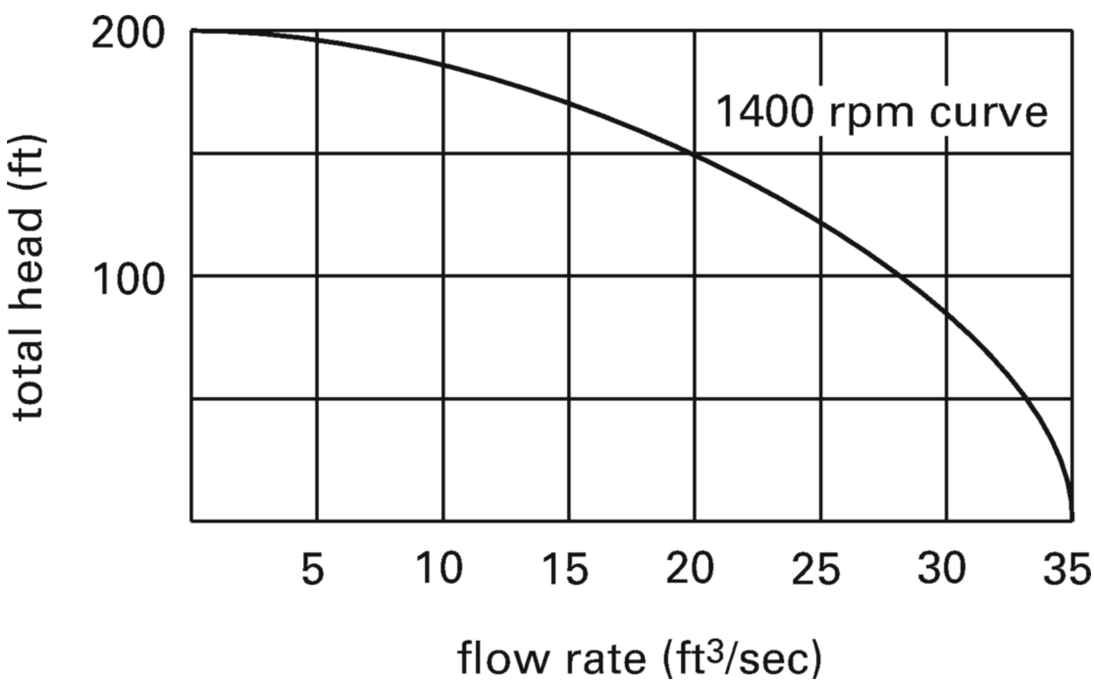
0.65 hp (0.49 kW)

(D)

0.75 hp (0.55 kW)

17.

A centrifugal pump running at 1400 rpm has the curve shown and an efficiency of 86%. The pump will be installed in an existing pipeline with known head requirements given by the formula $H = 30 + 2Q^2$. H is the system head in feet of water. Q is the flow rate in cubic feet per second.



The power required to drive the pump is most nearly

(A)

190 hp
(B)

210 hp

(C)

230 hp

(D)

260 hp
18.

A horizontal turbine reduces 100 ft^3/sec of water from 30 psia to 5 psia. Friction is negligible. The power developed is most nearly

(A)

350 hp

(B)

500 hp

(C)

650 hp

(D)

800 hp

19.

1000 ft^3/sec of 60°F water flows from a high reservoir through a hydroelectric turbine installation, exiting 625 ft lower. The head loss due to friction is 58 ft. The turbine efficiency is 89%. The power developed in the turbines is most nearly

(A)

40 kW

(B)

18 MW

(C)

43 MW

(D)

71 MW

20.

A Francis-design hydraulic reaction turbine with 22 in (560 mm) diameter blades runs at 610 rpm. The turbine develops 250 hp (185 kW) when 25 ft^3/sec (700 L/s) of water flow through it. The pressure head at the turbine entrance is 92.5 ft (28.2 m). The elevation of the turbine above the tailwater level is 5.26 ft (1.75 m). The inlet velocity is 12 ft/s (3.6 m/s) greater than the outlet velocity. The overall turbine efficiency is most nearly

(A)

81%

(B)

88%

(C)

93%

(D)

96%

Solutions

1.

Theoretically, when operating in parallel, each pump performs as if the other pump is not present. The capacities of each pump at a 40 ft discharge head are cumulative: 50 gpm for pump 2 and 75 gpm for pump 1.

$$\begin{aligned} Q_{\text{parallel}} &= Q_2 + Q_1 = 50\ \frac{\text{gal}}{\text{min}} + 75\ \frac{\text{gal}}{\text{min}} \\ &= 125\ \text{gpm} \quad (130\ \text{gpm}) \end{aligned}$$

The answer is (D).

2.

The system and pump curves intersect at 1000 gpm and 30 ft. From tableCERM18005 (also *NCEES Handbook:* Pump Power), the hydraulic horsepower is

$$\begin{aligned} \text{WHP} &= \frac{h_A Q\,(\text{SG})}{3956} = \frac{(30\ \text{ft})\left(1000\ \frac{\text{gal}}{\text{min}}\right)(0.7)}{3956\ \frac{\text{ft-gal}}{\text{hp-min}}} \\ &= 5.31\ \text{hp} \quad (5.3\ \text{hp}) \end{aligned}$$

This is the minimum power that the electric motor can produce.

The answer is (B).

3.

When operated in series, the second pump receives water at the rate of the first pump's discharge, so both pumps experience the same flow rate. The second pump adds pressure head to the first pump's pressurization, so the discharge heads are cumulative. At 50 gpm, the discharge heads are 60 ft for pump 1 and 40 ft for pump 2, respectively.

$$h_{A,\text{series}} = h_{A,1} + h_{A,2} = 60\ \text{ft} + 40\ \text{ft} = 100\ \text{ft}$$

The answer is (D).

4.

The flow rate is

$$\dot{V} = \frac{2000\ \frac{\text{gal}}{\text{min}}}{\left(7.4805\ \frac{\text{gal}}{\text{ft}^3}\right)\left(60\ \frac{\text{sec}}{\text{min}}\right)} = 4.456\ \text{ft}^3/\text{sec}$$

From appendixCERM16B (also *NCEES Handbook* table “Pipe Dimensions and Weights”),

$$\begin{aligned} &12\ \text{in: } D_1 = 0.99483\ \text{ft} \qquad A_1 = 0.7773\ \text{ft}^2 \\ &8\ \text{in: } D_2 = 0.6651\ \text{ft} \qquad A_2 = 0.3474\ \text{ft}^2 \end{aligned}$$

$$\begin{aligned} p_1 &= \left(14.7\ \frac{\text{lbf}}{\text{in}^2} - (8\ \text{in})\left(0.491\ \frac{\text{lbf}}{\text{in}^3}\right)\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2 \\ &= 1551.2\ \text{lbf/ft}^2 \\ p_2 &= \left(14.7\ \frac{\text{lbf}}{\text{in}^2} + 20\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2 \\ &\quad + (4\ \text{ft})(1.2)\left(62.4\ \frac{\text{lbf}}{\text{ft}^3}\right) \\ &= 5296.3\ \text{lbf/ft}^2 \end{aligned}$$

As in *NCEES Handbook:* Conservation of Mass,

$$\begin{aligned} \text{v}_1 &= \frac{\dot{V}}{A_1} = \frac{4.456\ \frac{\text{ft}^3}{\text{sec}}}{0.7773\ \text{ft}^2} = 5.73\ \text{ft/sec} \\ \text{v}_2 &= \frac{\dot{V}}{A_2} = \frac{4.456\ \frac{\text{ft}^3}{\text{sec}}}{0.3474\ \text{ft}^2} = 12.83\ \text{ft/sec} \end{aligned}$$

Using a modified Bernoulli equation from equationCERM18009 (also *NCEES Handbook:* The Bernoulli Equation), the total heads (in feet of sludge) at points 1 and 2 are

$$\begin{aligned} h_{t,1} &= h_{t,s} = \frac{p_1}{\gamma} + \frac{\text{v}_1^2}{2g} \\ &= \frac{1551.2\ \frac{\text{lbf}}{\text{ft}^2}}{\left(62.4\ \frac{\text{lbf}}{\text{ft}^3}\right)(1.2)} + \frac{\left(5.73\ \frac{\text{ft}}{\text{sec}}\right)^2}{(2)\left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)} \\ &= 21.23\ \text{ft} \end{aligned}$$

$$\begin{aligned} h_{t,2} &= h_{t,d} = \frac{p_2}{\gamma} + \frac{\text{v}_2^2}{2g} \\ &= \frac{5296.3\ \frac{\text{lbf}}{\text{ft}^2}}{\left(62.4\ \frac{\text{lbf}}{\text{ft}^3}\right)(1.2)} + \frac{\left(12.83\ \frac{\text{ft}}{\text{sec}}\right)^2}{(2)\left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)} \\ &= 73.29\ \text{ft} \end{aligned}$$

The pump must add 73.29 ft – 21.23 ft = 52.06 ft of head (sludge head).

The power required is given in tableCERM18005 (also *NCEES Handbook:* Pump Power).

$$\begin{aligned} P_{\text{ideal}} &= \frac{\Delta p\dot{V}}{550} = \frac{\Delta h\gamma\dot{V}}{550} = \frac{\Delta h\,(\text{SG})\,\gamma_w\dot{V}}{550} \\ &= \frac{(52.06\ \text{ft})(1.2)\left(62.4\ \frac{\text{lbf}}{\text{ft}^3}\right)\left(4.456\ \frac{\text{ft}^3}{\text{sec}}\right)}{550\ \frac{\text{ft-lbf}}{\text{hp-sec}}} \\ &= 31.58\ \text{hp} \end{aligned}$$

The input horsepower is

$$P_{\text{in}} = \frac{P_{\text{ideal}}}{\eta} = \frac{31.58 \text{ hp}}{0.85} = 37.15 \text{ hp} \quad (37 \text{ hp})$$

The answer is (C).
5.

Customary U.S. Solution

From appendixCERM16B (also *NCEES Handbook* table "Pipe Dimensions and Weights"), data for 4 in schedule-40 steel pipe are

$$\begin{aligned} D &= 0.3355 \text{ ft} \\ A &= 0.08841 \text{ ft}^2 \end{aligned}$$

The velocity in the pipe is in *NCEES Handbook:* Conservation of Mass.

$$\text{v} = \frac{\dot{V}}{A} = \frac{1.25 \ \frac{\text{ft}^3}{\text{sec}}}{0.08841 \text{ ft}^2} = 14.139 \text{ ft/sec}$$

From appendixCERM17D (also *NCEES Handbook:* Head Loss in Pipe or Conduit), typical equivalent lengths for schedule-40, screwed steel fittings for 4 in pipes are

$$\begin{aligned} &90^\circ \text{ elbow: } 13 \text{ ft} \\ &\text{gate valve: } 2.5 \text{ ft} \\ &\text{check valve: } 38 \text{ ft} \end{aligned}$$

The total equivalent length is

$$(2)(13 \text{ ft}) + (1)(2.5 \text{ ft}) + (1)(38 \text{ ft}) = 66.5 \text{ ft}$$

From appendixCERM14A (also *NCEES Handbook* table "Physical Properties of Liquid Water (U.S. Units)"), the density of water is 62.3 lbm/ft^3, and the kinematic viscosity of water, ν, at 70°F is 1.059×10^{-5} ft^2/sec. The Reynolds number is from *NCEES Handbook:* Similitude.

$$\begin{aligned} \text{Re} &= \frac{D\text{v}}{\nu} = \frac{(0.3355 \text{ ft})\left(14.139 \ \frac{\text{ft}}{\text{sec}}\right)}{1.059 \times 10^{-5} \ \frac{\text{ft}^2}{\text{sec}}} \\ &= 4.479 \times 10^5 \end{aligned}$$

From appendixCERM17A (also *NCEES Handbook:* Absolute Roughness and Relative Roughness), for steel, ϵ = 0.0002 ft.

So,

$$\frac{\epsilon}{D} = \frac{0.0002 \text{ ft}}{0.3355 \text{ ft}} \approx 0.0006$$

Interpolating from appendixCERM17B (also *NCEES Handbook:* Friction Factors for Turbulent Flow), the friction factor is $f = 0.01835$.

The friction head is given by equationCERM18006 (also *NCEES Handbook:* Head Loss in Pipe or Conduit).

$$
\begin{aligned}
h_f &= \frac{fL\mathrm{v}^2}{2Dg} \\
&= \frac{(0.01835)\,(700\ \mathrm{ft} + 66.5\ \mathrm{ft})\left(14.139\ \frac{\mathrm{ft}}{\mathrm{sec}}\right)^2}{(2)\,(0.3355\ \mathrm{ft})\left(32.2\ \frac{\mathrm{ft}}{\mathrm{sec}^2}\right)} \\
&= 130.1\ \mathrm{ft}
\end{aligned}
$$

The total dynamic head is given by equationCERM18009 (also *NCEES Handbook:* Pump Similitude). Point 1 is taken as the bottom of the supply tank. Point 2 is taken as the end of the discharge pipe.

$$
\begin{aligned}
h &= \frac{(p_2 - p_1)\,g_c}{\rho g} + \frac{\mathrm{v}_2^2 - \mathrm{v}_1^2}{2g} + z_2 - z_1 \\
\mathrm{v}_1 &\approx 0 \\
z_2 - z_1 &= 50\ \mathrm{ft} \quad \text{[given as rise in elevation]}
\end{aligned}
$$

The outlet and inlet pressures are

$$
\begin{aligned}
p_2 &= 20\ \mathrm{psig} \\
p_1 &= 50\ \mathrm{psig}
\end{aligned}
$$

The pressure head added by the pump is

$$
\begin{aligned}
h &= \frac{(p_2 - p_1)\,g_c}{\rho g} + \frac{\mathrm{v}_2^2 - \mathrm{v}_1^2}{2g} + z_2 - z_1 \\
&= \frac{\left(20\ \frac{\mathrm{lbf}}{\mathrm{in}^2} - 50\ \frac{\mathrm{lbf}}{\mathrm{in}^2}\right)\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2\left(32.2\ \frac{\mathrm{lbm\text{-}ft}}{\mathrm{lbf\text{-}sec}^2}\right)}{\left(62.3\ \frac{\mathrm{lbm}}{\mathrm{ft}^3}\right)\left(32.2\ \frac{\mathrm{ft}}{\mathrm{sec}^2}\right)} \\
&\quad + \frac{\left(14.139\ \frac{\mathrm{ft}}{\mathrm{sec}}\right)^2}{(2)\left(32.2\ \frac{\mathrm{ft}}{\mathrm{sec}^2}\right)} + 50\ \mathrm{ft} \\
&= -16.2\ \mathrm{ft}
\end{aligned}
$$

The head added is

$$
\begin{aligned}
h_A &= h + h_f \\
&= -16.2\ \mathrm{ft} + 130.1\ \mathrm{ft} \\
&= 113.9\ \mathrm{ft}
\end{aligned}
$$

The mass flow rate is

$$
\begin{aligned}
\dot{m} &= \rho \dot{V} \\
&= \left(62.3\ \frac{\mathrm{lbm}}{\mathrm{ft}^3}\right)\left(1.25\ \frac{\mathrm{ft}^3}{\mathrm{sec}}\right) \\
&= 77.875\ \mathrm{lbm/sec}
\end{aligned}
$$

From tableCERM18005 (also *NCEES Handbook:* Pump Power), the hydraulic horsepower is

$$
\begin{aligned}
\mathrm{WHP} &= \frac{h_A \dot{m}}{550} \times \frac{g}{g_c} \\
&= \left(\frac{(113.9\ \mathrm{ft})\left(77.875\ \frac{\mathrm{lbm}}{\mathrm{sec}}\right)}{550\ \frac{\mathrm{ft\text{-}lbf}}{\mathrm{hp\text{-}sec}}}\right)\left(\frac{32.2\ \frac{\mathrm{ft}}{\mathrm{sec}^2}}{32.2\ \frac{\mathrm{lbm\text{-}ft}}{\mathrm{lbf\text{-}sec}^2}}\right) \\
&= 16.13\ \mathrm{hp} \quad (16\ \mathrm{hp})
\end{aligned}
$$

The answer is (A).

SI Solution

From appendixCERM16C (also *NCEES Handbook* table “Pipe Dimensions and Weights”), data for 4 in schedule-40 steel pipe are

$$\begin{aligned} D &= 102.26 \text{ mm} \\ A &= 82.30 \text{ cm}^2 \end{aligned}$$

As in *NCEES Handbook:* Conservation of Mass, the velocity in the pipe is

$$\text{v} = \frac{\dot{V}}{A} = \frac{\left(35\ \frac{\text{L}}{\text{s}}\right)\left(100\ \frac{\text{cm}}{\text{m}}\right)^2}{(82.30\text{ cm}^2)\left(1000\ \frac{\text{L}}{\text{m}^3}\right)} = 4.25 \text{ m/s}$$

From appendixCERM17D (also *NCEES Handbook:* Head Loss in Pipe or Conduit), typical equivalent lengths for schedule-40, screwed steel fittings for 4 in pipes are

$$\begin{aligned} &90^\circ \text{ elbow: } 13.0 \text{ ft} \\ &\text{gate valve: } 2.5 \text{ ft} \\ &\text{check valve: } 38.0 \text{ ft} \end{aligned}$$

The total equivalent length is

$$\begin{aligned} (2)(13.0\text{ ft}) + (1)(2.5\text{ ft}) + (1)(38.0\text{ ft}) &= 66.5 \text{ ft} \\ (66.5\text{ ft})\left(0.3048\ \frac{\text{m}}{\text{ft}}\right) &= 20.27 \text{ m} \end{aligned}$$

At 21°C, from appendixCERM14B (also *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units)”), the water properties are

$$\begin{aligned} \rho &= 998 \text{ kg/m}^3 \\ \mu &= 0.9827 \times 10^{-3}\ \text{Pa·s} \\ \nu &= \frac{\mu}{\rho} = \frac{0.9827 \times 10^{-3}\ \text{Pa·s}}{998\ \frac{\text{kg}}{\text{m}^3}} \\ &= 9.85 \times 10^{-7}\ \text{m}^2/\text{s} \end{aligned}$$

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\begin{aligned} \text{Re} &= \frac{D\text{v}}{\nu} = \frac{(102.26\text{ mm})\left(4.25\ \frac{\text{m}}{\text{s}}\right)}{\left(9.85 \times 10^{-7}\ \frac{\text{m}^2}{\text{s}}\right)\left(1000\ \frac{\text{mm}}{\text{m}}\right)} \\ &= 4.417 \times 10^5 \end{aligned}$$

From tableCERM17002 (also *NCEES Handbook:* Absolute Roughness and Relative Roughness), for steel, $\epsilon = 6.0 \times 10^{-5}$ m.

$$\begin{aligned} \frac{\epsilon}{D} &= \frac{(6.0 \times 10^{-5}\ \text{m})\left(1000\ \frac{\text{mm}}{\text{m}}\right)}{102.26 \text{ mm}} \\ &= 0.0006 \end{aligned}$$

Interpolating from appendixCERM17B (also *NCEES Handbook:* Friction Factors for Turbulent Flow), the friction factor is $f = 0.01836$.

From equationCERM18006 (also *NCEES Handbook:* Head Loss in Pipe or Conduit), the friction head is

$$\begin{aligned}h_f &= \frac{fL\mathrm{v}^2}{2Dg}\\ &= \frac{(0.01836)\,(230\ \mathrm{m}+20.27\ \mathrm{m})\times\left(4.25\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2\left(1000\ \frac{\mathrm{mm}}{\mathrm{m}}\right)}{(2)\,(102.26\ \mathrm{mm})\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)}\\ &= 41.4\ \mathrm{m}\end{aligned}$$

The total dynamic head is given by equationCERM18009 (also *NCEES Handbook:* Pump Similitude). Point 1 is taken as the bottom of the supply tank. Point 2 is taken as the end of the discharge pipe.

$$\begin{aligned}h &= \frac{p_2-p_1}{\rho g}+\frac{\mathrm{v}_2^2-\mathrm{v}_1^2}{2g}+z_2-z_1\\ \mathrm{v}_1 &\approx 0\\ z_2-z_1 &= 15\ \mathrm{m}\quad [\text{given as rise in elevation}]\end{aligned}$$

The difference between outlet and inlet pressure is

$$\begin{aligned}p_2-p_1 &= 140\ \mathrm{kPa}-345\ \mathrm{kPa}=-205\ \mathrm{kPa}\\ h &= \frac{(-205\ \mathrm{kPa})\left(1000\ \frac{\mathrm{Pa}}{\mathrm{kPa}}\right)}{\left(998\ \frac{\mathrm{kg}}{\mathrm{m}^3}\right)\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)}\\ &\quad+\frac{\left(4.25\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2}{(2)\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)}+15\ \mathrm{m}\\ &= -5.0\ \mathrm{m}\end{aligned}$$

The head added by the pump is

$$h_A = h+h_f = -5.0\ \mathrm{m}+41.4\ \mathrm{m} = 36.4\ \mathrm{m}$$

The mass flow rate is

$$\begin{aligned}\dot{m} = \rho\dot{V} &= \frac{\left(998\ \frac{\mathrm{kg}}{\mathrm{m}^3}\right)\left(35\ \frac{\mathrm{L}}{\mathrm{s}}\right)}{1000\ \frac{\mathrm{L}}{\mathrm{m}^3}}\\ &= 34.93\ \mathrm{kg/s}\end{aligned}$$

From tableCERM18006 (also *NCEES Handbook:* Pump Power), the hydraulic power is

$$\begin{aligned}\mathrm{WkW} = \frac{9.81h_A\dot{m}}{1000} &= \frac{\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)(36.4\ \mathrm{m})\left(34.93\ \frac{\mathrm{kg}}{\mathrm{s}}\right)}{1000\ \frac{\mathrm{W}}{\mathrm{kW}}}\\ &= 12.46\ \mathrm{kW}\quad (12\ \mathrm{kW})\end{aligned}$$

The answer is (A).
6.

Customary U.S. Solution

The area of the rubber hose is

$$A=\frac{\pi D^2}{4}=\frac{\pi\left(\frac{2\ \text{in}}{12\ \frac{\text{in}}{\text{ft}}}\right)^2}{4}=0.0218\ \text{ft}^2$$

As in *NCEES Handbook:* Conservation of Mass, the velocity of water in the hose is

$$\begin{aligned}\text{v}=\frac{\dot{V}}{A}&=\frac{80\ \frac{\text{gal}}{\text{min}}}{(0.0218\ \text{ft}^2)\left(7.4805\ \frac{\text{gal}}{\text{ft}^3}\right)\left(60\ \frac{\text{sec}}{\text{min}}\right)}\\&=8.176\ \text{ft/sec}\end{aligned}$$

At 80°F, as in *NCEES Handbook* table "Physical Properties of Liquid Water (U.S. Units)," the kinematic viscosity of water is $\nu = 0.930 \times 10^{-5}\ \text{ft}^2/\text{sec}$.

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\begin{aligned}\text{Re}=\frac{\text{v}D}{\nu}&=\frac{\left(8.176\ \frac{\text{ft}}{\text{sec}}\right)(2\ \text{in})}{\left(0.930\times10^{-5}\ \frac{\text{ft}^2}{\text{sec}}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)}\\&=1.47\times10^5\end{aligned}$$

Since the rubber hose is smooth, from *NCEES Handbook:* Friction Factors for Turbulent Flow, the friction factor is $f = 0.0166$.

From equationCERM18006 (also *NCEES Handbook:* Head Loss in Pipe or Conduit), the friction head is

$$\begin{aligned}h_f=\frac{fL\text{v}^2}{2Dg}&=\frac{(0.0166)(50\ \text{ft})\left(8.176\ \frac{\text{ft}}{\text{sec}}\right)^2\left(12\ \frac{\text{in}}{\text{ft}}\right)}{(2)(2\ \text{in})\left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)}\\&=5.17\ \text{ft}\end{aligned}$$

Neglecting entrance and exit losses, the head added by the pump is

$$\begin{aligned}h_A&=h_f+h_z=5.17\ \text{ft}+(12\ \text{ft}-4\ \text{ft})\\&=13.17\ \text{ft}\quad(13\ \text{ft})\end{aligned}$$

The answer is (B).

SI Solution

The area of the rubber hose is

$$A=\frac{\pi D^2}{4}=\frac{\pi(5.1\ \text{cm})^2}{(4)\left(100\ \frac{\text{cm}}{\text{m}}\right)^2}=0.00204\ \text{m}^2$$

As in *NCEES Handbook:* Conservation of Mass, the velocity of water in the hose is

$$\text{v}=\frac{\dot{V}}{A}=\frac{5\ \frac{\text{L}}{\text{s}}}{(0.00204\ \text{m}^2)\left(1000\ \frac{\text{L}}{\text{m}^3}\right)}=2.45\ \text{m/s}$$

At 27°C, from appendixCERM14B (also *NCEES Handbook* table "Physical Properties of Liquid Water (SI Units)"), the kinematic viscosity of water is $\nu = 0.854 \times 10^{-6}\ \text{m}^2/\text{s}$.

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\mathrm{Re} = \frac{\mathrm{v}D}{\nu} = \frac{\left(2.45\ \frac{\mathrm{m}}{\mathrm{s}}\right)(5.1\ \mathrm{cm})}{\left(0.854\times 10^{-6}\ \frac{\mathrm{m}^2}{\mathrm{s}}\right)\left(100\ \frac{\mathrm{cm}}{\mathrm{m}}\right)} = 1.46\times 10^5$$

Since the rubber hose is smooth, from appendixCERM17B (also *NCEES Handbook:* Friction Factors for Turbulent Flow), the friction factor is $f = 0.0166$.

From equationCERM18006 (also *NCEES Handbook:* Head Loss in Pipe or Conduit), the friction head is

$$\begin{aligned} h_f &= \frac{fL\mathrm{v}^2}{2Dg} = \frac{(0.0166)(15\ \mathrm{m})\left(2.45\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2\left(100\ \frac{\mathrm{cm}}{\mathrm{m}}\right)}{(2)(5.1\ \mathrm{cm})\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)} \\ &= 1.49\ \mathrm{m} \end{aligned}$$

Neglecting entrance and exit losses, the head added by the pump is

$$\begin{aligned} h_A &= h_f + h_z \\ &= 1.49\ \mathrm{m} + 4\ \mathrm{m} - 1.5\ \mathrm{m} \\ &= 3.99\ \mathrm{m} \quad (4.0\ \mathrm{m}) \end{aligned}$$

The answer is (B).
7.

Customary U.S. Solution

From appendixCERM16B (also *NCEES Handbook* table "Pipe Dimensions and Weights"), the diameters (inside) for 8 in and 6 in schedule-40 steel pipe are

$$\begin{aligned} D_1 &= 7.981\ \mathrm{in} \\ D_2 &= 6.065\ \mathrm{in} \end{aligned}$$

At 60°F, from appendixCERM14A, the density of water is 62.37 lbm/ft^3.

The mass flow rate through 6 in pipe is from *NCEES Handbook:* Conservation of Mass.

$$\begin{aligned} \dot{m} &= A_2\mathrm{v}_2\rho = \frac{\pi\left(\frac{(6.065\ \mathrm{in})^2}{4}\right)\left(12\ \frac{\mathrm{ft}}{\mathrm{sec}}\right)\left(62.37\ \frac{\mathrm{lbm}}{\mathrm{ft}^3}\right)}{\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2} \\ &= 150.2\ \mathrm{lbm/sec} \end{aligned}$$

The inlet (suction) pressure is

$$(14.7\ \mathrm{psia} - 5\ \mathrm{psig})\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2 = 1397\ \mathrm{lbf/ft}^2$$

From tableCERM18005 (also *NCEES Handbook:* Pump Power), the head added by the pump is

$$\begin{aligned} h_A &= \frac{550\,(\mathrm{BHP})\,\eta}{\dot{m}} \times \frac{g_c}{g} \\ &= \left(\frac{\left(550\ \frac{\mathrm{ft\text{-}lbf}}{\mathrm{hp\text{-}sec}}\right)(20\ \mathrm{hp})(0.70)}{150.2\ \frac{\mathrm{lbm}}{\mathrm{sec}}}\right)\left(\frac{32.2\ \frac{\mathrm{lbm\text{-}ft}}{\mathrm{lbf\text{-}sec}^2}}{32.2\ \frac{\mathrm{ft}}{\mathrm{sec}^2}}\right) \\ &= 51.26\ \mathrm{ft} \end{aligned}$$

At 1 (pump inlet),

$$
\begin{aligned}
p_1 &= 1397 \text{ lbf/ft}^2 \quad [\text{absolute}] \\
z_1 &= 0 \\
\text{v}_1 &= \frac{\text{v}_2 A_2}{A_1} = \text{v}_2 \left(\frac{D_2}{D_1}\right)^2 = \left(12 \ \frac{\text{ft}}{\text{sec}}\right)\left(\frac{6.065 \text{ in}}{7.981 \text{ in}}\right)^2 \\
&= 6.93 \text{ ft/sec}
\end{aligned}
$$

At 2 (pump outlet),

$$
\begin{aligned}
p_2 & \quad [\text{unknown}] \\
\text{v}_2 &= 12 \text{ ft/sec} \quad [\text{given}] \\
z_2 &= z_1 = 0 \\
h_{f,1-2} &= 0
\end{aligned}
$$

Let z_3 be the additional head above atmospheric. As in *NCEES Handbook:* Pump Head, the head added by the pump is

$$
\begin{aligned}
h_A &= \frac{(p_2 - p_1)\, g_c}{\rho g} + \frac{\text{v}_2^2 - \text{v}_1^2}{2g} + z_2 - z_1 + h_{f,1-2} \\
51.26 \text{ ft} &= \frac{\left(p_2 - 1397 \ \frac{\text{lbf}}{\text{ft}^2}\right)\left(32.2 \ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}\right)}{\left(62.37 \ \frac{\text{lbm}}{\text{ft}^3}\right)\left(32.2 \ \frac{\text{ft}}{\text{sec}^2}\right)} \\
&\quad + \frac{\left(12 \ \frac{\text{ft}}{\text{sec}}\right)^2 - \left(6.93 \ \frac{\text{ft}}{\text{sec}}\right)^2}{(2)\left(32.2 \ \frac{\text{ft}}{\text{sec}^2}\right)} \\
&\quad + 0 \text{ ft} - 0 \text{ ft} + 0 \text{ ft} \\
p_2 &= 4501.2 \text{ lbf/ft}^2
\end{aligned}
$$

At 3 (discharge),

$$
\begin{aligned}
p_3 &= \left(14.7 \ \frac{\text{lbf}}{\text{in}^2}\right)\left(12 \ \frac{\text{in}}{\text{ft}}\right)^2 = 2117 \text{ lbf/ft}^2 \\
\text{v}_3 &= 12 \text{ ft/sec} \quad [\text{given}] \\
z_3 & \quad [\text{unknown}] \\
h_{f,2-3} &= 10 \text{ ft} \\
h_A &= 0 \quad [\text{no pump between points 2 and 3}] \\
h_A &= \frac{(p_3 - p_2)\, g_c}{\rho g} + \frac{\text{v}_3^2 - \text{v}_2^2}{2g} + z_3 - z_2 + h_{f,2-3} \\
0 &= \frac{\left(2117 \ \frac{\text{lbf}}{\text{ft}^2} - 4501.2 \ \frac{\text{lbf}}{\text{ft}^2}\right)\left(32.2 \ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}\right)}{\left(62.37 \ \frac{\text{lbm}}{\text{ft}^3}\right)\left(32.2 \ \frac{\text{ft}}{\text{sec}^2}\right)} \\
&\quad + \frac{\left(12 \ \frac{\text{ft}}{\text{sec}}\right)^2 - \left(12 \ \frac{\text{ft}}{\text{sec}}\right)^2}{(2)\left(32.2 \ \frac{\text{ft}}{\text{sec}^2}\right)} \\
&\quad + z_3 - 0 \text{ ft} + 10 \text{ ft} \\
z_3 &= 28.2 \text{ ft} \quad (28 \text{ ft})
\end{aligned}
$$

z_3 could have been found directly without determining the intermediate pressure, p_2. This method is illustrated in the SI solution.

The answer is (A).

SI Solution

From appendixCERM16C (also *NCEES Handbook* table “Pipe Dimensions and Weights”), the inside diameters for 8 in and 6 in steel schedule-40 pipe are

$$\begin{aligned} D_1 &= 202.717\ \text{mm} \\ D_2 &= 154.051\ \text{mm} \end{aligned}$$

At 16°C, from appendixCERM14B (also *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units)”), the density of water is 998.95 kg/m^3.

As in *NCEES Handbook:* Conservation of Mass, the mass flow rate through the 6 in pipe is

$$\begin{aligned} \dot{m} &= A_2 \text{v}_2 \rho = \frac{\pi \left(\frac{(154.051\ \text{mm})^2}{4} \right) \left(4\ \frac{\text{m}}{\text{s}} \right) \left(998.95\ \frac{\text{kg}}{\text{m}^3} \right)}{\left(1000\ \frac{\text{mm}}{\text{m}} \right)^2} \\ &= 74.5\ \text{kg/s} \end{aligned}$$

The inlet (suction) pressure is

$$101.3\ \text{kPa} - 35\ \text{kPa} = 66.3\ \text{kPa}$$

From tableCERM18006 (also *NCEES Handbook:* Pump Power), the head added by the pump is

$$\begin{aligned} h_A &= \frac{1000\,(\text{BkW})\,\eta}{9.81\dot{m}} \\ &= \frac{\left(1000\ \frac{\text{W}}{\text{kW}} \right) (20\ \text{hp}) \left(0.7457\ \frac{\text{kW}}{\text{hp}} \right) (0.70)}{\left(9.81\ \frac{\text{m}}{\text{s}^2} \right) \left(74.5\ \frac{\text{kg}}{\text{s}} \right)} \\ &= 14.29\ \text{m} \end{aligned}$$

At 1 (pump inlet),

$$\begin{aligned} p_1 &= 66.3\ \text{kPa} \\ z_1 &= 0 \\ \text{v}_1 &= \text{v}_2 \left(\frac{A_2}{A_1} \right) = \text{v}_2 \left(\frac{D_2}{D_1} \right)^2 = \left(4\ \frac{\text{m}}{\text{s}} \right) \left(\frac{154.051\ \text{mm}}{202.717\ \text{mm}} \right)^2 \\ &= 2.31\ \text{m/s} \end{aligned}$$

At 2 (pump outlet),

$$\begin{aligned} p_2 &= 101.3\ \text{kPa} \\ \text{v}_2 &= 4\ \text{m/s} \quad [\text{given}] \end{aligned}$$

As in *NCEES Handbook:* Pump Head, the head added by the pump is

$$\begin{aligned} h_A &= \frac{p_2 - p_1}{\rho g} + \frac{\text{v}_2^2 - \text{v}_1^2}{2g} + z_2 - z_1 + h_f + z_3 \\ 14.29\ \text{m} &= \frac{(101.3\ \text{kPa} - 66.3\ \text{kPa}) \left(1000\ \frac{\text{Pa}}{\text{kPa}} \right)}{\left(998.95\ \frac{\text{kg}}{\text{m}^3} \right) \left(9.81\ \frac{\text{m}}{\text{s}^2} \right)} \\ &\quad + \frac{\left(4\ \frac{\text{m}}{\text{s}} \right)^2 - \left(2.31\ \frac{\text{m}}{\text{s}} \right)^2}{(2) \left(9.81\ \frac{\text{m}}{\text{s}^2} \right)} \\ &\quad + 0\ \text{m} - 0\ \text{m} + 3.3\ \text{m} + z_3 \\ z_3 &= 6.87\ \text{m} \quad (6.9\ \text{m}) \end{aligned}$$

The answer is (A).

8.

Customary U.S. Solution

The flow rate is

$$\dot{V} = \left(10{,}000\ \frac{\text{gal}}{\text{hr}}\right)\left(0.1337\ \frac{\text{ft}^3}{\text{gal}}\right) = 1337\ \text{ft}^3/\text{hr}$$

From appendixCERM16B (also *NCEES Handbook* table "Pipe Dimensions and Weights"), for 4 in schedule-40 steel pipe,

$$\begin{aligned} D &= 0.3355\ \text{ft} \\ A &= 0.08841\ \text{ft}^2 \end{aligned}$$

As in *NCEES Handbook:* Conservation of Mass, the velocity in the pipe is

$$\begin{aligned} \text{v} = \frac{\dot{V}}{A} &= \frac{1337\ \frac{\text{ft}^3}{\text{hr}}}{\left(0.08841\ \text{ft}^2\right)\left(3600\ \frac{\text{sec}}{\text{hr}}\right)} \\ &= 4.20\ \text{ft/sec} \end{aligned}$$

From appendixCERM14A (also *NCEES Handbook* table "Physical Properties of Liquid Water (U.S. Units)"), the kinematic viscosity of water at 60°F is

$$\begin{aligned} \nu &= 1.217 \times 10^{-5}\ \text{ft}^2/\text{sec} \\ \rho &= 62.37\ \text{lbm/ft}^3 \end{aligned}$$

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\begin{aligned} \text{Re} = \frac{D\text{v}}{\nu} &= \frac{(0.3355\ \text{ft})\left(4.20\ \frac{\text{ft}}{\text{sec}}\right)}{1.217 \times 10^{-5}\ \frac{\text{ft}^2}{\text{sec}}} \\ &= 1.16 \times 10^5 \end{aligned}$$

From appendixCERM17A (also *NCEES Handbook:* Absolute Roughness and Relative Roughness), for welded and seamless steel, $\epsilon = 0.0002$ ft.

$$\frac{\epsilon}{D} = \frac{0.0002\ \text{ft}}{0.3355\ \text{ft}} \approx 0.0006$$

From appendixCERM17B (also *NCEES Handbook:* Friction Factors for Turbulent Flow), the friction factor, f, is 0.0205. The 7000 ft of equivalent length includes the pipe between the lake and the pump. Using *NCEES Handbook:* Head Loss in Pipe or Conduit, the friction head is

$$\begin{aligned} h_f = \frac{fL\text{v}^2}{2Dg} &= \frac{(0.0205)(7000\ \text{ft})\left(4.20\ \frac{\text{ft}}{\text{sec}}\right)^2}{(2)(0.3355\ \text{ft})\left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)} \\ &= 117.2\ \text{ft} \end{aligned}$$

The head added by the pump is

$$\begin{aligned} h_A &= h_f + h_z = 117.2\ \text{ft} + (12\ \text{ft} + 350\ \text{ft}) \\ &= 479.2\ \text{ft} \end{aligned}$$

From tableCERM18005 (also *NCEES Handbook:* Pump Power), the hydraulic horsepower is

$$\begin{aligned}\text{WP} &= \frac{h_A Q\,(\text{SG})}{3956} = \frac{(479.2\ \text{ft})\left(10{,}000\ \frac{\text{gal}}{\text{hr}}\right)(1)}{\left(3956\ \frac{\text{ft-gal}}{\text{hp-min}}\right)\left(60\ \frac{\text{min}}{\text{hr}}\right)} \\ &= 20.2\ \text{hp}\end{aligned}$$

From equationCERM18016 (also *NCEES Handbook:* Pump Power), the electrical horsepower is

$$\begin{aligned}\text{EHP} &= \frac{\text{WP}}{\eta} = \frac{20.2\ \text{hp}}{0.7} \\ &= 28.9\ \text{hp}\end{aligned}$$

At \$0.04/kW-hr, power costs for 1 hr are

$$\begin{aligned}&(28.9\ \text{hp})\left(0.7457\ \frac{\text{kW}}{\text{hp}}\right)(1\ \text{hr})\left(0.04\ \frac{\$}{\text{kW-hr}}\right) \\ &= \$0.86\ \text{per hour} \quad (\$1\ \text{per hour})\end{aligned}$$

The answer is (B).

SI Solution

From appendixCERM16C (also *NCEES Handbook* table “Pipe Dimensions and Weights”), for 4 in schedule-40 steel pipe,

$$\begin{aligned}D &= 102.26\ \text{mm} \\ A &= 82.30 \times 10^{-4}\ \text{m}^2\end{aligned}$$

As in *NCEES Handbook:* Conservation of Mass, the velocity in the pipe is

$$\begin{aligned}\text{v} &= \frac{\dot{V}}{A} = \frac{10.5\ \frac{\text{L}}{\text{s}}}{\left(82.30 \times 10^{-4}\ \text{m}^2\right)\left(1000\ \frac{\text{L}}{\text{m}^3}\right)} \\ &= 1.28\ \text{m/s}\end{aligned}$$

From appendixCERM14B (also *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units)”), at 16°C the water data are

$$\begin{aligned}\rho &= 998.95\ \text{kg/m}^3 \\ \mu &= 1.1081 \times 10^{-3}\ \text{Pa·s}\end{aligned}$$

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\begin{aligned}\text{Re} &= \frac{\rho \text{v} D}{\mu} = \frac{\left(998.95\ \frac{\text{kg}}{\text{m}^3}\right)\left(1.28\ \frac{\text{m}}{\text{s}}\right)(102.26\ \text{mm})}{\left(1.1081 \times 10^{-3}\ \text{Pa·s}\right)\left(1000\ \frac{\text{mm}}{\text{m}}\right)} \\ &= 1.18 \times 10^5\end{aligned}$$

From tableCERM17002 (also *NCEES Handbook:* Absolute Roughness and Relative Roughness), for welded and seamless steel, $\epsilon = 6.0 \times 10^{-5}$ m.

$$\frac{\epsilon}{D} = \frac{\left(6.0 \times 10^{-5}\ \text{m}\right)\left(1000\ \frac{\text{mm}}{\text{m}}\right)}{102.26\ \text{mm}} \approx 0.0006$$

From appendixCERM17B (also *NCEES Handbook:* Friction Factors for Turbulent Flow), the friction factor is $f = 0.0205$.

From equationCERM18006 (also *NCEES Handbook:* Head Loss in Pipe or Conduit), the friction head is

$$h_f = \frac{fLv^2}{2Dg} = \frac{(0.0205)\,(2300\ \mathrm{m})\left(1.28\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2\left(1000\ \frac{\mathrm{mm}}{\mathrm{m}}\right)}{(2)\,(102.26\ \mathrm{mm})\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)}$$
$$= 38.5\ \mathrm{m}$$

The head added by the pump is

$$h_A = h_f + h_z = 38.5\ \mathrm{m} + 4\ \mathrm{m} + 115\ \mathrm{m} = 157.5\ \mathrm{m}$$

From tableCERM18006 (also *NCEES Handbook:* Pump Power), the hydraulic power is

$$\mathrm{WkW} = \frac{9.81 h_A Q\,(\mathrm{SG})}{1000}$$
$$= \frac{\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)(157.5\ \mathrm{m})\left(10.5\ \frac{\mathrm{L}}{\mathrm{s}}\right)(1)}{1000\ \frac{\mathrm{W{\cdot}L}}{\mathrm{kW{\cdot}kg}}}$$
$$= 16.22\ \mathrm{kW}$$

From equationCERM18016 (also *NCEES Handbook:* Pump Power), the electrical power is

$$\mathrm{EHP} = \frac{\mathrm{WkW}}{\eta} = \frac{16.22\ \mathrm{kW}}{0.7} = 23.2\ \mathrm{kW}$$

At \$0.04/kW·h, power costs for 1 h are

$$(23.2\ \mathrm{kW})\,(1\ \mathrm{h})\left(0.04\ \frac{\$}{\mathrm{kW{\cdot}h}}\right) = \$0.93 \quad (\$1)$$

The answer is (B).
9.

The static suction lift, $h_{p(s)}$, is 20 ft.

The static discharge head, $h_{p(d)}$, is 15 ft.

There is no pipe size specified, so h_v cannot be calculated. Even so, v is typically in the 5–10 ft/sec range, and $h_v \approx 0$. Since pipe lengths are not given, assume $h_f \approx 0$.

$$20\ \mathrm{ft} + 15\ \mathrm{ft} + \frac{\left(80\ \frac{\mathrm{lbf}}{\mathrm{in}^2}\right)\left(12\ \frac{\mathrm{in}}{\mathrm{ft}}\right)^2}{62.4\ \frac{\mathrm{lbf}}{\mathrm{ft}^3}} + 10\ \mathrm{ft}$$
$$= 229.6\ \mathrm{ft\ of\ water}$$

The mass flow rate is

$$\frac{(3.5\ \mathrm{MGD})\left(62.4\ \frac{\mathrm{lbm}}{\mathrm{ft}^3}\right)\left(10^6\ \frac{\mathrm{gal}}{\mathrm{MG}}\right)}{\left(7.4805\ \frac{\mathrm{gal}}{\mathrm{ft}^3}\right)\left(24\ \frac{\mathrm{hr}}{\mathrm{day}}\right) \times \left(60\ \frac{\mathrm{min}}{\mathrm{hr}}\right)\left(60\ \frac{\mathrm{sec}}{\mathrm{min}}\right)} = 337.9\ \mathrm{lbm/sec}$$

The rated motor output power does not depend on the motor efficiency. The motor produces what it is rated to produce. From tableCERM18005 (also *NCEES Handbook:* Pump Power),

$$\begin{aligned}P &= \frac{h_A \dot{m}}{550\eta_{\text{pump}}} \times \frac{g}{g_c} \\ &= \left(\frac{(229.6 \text{ ft})\left(337.9 \, \frac{\text{lbm}}{\text{sec}}\right)}{\left(550 \, \frac{\text{ft-lbf}}{\text{hp-sec}}\right)(0.85)} \right) \left(\frac{32.2 \, \frac{\text{ft}}{\text{sec}^2}}{32.2 \, \frac{\text{lbm-ft}}{\text{lbf-sec}^2}} \right) \\ &= 166.0 \text{ hp}\end{aligned}$$

Use a 200 hp motor.

The answer is (D).
10.

Customary U.S. Solution

From the appendixCERM16B (also *NCEES Handbook* table "Pipe Dimensions and Weights"), for 3 in schedule-40 steel pipe,

$$\begin{aligned}D &= 0.2557 \text{ ft} \\ A &= 0.05134 \text{ ft}^2\end{aligned}$$

As in *NCEES Handbook:* Head Loss in Pipe or Conduit, the equivalent lengths for various fittings are

flanged elbow, $L_e = (20)(3 \text{ in}) = 60 \text{ in} = 5 \text{ ft}$

wide-open gate valve, $L_e = (10)(3 \text{ in}) = 30 \text{ in} = 2.5 \text{ ft}$

The total equivalent length of pipe and fittings is

$$\begin{aligned}L_e &= 500 \text{ ft} + (6)(5 \text{ ft}) + (2)(2.5 \text{ ft}) \\ &= 535 \text{ ft}\end{aligned}$$

The flow rate is 100 gal/min.

As in *NCEES Handbook:* Conservation of Mass, the velocity in the pipe is

$$\begin{aligned}\text{v} &= \frac{\dot{V}}{A} = \frac{100 \, \frac{\text{gal}}{\text{min}}}{(0.05134 \text{ ft}^2)\left(7.4805 \, \frac{\text{gal}}{\text{ft}^3}\right)\left(60 \, \frac{\text{sec}}{\text{min}}\right)} \\ &= 4.34 \text{ ft/sec}\end{aligned}$$

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\text{Re} = \frac{\text{v}D}{\nu} = \frac{\left(4.34 \, \frac{\text{ft}}{\text{sec}}\right)(0.2557 \text{ ft})}{6 \times 10^{-6} \, \frac{\text{ft}^2}{\text{sec}}} = 1.85 \times 10^5$$

From appendixCERM17A (also *NCEES Handbook:* Absolute Roughness and Relative Roughness), $\epsilon = 0.0002$ ft.

$$\frac{\epsilon}{D} = \frac{0.0002 \text{ ft}}{0.2557 \text{ ft}} \approx 0.0008$$

From the friction factor table, $f \approx 0.0204$.

For higher flow rates, f approaches 0.0186. Since the chosen flow rate was almost the lowest, $f = 0.0186$ should be used.

From equationCERM18006 (also *NCEES Handbook:* Friction Factors for Turbulent Flow), the friction head loss is

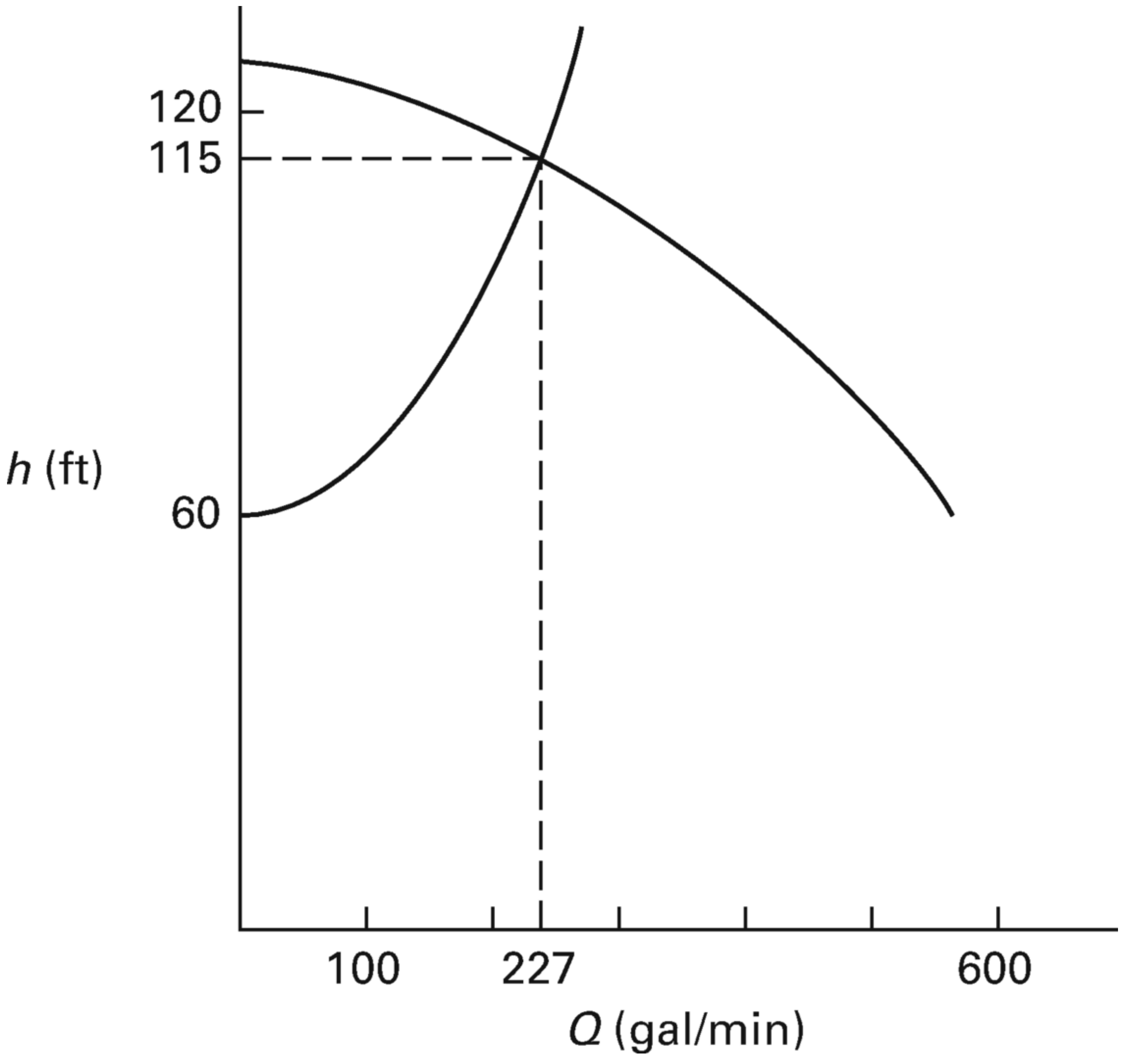
$$h_f = \frac{fLv^2}{2Dg} = \frac{(0.0186)(535\text{ ft})\left(4.34\ \frac{\text{ft}}{\text{sec}}\right)^2}{(2)(0.2557\text{ ft})\left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)}$$
$$= 11.4\text{ ft of gasoline}$$

The friction head loss neglects the small velocity head. The other system points can be found using equationCERM18042 (also *NCEES Handbook:* Pump Similitude).

$$\frac{h_{f_1}}{h_{f_2}} = \left(\frac{Q_1}{Q_2}\right)^2$$
$$h_{f_2} = h_{f_1}\left(\frac{Q_2}{100\ \frac{\text{gal}}{\text{min}}}\right)^2 = (11.4\text{ ft})\left(\frac{Q_2}{100\ \frac{\text{gal}}{\text{min}}}\right)^2$$
$$= 0.00114Q_2^2$$

Q (gal/min)	h_f (ft)	$h_f + 60$ (ft)
100	11.4	71.3
200	45.2	105.2
300	101.7	161.7
400	180.8	240.8
500	282.5	342.5
600	406.8	466.8

Plot the system and pump curves. The pump's characteristic curve is independent of the liquid's specific gravity.



$$h = 115 \text{ ft}$$

The transfer rate is

$$Q = 227 \text{ gal/min}$$

(This value could be used to determine a new friction factor.)

From tableCERM18005 (also *NCEES Handbook:* Pump Power), the electrical power supplied to the motor is

$$\begin{aligned}\text{EHP} &= \frac{h_A Q\,(\text{SG})}{3956\eta_{\text{pump}}\eta_{\text{motor}}} = \frac{(115 \text{ ft})\left(227\ \frac{\text{gal}}{\text{min}}\right)(0.7)}{\left(3956\ \frac{\text{ft-gal}}{\text{hp-min}}\right)(0.88)\,(0.88)} \\ &= 5.96 \text{ hp}\end{aligned}$$

The cost per hour is

$$(5.96 \text{ hp})\left(0.7457\ \frac{\text{kW}}{\text{hp}}\right)(1 \text{ hr})\left(0.045\ \frac{\$}{\text{kW}\cdot\text{h}}\right) = \$0.20$$

The answer is (A).

SI Solution

From appendixCERM16C (also *NCEES Handbook* table "Pipe Dimensions and Weights"), for 3 in schedule-40 pipe,

$$\begin{aligned}D &= 77.92 \text{ mm} \\ A &= 47.69 \times 10^{-4} \text{ m}^2\end{aligned}$$

From appendixCERM17D (also *NCEES Handbook:* Head Loss in Pipe or Conduit), the equivalent lengths for various fittings are

flanged elbow: $L_e = (20)(77.92\ \text{mm}) = 1558.4\ \text{mm} = 1.6\ \text{m}$

wide-open gate valve: $L_e = (10)(77.92\ \text{mm}) = 779.2\ \text{mm} = 0.8\ \text{m}$

The total equivalent length of pipe and fittings is

$$\begin{aligned} L_e &= 170\ \text{m} + \big((6)\,(1.6\text{m}) + (2)\,(0.8\ \text{m})\big) \\ &= 181.2\ \text{m} \end{aligned}$$

The flow rate is 6.3 L/s. As in *NCEES Handbook:* Conservation of Mass, the velocity in the pipe is

$$\begin{aligned} \text{v} &= \frac{\dot{V}}{A} = \frac{6.3\ \frac{\text{L}}{\text{s}}}{\left(47.69 \times 10^{-4}\ \text{m}^2\right)\left(1000\ \frac{\text{L}}{\text{m}^3}\right)} \\ &= 1.32\ \text{m/s} \end{aligned}$$

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\text{Re} = \frac{\text{v}D}{\nu} = \frac{\left(1.32\ \frac{\text{m}}{\text{s}}\right)(77.92\ \text{mm})}{\left(5.6 \times 10^{-7}\ \frac{\text{m}^2}{\text{s}}\right)\left(1000\ \frac{\text{mm}}{\text{m}}\right)} = 1.84 \times 10^5$$

From tableCERM17002 (also *NCEES Handbook:* Absolute Roughness and Relative Roughness), $\epsilon = 6.0 \times 10^{-5}$ m.

$$\frac{\epsilon}{D} = \frac{\left(6.0 \times 10^{-5}\ \text{m}\right)\left(1000\ \frac{\text{mm}}{\text{m}}\right)}{77.92\ \text{mm}} \approx 0.0008$$

From appendixCERM17B (also *NCEES Handbook:* Friction Factors for Turbulent Flow), $f = 0.0204$.

For higher flow rates, f approaches 0.0186. Since the chosen flow rate was almost the lowest, $f = 0.0186$ should be used.

From equationCERM18006 (also *NCEES Handbook:* Head Loss in Pipe or Conduit), the friction head loss is

$$\begin{aligned} h_f &= \frac{fL\text{v}^2}{2Dg} = \frac{(0.0186)\,(181.2\ \text{m})\left(1.32\ \frac{\text{m}}{\text{s}}\right)^2\left(1000\ \frac{\text{mm}}{\text{m}}\right)}{(2)\,(77.92\ \text{mm})\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)} \\ &= 3.80\ \text{m of gasoline} \end{aligned}$$

The friction head loss neglects the small velocity head. The other system points can be found using equationCERM18042 (also *NCEES Handbook:* Pump Similitude).

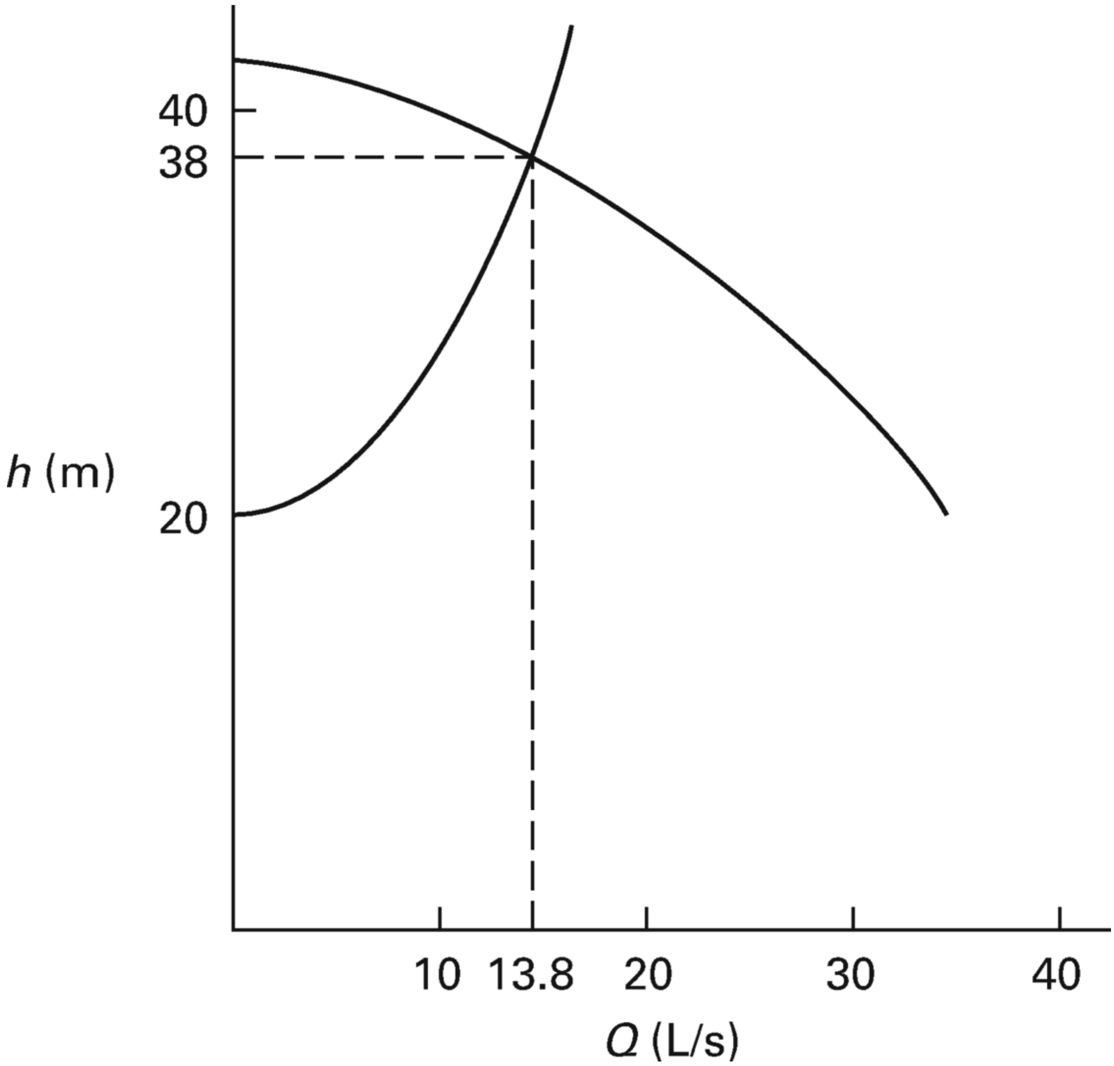
$$\frac{h_{f1}}{h_{f2}} = \left(\frac{Q_1}{Q_2}\right)^2$$

$$\begin{aligned} h_{f2} &= h_{f1}\left(\frac{Q_2}{Q_1}\right)^2 = (3.80\ \text{m})\left(\frac{Q_2}{6.3\ \frac{\text{L}}{\text{s}}}\right)^2 \\ &= 0.0957Q_2^2 \end{aligned}$$

Q (L/s)	h_f (m)	$h_f + 20$(m)
6.3	3.80	23.80

Q (L/s)	h_f (m)	$h_f + 20$(m)
12	13.78	33.78
18	31.0	51.0
24	55.1	75.1
30	86.1	106.1
36	124.0	144.0

Plot the system and pump curves. The pump's characteristic curve is independent of the liquid's specific gravity.



$$h = 38.0 \text{ m}$$

The transfer rate is

$$Q = 13.8 \text{ L/s}$$

(This value could be used to determine a new friction factor.)

From tableCERM18006 (also *NCEES Handbook:* Pump Power), the electric power delivered to the motor is

$$\begin{aligned} \text{EkW} &= \frac{9.81 h_A Q\,(\text{SG})}{1000 \eta_{\text{pump}} \eta_{\text{motor}}} \\ &= \frac{\left(9.81 \ \frac{\text{m}}{\text{s}^2}\right)(38.0 \text{ m})\left(13.8 \ \frac{\text{L}}{\text{s}}\right)(0.7)}{\left(1000 \ \frac{\text{W}}{\text{kW}}\right)(0.88)(0.88)} \\ &= 4.65 \text{ kW} \end{aligned}$$

The cost per hour is

$$(4.65\ \text{kW})\,(1\ \text{h})\left(0.045\ \frac{\$}{\text{kW}\cdot\text{h}}\right) = \$0.21 \quad (\$0.20)$$

The answer is (A).
11.

Customary U.S. Solution

At base form,

$$Power = \Delta pQ$$

However, unit conversion is necessary to take a pressure and flow rate in the units of psi and gpm and achieve horsepower.

$$WHP = k\left(\frac{lb_f}{in^2}\right)\left(\frac{gal}{min}\right)$$

$$1\ hp = 746.04\ W = 746.04\ \frac{kg\ m^2}{s^3}$$

$$1\ \frac{lb_f}{in^2} = 6{,}894.64\ \frac{N}{m^2} = 6{,}894.64\ \frac{kg}{m\ s^2}$$

$$1\ \frac{gal}{min} = \frac{3.785\ m^3}{60\ s} = 6.31\ x\ 10^{-5}\ \frac{m^3}{s}$$

$$k = \frac{\left(6{,}894.64\ \frac{kg}{m\ s^2}\right)\left(6.31\ x\ 10^{-5}\ \frac{m^3}{s}\right)}{746.04\ \frac{kg\ m^2}{s^3}} = 5.834\ x\ 10^{-4}\ \frac{psi * gpm}{hp} = \frac{1}{1714}\ \frac{psi * gpm}{hp}$$

$$\text{WHP} = \frac{\Delta pQ}{1714}$$
$$\Delta p = p_d - p_s$$

The absolute pressures are

$$p_d = 40\ \text{psig} + 14.7\ \text{psia} = 54.7\ \text{psia}$$
$$p_s = 1\ \text{atm} = 14.7\ \text{psia}$$
$$\Delta p = p_d - p_s = 54.7\ \text{psia} - 14.7\ \text{psia} = 40\ \text{psia}$$
$$\text{WHP} = \frac{\left(40\ \frac{\text{lbf}}{\text{in}^2}\right)\left(37\ \frac{\text{gal}}{\text{min}}\right)}{1714\ \frac{\text{lbf-gal}}{\text{in}^2\text{-min-hp}}} = 0.863\ \text{hp} \quad (0.9\ \text{hp})$$

The answer is (B).

SI Solution

From tableCERM18006 (also *NCEES Handbook:* Pump Power), the hydraulic kilowatts are

$$\text{WkW} = \frac{\Delta pQ}{1000}$$
$$\Delta p = p_d - p_s$$

The absolute pressures are

$$p_d = 275 \text{ kPa} + 101.3 \text{ kPa} = 376.3 \text{ kPa}$$
$$p_s = 1 \text{ atm} = 101.3 \text{ kPa}$$
$$\Delta p = p_d - p_s = 376.3 \text{ kPa} - 101.3 \text{ kPa} = 275 \text{ kPa}$$

$$\text{WkW} = \frac{(275 \text{ kPa})\left(65 \ \frac{\text{L}}{\text{s}}\right)}{1000 \ \frac{\text{W}}{\text{kW}}} = 17.88 \text{ kW} \quad (18 \text{ kW})$$

The answer is (B).

12.

Customary U.S. Solution

From equationCERM18028(b) (also *NCEES Handbook:* Specific Speed (N_S) at the BEP), the specific speed is

$$N_s = \frac{n\sqrt{Q}}{h_A^{0.75}}$$

For a double-suction pump, Q in the preceding equation is half of the full flow rate.

$$N_s = \frac{\left(900 \ \frac{\text{rev}}{\text{min}}\right)\sqrt{\left(\frac{1}{2}\right)\left(300 \ \frac{\text{gal}}{\text{sec}}\right)\left(60 \ \frac{\text{sec}}{\text{min}}\right)}}{(20 \text{ ft})^{0.75}}$$
$$= 9028 \text{ rpm} \quad (9000 \text{ rpm})$$

The answer is (C).

SI Solution

From equationCERM18028(a) (also *NCEES Handbook:* Specific Speed (N_s) at the BEP), the specific speed is

$$N_s = \frac{n\sqrt{\dot{V}}}{h_A^{0.75}}$$

For a double-suction pump, $\dot{V}$ in the preceding equation is half of the full flow rate.

$$N_s = \frac{\left(900 \ \frac{\text{rev}}{\text{min}}\right)\sqrt{\left(\frac{1}{2}\right)\left(1.1 \ \frac{\text{kL}}{\text{s}}\right)\left(1 \ \frac{\text{m}^3}{\text{kL}}\right)}}{(7 \text{ m})^{0.75}}$$
$$= 155.1 \text{ rpm} \quad (160 \text{ rpm})$$

The answer is (C).

13.

Customary U.S. Solution

From appendixCERM16B (also *NCEES Handbook* table “Pipe Dimensions and Weights”), for 1.5 in schedule-40 steel pipe,

$$D = 0.1342 \text{ ft}$$
$$A = 0.01414 \text{ ft}^2$$

As in *NCEES Handbook:* Conservation of Mass, The velocity in the pipe is

$$\text{v} = \frac{\dot{V}}{A} = \frac{100 \ \frac{\text{gal}}{\text{min}}}{(0.01414 \text{ ft}^2)\left(7.4805 \ \frac{\text{gal}}{\text{ft}^3}\right)\left(60 \ \frac{\text{sec}}{\text{min}}\right)}$$
$$= 15.76 \text{ ft/sec}$$

From appendixCERM17A (also *NCEES Handbook:* Absolute Roughness and Relative Roughness), for steel, ϵ = 0.0002 ft.

$$\frac{\epsilon}{D} = \frac{0.0002\ \text{ft}}{0.1342\ \text{ft}} = 0.0015$$

At 281°F, $\nu = 0.239 \times 10^{-5}$ ft^2/sec. As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\begin{aligned}\text{Re} &= \frac{D\text{v}}{\nu} = \frac{(0.1342\ \text{ft})\left(15.76\ \frac{\text{ft}}{\text{sec}}\right)}{0.239 \times 10^{-5}\ \frac{\text{ft}^2}{\text{sec}}} \\ &= 8.85 \times 10^5\end{aligned}$$

From appendixCERM17B (also *NCEES Handbook:* Friction Factors for Turbulent Flow), the friction factor is f = 0.022.

From appendixCERM17D (also *NCEES Handbook:* Head Loss in Pipe or Conduit and *NCEES Handbook:* Loss Coefficients for Pipe Entrance and Exit), the equivalent lengths for screwed steel fittings are

$$\begin{aligned}\text{inlet (square mouth):}\quad L_e &= \left(\tfrac{D}{f}\right)\left(\tfrac{160}{\text{Re}} + (0.5)\left(1 + \tfrac{1}{D_{\text{inches}}}\right)\right) \\ &= \left(\tfrac{1.5\ \text{in}}{0.022}\right) \\ &\quad \times\left(\tfrac{160}{8.85\times10^5} + (0.5)\left(1 + \tfrac{1}{1.5}\right)\right) \\ &= 56.8\ \text{in} \\ &= 4.7\ \text{ft}\end{aligned}$$

long radius 90° elbow: $L_e = (16)(1.5\ \text{in}) = 24\ \text{in} = 2\ \text{ft}$

wide-open gate valves: $L_e = (10)(1.5\ \text{in}) = 15\ \text{in} = 1.3\ \text{ft}$

The total equivalent length is

$$30\ \text{ft} + 4.7\ \text{ft} + (2)(2\ \text{ft}) + (2)(1.3\ \text{ft}) = 41.3\ \text{ft}$$

From equationCERM18006 (also *NCEES Handbook:* Head Loss in Pipe or Conduit), the friction head is

$$\begin{aligned}h_f &= \frac{fL\text{v}^2}{2Dg} = \frac{(0.022)(41.3\ \text{ft})\left(15.76\ \frac{\text{ft}}{\text{sec}}\right)^2}{(2)(0.1342\ \text{ft})\left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)} \\ &= 26.11\ \text{ft}\end{aligned}$$

The density of the liquid is the reciprocal of the specific volume, taken from appendixMERM24B (also *NCEES Handbook* table “Physical Properties of Liquid Water (U.S. Units)”), at 281°F.

$$\rho = \frac{1}{\upsilon_f} = \frac{1}{0.01727\ \frac{\text{ft}^3}{\text{lbm}}} = 57.9\ \text{lbm/ft}^3$$

Extracted from equationCERM18005(b) (also *NCEES Handbook:* The Bernoulli Equation), the vapor pressure head is

$$\begin{aligned} h_{\text{vp}} &= \frac{p_{\text{vapor}}}{\rho} \times \frac{g_c}{g} \\ &= \left(\frac{\left(50.06 \ \frac{\text{lbf}}{\text{in}^2}\right)\left(12 \ \frac{\text{in}}{\text{ft}}\right)^2}{57.9 \ \frac{\text{lbm}}{\text{ft}^3}} \right) \left(\frac{32.2 \ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}}{32.2 \ \frac{\text{ft}}{\text{sec}^2}} \right) \\ &= 124.5 \text{ ft} \end{aligned}$$

Extracted from equationCERM18005(b) (also *NCEES Handbook:* The Bernoulli Equation), the pressure head is

$$\begin{aligned} h_p &= \frac{p}{\rho} \times \frac{g_c}{g} = \left(\frac{\left(80 \ \frac{\text{lbf}}{\text{in}^2}\right)\left(12 \ \frac{\text{in}}{\text{ft}}\right)^2}{57.9 \ \frac{\text{lbm}}{\text{ft}^3}} \right) \left(\frac{32.2 \ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}}{32.2 \ \frac{\text{ft}}{\text{sec}^2}} \right) \\ &= 199.0 \text{ ft} \end{aligned}$$

From equationCERM18030 (also *NCEES Handbook:* Net-Positive Suction Head (NPSH)), the NPSHA is

$$\begin{aligned} \text{NPSHA} &= h_p + h_{z(s)} - h_{f(s)} - h_{\text{vp}} \\ &= 199.0 \text{ ft} + 20 \text{ ft} - 26.11 \text{ ft} - 124.5 \text{ ft} \\ &= 68.5 \text{ ft} \quad (68 \text{ ft}) \end{aligned}$$

Since NPSHR = 10 ft, the pump will not cavitate.

(A pump may not be needed in this configuration.)

The answer is (D).

SI Solution

From appendixCERM16C (also *NCEES Handbook* table “Pipe Dimensions and Weights”), for 1.5 in schedule-40 steel pipe,

$$\begin{aligned} D &= 40.89 \text{ mm} \\ A &= 13.13 \times 10^{-4} \text{ m}^2 \end{aligned}$$

As in *NCEES Handbook:* Conservation of Mass, the velocity in the pipe is

$$\begin{aligned} \text{v} &= \frac{\dot{V}}{A} = \frac{6.3 \ \frac{\text{L}}{\text{s}}}{\left(13.13 \times 10^{-4} \text{ m}^2\right)\left(1000 \ \frac{\text{L}}{\text{m}^3}\right)} \\ &= 4.80 \text{ m/s} \end{aligned}$$

From tableCERM17002 (also *NCEES Handbook:* Absolute Roughness and Relative Roughness), for steel, $\epsilon = 6.0 \times 10^{-5}$ m.

$$\begin{aligned} \frac{\epsilon}{D} &= \frac{\left(6.0 \times 10^{-5} \text{ m}\right)\left(1000 \ \frac{\text{mm}}{\text{m}}\right)}{40.89 \text{ mm}} \\ &\approx 0.0015 \end{aligned}$$

Using *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units),” at 138°C, $\nu = 0.222 \times 10^{-6}$ m^2/s.

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\begin{aligned} \text{Re} &= \frac{D\text{v}}{\nu} = \frac{(40.89 \text{ mm})\left(4.80 \ \frac{\text{m}}{\text{s}}\right)}{\left(0.222 \times 10^{-6} \ \frac{\text{m}^2}{\text{s}}\right)\left(1000 \ \frac{\text{mm}}{\text{m}}\right)} \\ &= 8.84 \times 10^5 \end{aligned}$$

From appendixCERM17B (also *NCEES Handbook:* Friction Factors for Turbulent Flow), the friction factor is $f = 0.022$.

From appendixCERM17D (also *NCEES Handbook:* Head Loss in Pipe or Conduit and *NCEES Handbook:* Loss Coefficients for Pipe Entrance and Exit), the equivalent lengths for screwed steel fittings are

$$\begin{aligned}\text{inlet (square mouth):}\quad L_e &= \left(\tfrac{D}{f}\right)\left(\tfrac{160}{\text{Re}} + (0.5)\left(1+\tfrac{1}{D_{\text{inches}}}\right)\right)\\ &= \left(\tfrac{40.89\ \text{mm}}{0.022}\right)\\ &\quad\times\left(\tfrac{160}{8.85\times 10^5} + (0.5)\left(1+\tfrac{1}{1.5}\right)\right)\\ &= 1548\ \text{mm}\\ &= 1.5\ \text{m}\end{aligned}$$

long radius 90° elbow: $L_e = (16)(40.89\ \text{mm}) = 654\ \text{mm} = 0.7\ \text{m}$

wide-open gate valves: $L_e = (10)(40.89\ \text{mm}) = 409\ \text{mm} = 0.4\ \text{m}$

The total equivalent length is

$$10\ \text{m} + 1.5\ \text{m} + (2)(0.7\ \text{m}) + (2)(0.4\ \text{m}) = 13.7\ \text{m}$$

As in *NCEES Handbook:* Head Loss in Pipe or Conduit, the friction head is

$$\begin{aligned}h_f &= \frac{fL\text{v}^2}{2Dg}\\ &= \frac{(0.022)\,(13.7\ \text{m})\left(4.80\ \frac{\text{m}}{\text{s}}\right)^2\left(1000\ \frac{\text{mm}}{\text{m}}\right)}{(2)\,(40.89\ \text{mm})\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)}\\ &= 8.66\ \text{m}\end{aligned}$$

The density of the liquid is the reciprocal of the specific volume. From appendixMERM24B (also *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units)”), at 138°C,

$$\rho = \frac{1}{\upsilon_f} = \frac{(1)\left(3.281\ \frac{\text{ft}}{\text{m}}\right)^3}{\left(0.01727\ \frac{\text{ft}^3}{\text{lbm}}\right)\left(2.205\ \frac{\text{lbm}}{\text{kg}}\right)} = 927.5\ \text{kg/m}^3$$

Extracted from equationCERM18005(a) (also *NCEES Handbook:* The Bernoulli Equation), the vapor pressure head is

$$\begin{aligned}h_{\text{vp}} &= \frac{p_{\text{vapor}}}{\rho g} = \frac{(3.431\ \text{bar})\left(1\times 10^5\ \frac{\text{Pa}}{\text{bar}}\right)}{\left(927.5\ \frac{\text{kg}}{\text{m}^3}\right)\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)}\\ &= 37.71\ \text{m}\end{aligned}$$

Extracted from equationCERM18005(a) (also *NCEES Handbook:* The Bernoulli Equation), the pressure head is

$$\begin{aligned}h_p &= \frac{p}{\rho g} = \frac{(550\ \text{kPa})\left(1000\ \frac{\text{Pa}}{\text{kPa}}\right)}{\left(927.5\ \frac{\text{kg}}{\text{m}^3}\right)\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)}\\ &= 60.45\ \text{m}\end{aligned}$$

From equationCERM18030 (also *NCEES Handbook:* Net-Positive Suction Head (NPSH)), the NPSHA is

$$\begin{aligned}\text{NPSHA} &= h_p + h_{z(s)} - h_{f(s)} - h_{\text{vp}} \\ &= 60.45\ \text{m} + 6\ \text{m} - 8.66\ \text{m} - 37.71\ \text{m} \\ &= 20.08\ \text{m} \quad (20.6\ \text{m})\end{aligned}$$

Since NPSHR is 3 m, the pump will not cavitate.

(A pump may not be needed in this configuration.)

The answer is (D).
14.

The solvent is the freshwater, and the solution is the seawater. Since seawater contains approximately $2^1/_2$% salt (NaCl) by weight, 100 lbm of seawater will yield 2.5 lbm salt and 97.5 lbm water. The molecular weight of salt is 23.0 + 35.5 = 58.5 lbm/lbmol. The number of moles of salt in 100 lbm of seawater is

$$n_{\text{salt}} = \frac{m}{\text{MW}} = \frac{2.5\ \text{lbm}}{58.5\ \frac{\text{lbm}}{\text{lbmol}}} = 0.043\ \text{lbmol}$$

Similarly, water's molecular weight is 18.016 lbm/lbmol. The number of moles of water is

$$n_{\text{water}} = \frac{97.5\ \text{lbm}}{18.016\ \frac{\text{lbm}}{\text{lbmol}}} = 5.412\ \text{lbmol}$$

The mole fraction of water is

$$\frac{5.412\ \text{lbmol}}{5.412\ \text{lbmol} + 0.043\ \text{lbmol}} = 0.992$$

Customary U.S. Solution

Cavitation will occur when

$$h_{\text{atm}} - h_{\text{v}} < h_{\text{vp}}$$

The density of seawater is 64.0 lbm/ft^3.

Extracted from equationCERM18005(b) (also *NCEES Handbook:* The Bernoulli Equation), the atmospheric head is

$$\begin{aligned}h_{\text{atm}} &= \frac{p}{\rho} \times \frac{g_c}{g} = \left(\frac{\left(14.7\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2}{64.0\ \frac{\text{lbm}}{\text{ft}^3}} \right) \left(\frac{32.2\ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}}{32.2\ \frac{\text{ft}}{\text{sec}^2}} \right) \\ &= 33.075\ \text{ft} \quad [\text{ft of seawater}] \\ h_{\text{depth}} &= 8\ \text{ft} \quad [\text{given}]\end{aligned}$$

Extracted from equationCERM18007 (also *NCEES Handbook:* The Bernoulli Equation), the velocity head is

$$h_{\text{v}} = \frac{\text{v}_{\text{propeller}}^2}{2g} = \frac{(4.2\text{v}_{\text{boat}})^2}{(2)\left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)} = 0.2739\text{v}_{\text{boat}}^2\ \text{sec}^2/\text{ft}$$

From appendixMERM24A (also *NCEES Handbook* table "Physical Properties of Liquid Water (U.S. Units)"), the vapor pressure of freshwater at 68°F is p_{vp} = 0.3393 psia.

From appendixCERM14A (also *NCEES Handbook* table "Physical Properties of Liquid Water (U.S. Units)"), the density of water at 68°F is 62.32 lbm/ft^3. Raoult's law predicts the actual vapor pressure of the solution.

$$p_{\text{vapor,solution}} = \begin{pmatrix}\text{mole fraction}\\ \text{of the solvent}\end{pmatrix} p_{\text{vapor,solvent}}$$
$$p_{\text{vapor,seawater}} = (0.992)\left(0.3393\ \frac{\text{lbf}}{\text{in}^2}\right) = 0.3366\ \text{lbf/in}^2$$

Extracted from equationCERM18005(b) (also *NCEES Handbook:* The Bernoulli Equation), the vapor pressure head is

$$\begin{aligned} h_{\text{vapor,seawater}} &= \frac{p}{\rho} \times \frac{g_c}{g} \\ &= \frac{\left(0.3366\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2}{\left(64.0\ \frac{\text{lbm}}{\text{ft}^3}\right)} \left(\frac{32.2\ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}}{32.2\ \frac{\text{ft}}{\text{sec}^2}}\right) \\ &= 0.7574\ \text{ft} \end{aligned}$$

Solve for the boat velocity.

$$\begin{aligned} 8\ \text{ft} + 33.075\ \text{ft} & \\ -0.2739\text{v}_{\text{boat}}^2 &= 0.7574\ \text{ft} \\ \text{v}_{\text{boat}} &= 12.13\ \text{ft/sec} \quad (12\ \text{ft/sec}) \end{aligned}$$

The answer is (B).

SI Solution

Cavitation will occur when

$$h_{\text{atm}} - h_{\text{v}} < h_{\text{vp}}$$

The density of seawater is 1024 kg/m^3.

Extracted from equationCERM18005(a) (also *NCEES Handbook:* The Bernoulli Equation), the atmospheric head is

$$h_{\text{atm}} = \frac{p}{\rho g} = \frac{(101.3\ \text{kPa})\left(1000\ \frac{\text{Pa}}{\text{kPa}}\right)}{\left(1024\ \frac{\text{kg}}{\text{m}^3}\right)\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)} = 10.08\ \text{m}$$
$$h_{\text{depth}} = 3\ \text{m} \quad [\text{given}]$$

Extracted from equationCERM18007 (also *NCEES Handbook:* The Bernoulli Equation), the velocity head is

$$h_{\text{v}} = \frac{\text{v}_{\text{propeller}}^2}{2g} = \frac{(4.2\text{v}_{\text{boat}})^2}{(2)\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)} = 0.899\text{v}_{\text{boat}}^2\ \text{sec}^2/\text{m}$$

As in *NCEES Handbook* table “Physical Properties of Liquid Water (U.S. Units),” the vapor pressure of 20°C freshwater is

$$p_{\text{vp}} = (0.02339\ \text{bar})\left(100\ \frac{\text{kPa}}{\text{bar}}\right) = 2.339\ \text{kPa}$$

From appendixCERM14B (also *NCEES Handbook* table “Physical Properties of Liquid Water (U.S. Units)”), the density of water at 20°C is 998.23 kg/m^3. Raoult’s law predicts the actual vapor pressure of the solution.

$$p_{\text{vapor,solution}} = p_{\text{vapor,solvent}} \begin{pmatrix}\text{mole fraction}\\ \text{of the solvent}\end{pmatrix}$$

The solvent is the freshwater and the solution is the seawater.

The mole fraction of water is 0.992.

$$p_{\text{vapor,seawater}} = (2.339 \text{ kPa})(0.992) = 2.320 \text{ kPa}$$

Extracted from equationCERM18005(a) (also *NCEES Handbook:* The Bernoulli Equation), the vapor pressure head is

$$h_{\text{vapor,seawater}} = \frac{p}{\rho g} = \frac{(2.320 \text{ kPa})\left(1000 \ \frac{\text{Pa}}{\text{kPa}}\right)}{\left(1024 \ \frac{\text{kg}}{\text{m}^3}\right)\left(9.81 \ \frac{\text{m}}{\text{s}^2}\right)} = 0.231 \text{ m}$$

Solve for the boat velocity.

$$\begin{aligned} 3 \text{ m} + 10.08 \text{ m} - 0.899\text{v}_{\text{boat}}^2 \text{ sec}^2/\text{m} &= 0.231 \text{ m} \\ \text{v}_{\text{boat}} &= 3.78 \text{ m/s} \quad (3.8 \text{ m/s}) \end{aligned}$$

The answer is (B).

15.

Customary U.S. Solution

From appendixCERM16C (also *NCEES Handbook* table "Pipe Dimensions and Weights"), for 2 in schedule-40 pipe,

$$\begin{aligned} D &= 0.1723 \text{ ft} \\ A &= 0.02330 \text{ ft}^2 \end{aligned}$$

Since the flow rate is unknown, it must be assumed in order to find velocity. Estimate 90 gal/min.

$$\dot{V} = \frac{90 \ \frac{\text{gal}}{\text{min}}}{\left(7.4805 \ \frac{\text{gal}}{\text{ft}^3}\right)\left(60 \ \frac{\text{sec}}{\text{min}}\right)} = 0.2005 \text{ ft}^3/\text{sec}$$

As in *NCEES Handbook:* Conservation of Mass, the velocity is

$$\text{v} = \frac{\dot{V}}{A} = \frac{0.2005 \ \frac{\text{ft}^3}{\text{sec}}}{0.02330 \text{ ft}^2} = 8.605 \text{ ft/sec}$$

From appendixCERM14B (also *NCEES Handbook* table "Physical Properties of Liquid Water (U.S. Units)"), the kinematic viscosity of water at 70°F is $\nu = 1.059 \times 10^{-5}$ ft^2/sec.

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\text{Re} = \frac{D\text{v}}{\nu} = \frac{(0.1723 \text{ ft})\left(8.605 \ \frac{\text{ft}}{\text{sec}}\right)}{1.059 \times 10^{-5} \ \frac{\text{ft}^2}{\text{sec}}} = 1.4 \times 10^5$$

From tableCERM17002 (also *NCEES Handbook:* Absolute Roughness and Relative Roughness), the specific roughness of steel pipe is $\epsilon = 0.0002 \text{ ft}$.

$$\frac{\epsilon}{D} = \frac{0.0002 \text{ ft}}{0.1723 \text{ ft}} \approx 0.0012$$

From appendixCERM17B (also *NCEES Handbook:* Friction Factors for Turbulent Flow), $f = 0.022$.

From appendixCERM17D (also *NCEES Handbook:* Head Loss in Pipe or Conduit and *NCEES Handbook:* Loss Coefficients for Pipe Entrance and Exit), the equivalent lengths of various screwed steel fittings are

$$\begin{aligned} \text{inlet (reentrant): } L_e &= \left(\tfrac{D}{f}\right)\left(\tfrac{160}{\text{Re}} + (1.0)\left(1 + \tfrac{1}{D_{\text{inches}}}\right)\right) \\ &= \left(\tfrac{2 \text{ in}}{0.022}\right) \\ &\quad \times \left(\tfrac{160}{1.4\times10^5} + (1.0)\left(1 + \tfrac{1}{2 \text{ in}}\right)\right) \\ &= 136.5 \text{ in} \\ &= 11.4 \text{ ft} \end{aligned}$$

swing check valve: $L_e = (125)(2 \text{ in}) = 250 \text{ in} = 20.8 \text{ ft}$

long radius elbows: $L_e = (16)(2 \text{ in}) = 32 \text{ in} = 2.7 \text{ ft}$

The total equivalent length of the 2 in line is

$$\begin{aligned} L_e &= 12 \text{ ft} + 11.4 \text{ ft} + 20.8 \text{ ft} + (3)(2.7 \text{ ft}) + 80 \text{ ft} \\ &= 132.3 \text{ ft} \end{aligned}$$

At 90 gal/min, the friction loss in the line from *NCEES Handbook:* Head Loss in Pipe or Conduit is

$$h_f = \frac{fLv^2}{2Dg} = \frac{(0.022)(132.3 \text{ ft})\left(8.605 \dfrac{\text{ft}}{\text{sec}}\right)^2}{(2)(0.1723 \text{ ft})\left(32.2 \dfrac{\text{ft}}{\text{sec}^2}\right)} = 19.4 \text{ ft}$$

Extracted from equationCERM18007 (also *NCEES Handbook:* The Bernoulli Equation), the velocity head at 90 gal/min is

$$h_v = \frac{v^2}{2g} = \frac{\left(8.605 \dfrac{\text{ft}}{\text{sec}}\right)^2}{(2)\left(32.2 \dfrac{\text{ft}}{\text{sec}^2}\right)} = 1.1 \text{ ft}$$

In general, the friction head and velocity head are proportional to v^2 and Q^2 (see*NCEES Handbook:* Pump Similitude).

$$h_f = (19.4 \text{ ft})\left(\frac{Q_2}{90 \dfrac{\text{gal}}{\text{min}}}\right)^2$$

$$h_v = (1.1 \text{ ft})\left(\frac{Q_2}{90 \dfrac{\text{gal}}{\text{min}}}\right)^2$$

(The 7 ft suction lift is included in the 20 ft static discharge head.)

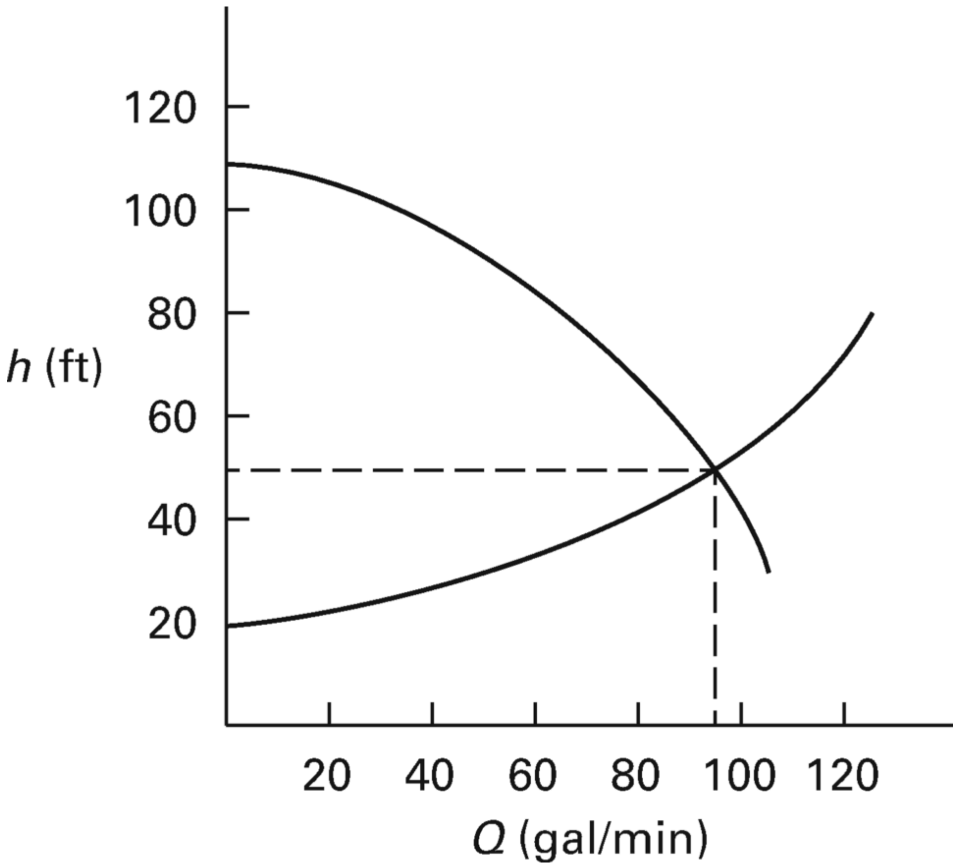
The equation for the total system head is

$$h = h_z + h_v + h_f = 20 \text{ ft} + (1.1 \text{ ft} + 19.4 \text{ ft})\left(\frac{Q_2}{90 \dfrac{\text{gal}}{\text{min}}}\right)^2$$

Q_2 (gal/min)	system head, h (ft)
0	20.0
10	20.2
20	21.0
30	22.2

Q_2 (gal/min)	system head, h (ft)
40	24.0
50	26.2
60	29.0
70	32.2
80	36.0
90	40.2
100	44.9
110	50.2

The intersection point of the system curve and the pump curve defines the operating flow rate.



The flow rate is $95\ \text{gal/min}$.

The answer is (D).

SI Solution

As in *NCEES Handbook* table "Pipe Dimensions and Weights," for 2 in schedule-40 pipe,

$$D = 52.501\ \text{mm}$$
$$A = 21.648 \times 10^{-4}\ \text{m}^2$$

Since the flow rate is unknown, it must be assumed in order to find velocity. Estimate 6 L/s.

$$\dot{V} = \frac{6\ \frac{\text{L}}{\text{s}}}{1000\ \frac{\text{L}}{\text{m}^3}} = 6 \times 10^{-3}\ \text{m}^3/\text{s}$$

As in *NCEES Handbook:* Conservation of Mass, the velocity is

$$\mathrm{v}=\frac{\dot{V}}{A}=\frac{6\times 10^{-3}\ \frac{\mathrm{m}^3}{\mathrm{s}}}{21.648\times 10^{-4}\ \ \mathrm{m}^2}=2.77\ \mathrm{m/s}$$

As in *NCEES Handbook* table "Physical Properties of Liquid Water (SI Units)," the kinematic viscosity of water at 21°C is approximately $\nu = 9.849 \times 10^{-7}$ m²/s.

As in *NCEES Handbook:* Similitude, the Reynolds number is

$$\begin{aligned}\mathrm{Re} &= \frac{\mathrm{v}D}{\nu}=\frac{\left(2.77\ \frac{\mathrm{m}}{\mathrm{s}}\right)(52.501\ \mathrm{mm})}{\left(9.849\times 10^{-7}\ \frac{\mathrm{m}^2}{\mathrm{s}}\right)\left(1000\ \frac{\mathrm{mm}}{\mathrm{m}}\right)}\\ &= 1.48\times 10^5\end{aligned}$$

As in *NCEES Handbook:* Absolute Roughness and Relative Roughness, the specific roughness of steel pipe is $\epsilon = 6.0\times 10^{-5}$ m.

$$\frac{\epsilon}{D}=\frac{(6.0\times 10^{-5}\ \mathrm{m})\left(1000\ \frac{\mathrm{mm}}{\mathrm{m}}\right)}{52.501\ \mathrm{mm}}\approx 0.0011$$

As in *NCEES Handbook:* Friction Factors for Turbulent Flow, $f = 0.022$. Use the equivalent lengths of various screwed steel fittings from *NCEES Handbook:* Head Loss in Pipe or Conduit. The total equivalent length of 5.08 cm schedule-40 pipe is

$$\begin{aligned}\text{inlet (reentrant): } L_e &= \left(\tfrac{D}{f}\right)\left(\tfrac{160}{\mathrm{Re}}+(1.0)\left(1+\tfrac{1}{D_{\text{inches}}}\right)\right)\\ &= \left(\tfrac{5.08\ \mathrm{cm}}{0.022}\right)\\ &\quad\times\left(\tfrac{160}{1.4\times 10^5}+(1.0)\left(1+\tfrac{1}{2\ \mathrm{in}}\right)\right)\\ &= 346.7\ \mathrm{cm}\\ &= 3.5\ \mathrm{m}\end{aligned}$$

swing check valve: $L_e = (125)(5.08\ \mathrm{cm}) = 635\ \mathrm{cm} = 6.4\ \mathrm{m}$

long radius elbows: $L_e = (16)(5.08\ \mathrm{cm}) = 81.3\ \mathrm{cm} = 0.8\ \mathrm{m}$

$$\begin{aligned}L_e &= 4\ \mathrm{m}+3.5\ \mathrm{m}+6.4\ \mathrm{m}+(3)(0.8\ \mathrm{m})+\ 27\ \mathrm{m}\\ &= 43.3\ \mathrm{m}\end{aligned}$$

At 6 L/s, the friction loss in the line from *NCEES Handbook:* Head Loss in Pipe or Conduit is

$$\begin{aligned}h_f &= \frac{fL\mathrm{v}^2}{2Dg}\\ &= \frac{(0.022)(43.3\ \mathrm{m})\left(2.77\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2\left(1000\ \frac{\mathrm{mm}}{\mathrm{m}}\right)}{(2)(52.501\ \mathrm{mm})\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)}\\ &= 7.1\ \mathrm{m}\end{aligned}$$

At 6 L/s, the velocity head is (see also *NCEES Handbook:* The Bernoulli Equation),

$$h_{\mathrm{v}}=\frac{\mathrm{v}^2}{2g}=\frac{\left(2.77\ \frac{\mathrm{m}}{\mathrm{s}}\right)^2}{(2)\left(9.81\ \frac{\mathrm{m}}{\mathrm{s}^2}\right)}=0.39\ \mathrm{m}$$

In general, the friction head and velocity head are proportional to v^2 and Q^2.

$$h_f = (7.1\ \mathrm{m})\left(\frac{Q_2}{6\ \frac{\mathrm{L}}{\mathrm{s}}}\right)^2$$

$$h_\mathrm{v} = (0.39\ \mathrm{m})\left(\frac{Q_2}{6\ \frac{\mathrm{L}}{\mathrm{s}}}\right)^2$$

(The 2.3 m suction lift is included in the 6.3 m static discharge head.)

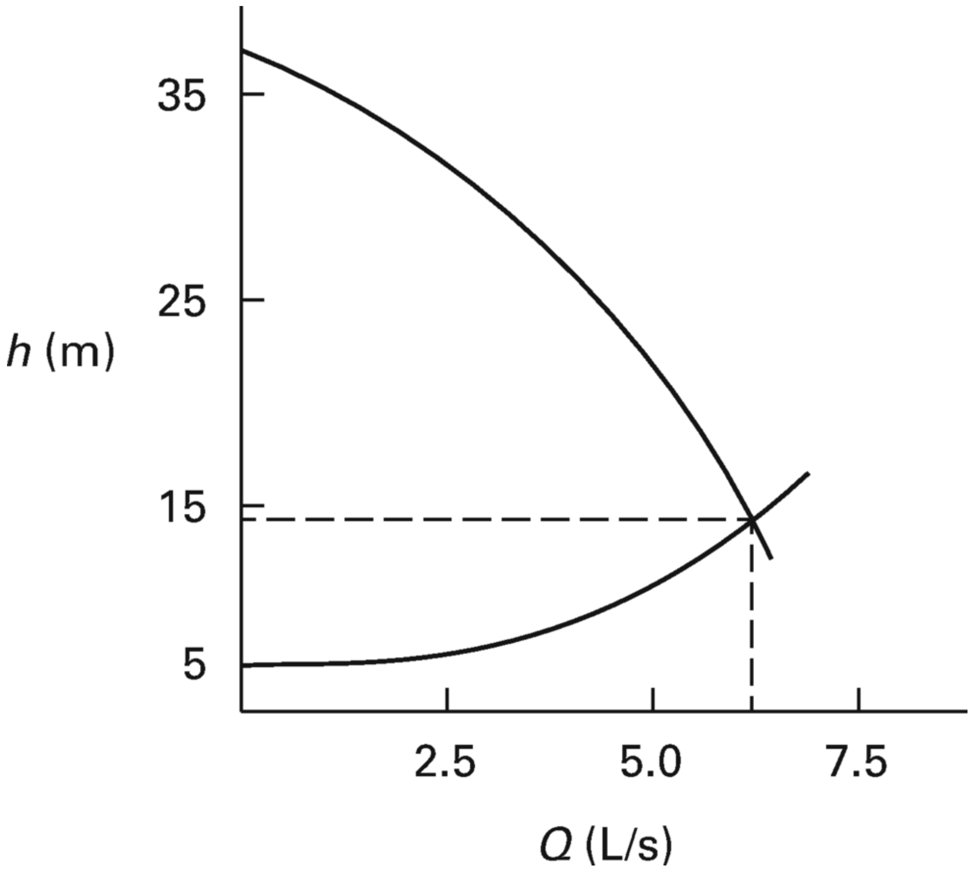
The equation for the total system head is

$$h = h_z + h_\mathrm{v} + h_f$$

$$= 6.3\ \mathrm{m} + (0.39\ \mathrm{m} + 7.1\ \mathrm{m})\left(\frac{Q_2}{6\ \frac{\mathrm{L}}{\mathrm{s}}}\right)^2$$

Q_2 (L/s)	h (m)
0	6.3
0.6	6.37
1.2	6.60
1.8	6.96
2.4	7.48
3.2	8.40
3.6	8.96
4.4	10.27
4.8	11.03
5.7	12.97
6.0	13.69
6.5	14.98
7.0	16.36
7.5	17.85

The intersection point of the system curve and the pump curve defines the operating flow rate.



The flow rate is $6.2\ \mathrm{L/s}$.

The answer is (D).
16.

As in *NCEES Handbook:* Pump Similitude,

$$P_2 = P_1\left(\frac{\rho_2 n_2^3 D_2^5}{\rho_1 n_1^3 D_1^5}\right) = P_1\left(\frac{n_2}{n_1}\right)^3 \quad [\rho_2 = \rho_1 \text{ and } D_2 = D_1]$$

Customary U.S. Solution

$$P_2 = (0.5\ \mathrm{hp})\left(\frac{2000\ \frac{\mathrm{rev}}{\mathrm{min}}}{1750\ \frac{\mathrm{rev}}{\mathrm{min}}}\right)^3 = 0.75\ \mathrm{hp}$$

The answer is (D).

SI Solution

$$P_2 = (0.37\ \mathrm{kW})\left(\frac{2000\ \frac{\mathrm{rev}}{\mathrm{min}}}{1750\ \frac{\mathrm{rev}}{\mathrm{min}}}\right)^3 = 0.55\ \mathrm{kW}$$

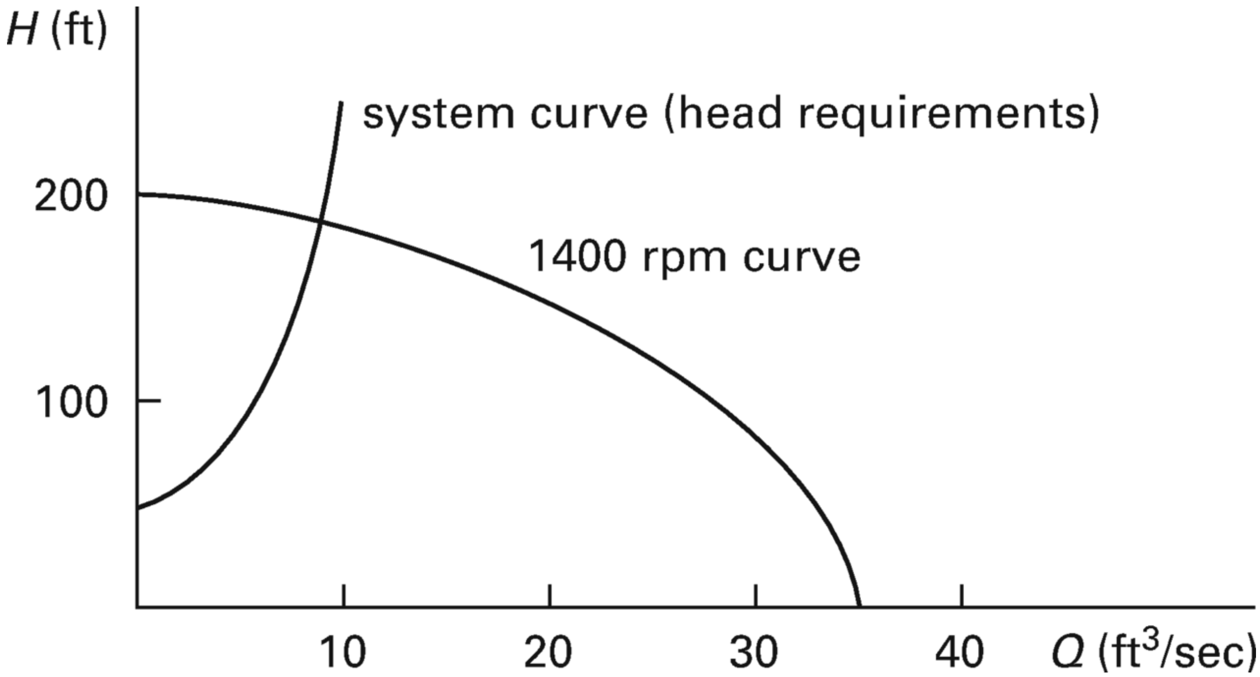
The answer is (D).

17.

Random values of Q are chosen, and the corresponding values of H are determined by the formula $H = 30 + 2Q^2$.

Q (ft^3/sec)	H (ft)
0	30
2.5	42.5
5	80
7.5	142.5
10	230
15	480
20	830
25	1280
30	1830

The intersection of the system curve and the 1400 rpm pump curve defines the operating point at that rpm.



From the intersection of the graphs, at 1400 rpm the flow rate is approximately 9 ft^3/sec, and the corresponding head is $30 + (2)(9)^2 \approx 192$ ft.

$$\begin{aligned} Q &= \left(9\ \frac{\text{ft}^3}{\text{sec}}\right)\left(7.4805\ \frac{\text{gal}}{\text{ft}^3}\right)\left(60\ \frac{\text{sec}}{\text{min}}\right) \\ &= 4039\ \text{gal/min} \end{aligned}$$

From tableCERM18005 (also *NCEES Handbook:* Pump Power), the hydraulic horsepower is

$$\text{WHP} = \frac{h_A \dot{V}\,(\text{SG})}{8.814} = \frac{(192\ \text{ft})\left(9\ \frac{\text{ft}^3}{\text{sec}}\right)(1)}{8.814\ \frac{\text{ft}^4}{\text{hp-sec}}} = 196\ \text{hp}$$

The minimum motor power should be

$$\frac{196\ \text{hp}}{0.86} = 228\ \text{hp} \quad (230\ \text{hp})$$

The answer is (C).
18.

Since turbines are essentially pumps running backward, use *NCEES Handbook:* Pump Power.

$$\Delta p = \left(30\ \frac{\text{lbf}}{\text{in}^2} - 5\ \frac{\text{lbf}}{\text{in}^2}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2$$
$$= 3600\ \text{lbf/ft}^2$$

$$P = \frac{\Delta p \dot{V}}{550} = \frac{\left(3600\ \frac{\text{lbf}}{\text{ft}^2}\right)\left(100\ \frac{\text{ft}^3}{\text{sec}}\right)}{550\ \frac{\text{ft-lbf}}{\text{hp-sec}}}$$
$$= 654.5\ \text{hp} \quad (650\ \text{hp})$$

The answer is (C).

19.

The flow rate is

$$\dot{m} = \rho \dot{V} = \left(62.4\ \frac{\text{lbm}}{\text{ft}^3}\right)\left(1000\ \frac{\text{ft}^3}{\text{sec}}\right)$$
$$= 6.24 \times 10^4\ \text{lbm/sec}$$

The head available for work is

$$\Delta h = 625\ \text{ft} - 58\ \text{ft} = 567\ \text{ft}$$

Use tableCERM18005 (also *NCEES Handbook:* Pump Power). The turbine efficiency is 89%. So, the power is

$$P = \frac{h_A \dot{m}}{550} \times \frac{g}{g_c}$$
$$= \frac{(0.89)\left(6.24 \times 10^4\ \frac{\text{lbm}}{\text{sec}}\right)(567\ \text{ft})\left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)}{\left(550\ \frac{\text{ft-lbf}}{\text{hp-sec}}\right)\left(32.2\ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}\right)}$$
$$= 57{,}253\ \text{hp}$$

Convert from hp to kW.

$$P = (57{,}253\ \text{hp})\left(0.7457\ \frac{\text{kW}}{\text{hp}}\right)$$
$$= 4.27 \times 10^4\ \text{kW} \quad (43\ \text{MW})$$

The answer is (C).

20.

Customary U.S. Solution

The total effective head is due to the pressure head, velocity head, and tailwater head.

$$h_{\text{eff}} = h_p + h_{\text{v}} - h_{z,\text{tailwater}} = h_p + \frac{\text{v}^2}{2g} - h_{z,\text{tailwater}}$$
$$= 92.5\ \text{ft} + \frac{\left(12\ \frac{\text{ft}}{\text{sec}}\right)^2}{(2)\left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)} - (-5.26\ \text{ft})$$
$$= 100\ \text{ft}$$

From tableCERM18005 (also *NCEES Handbook:* Fans), the theoretical hydraulic horsepower is

$$P_{\text{th}} = \frac{h_A \dot{V}\,(\text{SG})}{8.814} = \frac{(100\text{ ft})\left(25\ \frac{\text{ft}^3}{\text{sec}}\right)(1)}{8.814\ \frac{\text{ft}^4}{\text{hp-sec}}}$$
$$= 283.6\text{ hp}$$

The overall turbine efficiency is

$$\eta = \frac{P_{\text{brake}}}{P_{\text{th}}} = \frac{250\text{ hp}}{283.6\text{ hp}} = 0.882 \quad (88\%)$$

The answer is (B).

SI Solution

The total effective head is due to the pressure head, velocity head, and tailwater head.

$$h_{\text{eff}} = h_p + h_{\text{v}} - h_{z,\text{tailwater}} = h_p + \frac{\text{v}^2}{2g} - h_{z,\text{tailwater}}$$
$$= 28.2\text{ m} + \frac{\left(3.6\ \frac{\text{m}}{\text{s}}\right)^2}{(2)\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)} - (-1.75\text{ m})$$
$$= 30.61\text{ m} \quad (31\text{ m})$$

From tableCERM18006 (also *NCEES Handbook:* Fans), the theoretical hydraulic kilowatts are

$$P_{\text{th}} = \frac{9.81 h_A Q\,(\text{SG})}{1000}$$
$$= \frac{\left(9.81\ \frac{\text{m}}{\text{s}^2}\right)(30.61\text{ m})\left(700\ \frac{\text{L}}{\text{s}}\right)(1)}{1000\ \frac{\text{W}}{\text{kW}}}$$
$$= 210.2\text{ kW}$$

The overall turbine efficiency is

$$\eta = \frac{P_{\text{brake}}}{P_{\text{th}}} = \frac{185\text{ kW}}{210.2\text{ kW}} = 0.88 \quad (88\%)$$

The answer is (B).