12.2C A purpose of a water pump is to turn the pump shaft work into an increase in
a) the pressure of the fluid. b) the volume of the fluid.
c) the density of the fluid. d) the enthalpy of the fluid.
12.3C When wind is acting on a windmill, the power produced will depend on
a) the velocity of the wind relative to the blade.
b) the velocity of the blade relative to the ground.
c) the velocity of the ground relative to the blade.
d) the velocity of the wind relative to the ground.

Additional conceptual questions are available in WileyPLUS at the instructor’s discretion.

Problems

Note: Unless specific values of required fluid properties are given in the problem statement, use the values found in the tables on the inside of the front cover. Answers to the even-numbered problems are listed at the end of the book. The Lab Problems as well as the videos that accompany problems can be accessed in WileyPLUS or the book’s web site, www.wiley.com/college/munson.

Section 12.1 Introduction and Section 12.2 Basic Energy Considerations

12.1 The rotor shown in Fig. P12.1 rotates clockwise. Assume that the fluid enters in the radial direction and the relative velocity is tangent to the blades and remains constant across the entire rotor. Is the device a pump or a turbine? Explain.

Section 12.3 Basic Angular Momentum Considerations

12.4 Water flows through a rotating sprinkler arm as shown in Fig. P12.4 and Video V12.2. Estimate the minimum water pressure necessary for an angular velocity of 150 rpm. Is this a turbine or a pump?
Section 12.4 The Centrifugal Pump and Section 12.4.1 Theoretical Considerations

12.12 The radial component of velocity of water leaving the centrifugal pump sketched in Fig. P12.12 is 45 ft/s. The magnitude of the absolute velocity at the pump exit is 90 ft/s. The fluid enters the pump rotor radially. Calculate the shaft work required per unit mass flowing through the pump.

![Figure P12.12]

12.13 A centrifugal water pump having an impeller diameter of 0.5 m operates at 900 rpm. The water enters the pump parallel to the pump shaft. If the exit blade angle, \( \beta_2 \) (see Fig. 12.8), is 25°, determine the shaft power required to turn the impeller when the flow through the pump is 1.6 m³/s. The uniform blade height is 50 mm.

12.14 A centrifugal pump impeller is rotating at 1200 rpm in the direction shown in Fig. P12.14. The flow enters parallel to the axis of rotation and leaves at an angle of 30° to the radial direction. The absolute exit velocity, \( V_2 \), is 90 ft/s. (a) Draw the velocity triangle for the impeller exit flow. (b) Estimate the torque necessary to turn the impeller if the fluid is water. What will the impeller rotation speed become if the shaft breaks?

![Figure P12.14]

12.15 A centrifugal radial water pump has the dimensions shown in Fig. P12.15. The volume rate of flow is 0.25 ft³/s, and the absolute inlet velocity is directed radially outward. The angular velocity of the impeller is 960 rpm. The exit velocity as seen from a coordinate system attached to the impeller can be assumed to be tangent to the vane at its trailing edge. Calculate the power required to drive the pump.

![Figure P12.15]

Section 12.4.2 Pump Performance Characteristics

12.16 Water is pumped with a centrifugal pump, and measurements made on the pump indicate that for a flow rate of 240 gpm the required input power is 6 hp. For a pump efficiency of 62%, what is the actual head rise of the water being pumped?

12.17 The performance characteristics of a certain centrifugal pump are determined from an experimental setup similar to that shown in Fig. 12.10. When the flow rate of a liquid (SG = 0.9) through the pump is 120 gpm, the pressure gage at (1) indicates a vacuum of 95 mm of mercury and the pressure gage at (2) indicates a pressure of 80 kPa. The diameter of the pipe at the inlet is 110 mm and at the exit it is 55 mm. If \( z_1 = z_2 = 0.5 \text{ m} \), what is the actual head rise across the pump? Explain how you would estimate the pump motor power requirement.

12.18 The performance characteristics of a certain centrifugal pump having a 9-in.-diameter impeller and operating at 1750 rpm are determined using an experimental setup similar to that shown in Fig. 12.10. The following data were obtained during a series of tests in which \( z_2 - z_1 = 0 \), \( V_2 = V_1 \), and the fluid was water.

<table>
<thead>
<tr>
<th>Q (gpm)</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
<th>120</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_2 - P_1 ) (psi)</td>
<td>40.2</td>
<td>40.1</td>
<td>38.1</td>
<td>36.2</td>
<td>33.5</td>
<td>30.1</td>
<td>25.8</td>
</tr>
<tr>
<td>Power input (hp)</td>
<td>1.58</td>
<td>2.27</td>
<td>2.67</td>
<td>2.95</td>
<td>3.19</td>
<td>3.49</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Based on these data, show or plot how the actual head rise, \( h_a \), and the pump efficiency, \( \eta \), vary with the flowrate. What is the design flowrate for this pump?

Section 12.4.3 Net Positive Suction Head (NPSH)

12.19 In Example 12.3, how will the maximum height, \( z_1 \), that the pump can be located above the water surface change if the water temperature is decreased to 40 °F?

12.20 In Example 12.3, how will the maximum height, \( z_1 \), that the pump can be located above the water surface change if (a) the water temperature is increased to 120 °F, or (b) the fluid is changed from water to gasoline at 60 °F?

12.21 A centrifugal pump with a 7-in.-diameter impeller has the performance characteristics shown in Fig. 12.12. The pump is used to pump water at 100 °F, and the pump inlet is located 12 ft above the open water surface. When the flowrate is 200 gpm, the head loss between the water surface and the pump inlet is 6 ft of water. Would you expect cavitation in the pump to be a problem? Assume standard atmospheric pressure. Explain how you arrived at your answer.
12.22 Water at 40 °C is pumped from an open tank through 200 m of 50-mm-diameter smooth horizontal pipe as shown in Fig. P12.22 and discharges into the atmosphere with a velocity of 3 m/s. Minor losses are negligible. (a) If the efficiency of the pump is 70%, how much power is being supplied to the pump? (b) What is the NPSHₐ at the pump inlet? Neglect losses in the short section of pipe connecting the pump to the tank. Assume standard atmospheric pressure.

![Figure P12.22](image)

12.23 A small model of a pump is tested in the laboratory and found to have a specific speed, $N_{sp}$, equal to 1000 when operating at peak efficiency. Predict the discharge of a larger, geometrically similar pump operating at peak efficiency at a speed of 1800 rpm across an actual head rise of 200 ft.

12.24 The centrifugal pump shown in Fig. P12.24 is not self-priming. That is, if the water is drained from the pump and pipe as shown in Fig. P12.24(a), the pump will not draw the water into the pump and start pumping when the pump is turned on. However, if the pump is primed (i.e., filled with water as in Fig. P12.24(b)), the pump does start pumping water when turned on. Explain this behavior.

![Figure P12.24](image)

12.28 A centrifugal pump having a 6-in.-diameter impeller and the characteristics shown in Fig. 12.12 is to be used to pump gasoline through 4000 ft of commercial steel 3-in.-diameter pipe. The pipe connects two reservoirs having open surfaces at the same elevation. Determine the flowrate. Do you think this pump is a good choice? Explain.

12.29 Determine the new flowrate for the system described in Problem 12.28 if the pipe diameter is increased from 3 in. to 4 in. Is this pump still a good choice? Explain.

12.30 A centrifugal pump having the characteristics shown in Example 12.4 is used to pump water between two large open tanks through 100 ft of 8-in.-diameter pipe. The pipeline contains four regular flanged 90° elbows, a check valve, and a fully open globe valve. Other minor losses are negligible. Assume the friction factor $f = 0.02$ for the 100-ft section of pipe. If the static head (difference in height of fluid surfaces in the two tanks) is 30 ft, what is the expected flowrate? Do you think this pump is a good choice? Explain.

12.31 In a chemical processing plant, liquid is pumped from an open tank, through a 0.1-m-diameter vertical pipe, and into another open tank as shown in Fig. P12.31(a). A valve is located in the pipe, and the minor loss coefficient for the valve as a function of the valve setting is shown in Fig. P12.31(b). The pump head-capacity relationship is given by the equation $h_p = 52.0 - 1.01 \times 10^2 Q^2$ with $h_p$ in meters when $Q$ is in m³/s. Assume the friction factor $f = 0.02$ for the pipe, and all minor losses, except for the valve, are negligible. The fluid levels in the two tanks can be assumed to remain constant. (a) Determine the flowrate with the valve wide open. (b) Determine the required valve setting (percent open) to reduce the flowrate by 50%.

![Figure P12.31](image)
12.32 Water is pumped between the two tanks described in Example 12.4 once a day, 365 days a year, with each pumping period lasting two hours. The water levels in the two tanks remain essentially constant. Estimate the annual cost of the electrical power needed to operate the pump if it were located in your city. You will have to make a reasonable estimate for the efficiency of the motor used to drive the pump. Due to aging, it can be expected that the overall resistance of the system will increase with time. If the operating point shown in Fig. 12.4 changes to a point where the flow rate has been reduced to 1000 gpm, what will be the new annual cost of operating the pump? Assume that the cost of electrical power remains the same.

Section 12.5 Dimensionless Parameters and Similarity Laws

12.33 What is the rationale for operating two geometrically similar pumps differing in feature size at the same flow coefficient?

12.34 A centrifugal pump having an impeller diameter of 1 m is to be constructed so that it will supply a head rise of 200 m at a flow rate of 4.1 m$^3$/s of water when operating at a speed of 1200 rpm. To study the characteristics of this pump, a 1/5 scale, geometrically similar model operated at the same speed is to be tested in the laboratory. Determine the required model discharge and head rise. Assume that both model and prototype operate with the same efficiency (and therefore the same flow coefficient).

12.35 A centrifugal pump with a 12-in.-diameter impeller requires a power input of 60 hp when the flow rate is 3200 gpm against a 60-ft head. The impeller is changed to one with a 10-in. diameter. Determine the expected flow rate, head, and input power if the pump speed remains the same.

12.36 Do the head–flowrate data shown in Fig. 12.12 appear to follow the similarity laws as expressed by Eqs. 12.39 and 12.40? Explain.

12.37 A centrifugal pump has the performance characteristics of the pump with the 6-in.-diameter impeller described in Fig. 12.12. Note that the pump in this figure is operating at 3500 rpm. What is the expected head gained if the speed of this pump is reduced to 2800 rpm while operating at peak efficiency?

12.38 A centrifugal pump provides a flow rate of 500 gpm when operating at 1750 rpm against a 200-ft head. Determine the pump’s flowrate and developed head if the pump speed is increased to 3500 rpm.

12.39 Use the data given in Problem 12.18 and plot the dimensionless coefficients $C_P$, $C_d$, $\eta$ versus $C_Q$ for this pump. Calculate a meaningful value of specific speed, discuss its usefulness, and compare the result with data of Fig. 12.18.

12.40 In a certain application, a pump is required to deliver 5000 gpm against a 300-ft head when operating at 1200 rpm. What type of pump would you recommend?

Section 12.6 Axial-Flow and Mixed-Flow Pumps

12.41 Explain how a marine propeller and an axial-flow pump are similar in the main effect they produce.

12.42 A certain axial-flow pump has a specific speed of $N_s = 5.0$. If the pump is expected to deliver 3000 gpm when operating against a 15-ft head, at what speed (rpm) should the pump be run?

12.43 A certain pump is known to have a capacity of 3 m$^3$/s when operating at a speed of 60 rad/s against a head of 20 m. Based on the information in Fig. 12.18, would you recommend a radial-flow, mixed-flow, or axial-flow pump?

12.44 Fuel oil (sp. wt = 48.0 lb/ft$^3$, viscosity = $2.0 \times 10^{-5}$ lb-ft/s/ft$^2$) is pumped through the piping system shown in Fig. 1.21 with a velocity of 4.6 ft/s. The pressure 200 ft upstream from the pump is 5 psi. Pipe losses downstream from the pump are negligible, but minor losses are not (minor loss coefficients are given on the figure). (a) For a pipe diameter of 2 in. with a relative roughness $e/D = 0.001$, determine the head that must be added by the pump. (b) For a pump operating speed of 1750 rpm, what type of pump (radial-flow, mixed-flow, or axial-flow) would you recommend for this application?

12.45 The axial-flow pump shown in Fig. 12.19 is designed to move 5000 gal/min of water over a head rise of 5 ft of water. Estimate the motor power requirement and the $U_1V_2$ needed to achieve this flow rate on a continuous basis. Comment on any caution associated with where the pump is placed vertically in the pipe.

Section 12.7 Fans

12.46 (See Fluids in the News Article titled "Hi-tech Ceiling Fans," Section 12.7.) Explain why reversing the direction of rotation of a ceiling fan results in airflow in the opposite direction.

12.47 For the fan of both Examples 5.19 and 5.28 discuss what fluid flow properties you would need to measure to estimate fan efficiency.

Section 12.8 Turbines (also see Sec. 12.3)

12.48 An inward-flow radial turbine (see Fig. P12.48) involves a nozzle angle, $\alpha$, of 60$^\circ$ and an inlet rotor tip speed, $U_1$, of 3 m/s.
The intersection of the pump performance curve and the system curve is the operating point.

There is also a unique relationship between the actual pump head gained by the fluid and the flowrate, which is governed by the pump design (as indicated by the pump performance curve). To select a pump for a particular application, it is necessary to utilize both the system curve, as determined by the system equation, and the pump performance curve. If both curves are plotted on the same graph, as illustrated in Fig. 12.15, their intersection (point A) represents the operating point for the system. That is, this point gives the head and flowrate that satisfy both the system equation and the pump equation. On the same graph the pump efficiency is shown. Ideally, we want the operating point to be near the best efficiency point (BEP) for the pump. For a given pump, it is clear that as the system equation changes, the operating point will shift. For example, if the pipe friction increases due to pipe wall fouling, the system curve changes, resulting in the operating point A shifting to point B in Fig. 12.15 with a reduction in flowrate and efficiency. The following example shows how the system and pump characteristics can be used to decide if a particular pump is suitable for a given application.

**Fluids in the News**

**Space Shuttle fuel pumps** The fuel pump of your car engine is vital to its operation. Similarly, the fuels (liquid hydrogen and oxygen) of each Space Shuttle main engine (there are three per shuttle) rely on multistage turbopumps to get from storage tanks to main combustors. High pressures are utilized throughout the pumps to avoid cavitation. The pumps, some centrifugal and some axial, are driven by axial-flow, multistage turbines. Pump speeds are as high as 35,360 rpm. The liquid oxygen is pumped from 100 to 7420 psia, the liquid hydrogen from 30 to 6515 psia. Liquid hydrogen and oxygen flowrates of about 17,200 gpm and 6100 gpm, respectively, are achieved. These pumps could empty your home swimming pool in seconds. The hydrogen goes from $-423 \degree F$ in storage to $+600 \degree F$ in the combustion chamber!

**Example 12.4 Use of Pump Performance Curves**

**Given** Water is to be pumped from one large, open tank to a second large, open tank as shown in Fig. E12.4a. The pipe diameter throughout is 6 in., and the total length of the pipe between the pipe entrance and exit is 200 ft. Minor loss coefficients for the entrance, exit, and the elbow are shown, and the friction factor for the pipe can be assumed constant and equal to 0.02. A certain centrifugal pump having the performance characteristics shown in Fig. E12.4b is suggested as a good pump for this flow system.

**Find** With this pump, what would be the flowrate between the tanks? Do you think this pump would be a good choice?
SOLUTION

Application of the energy equation between the two free surfaces, points (1) and (2) as indicated, gives

\[
\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_u = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + f \left( \frac{V^2}{Dg} + \sum K_L \frac{V^2}{2g} \right)
\]

(1)

Thus, with \( p_1 = p_2 = 0, \ V_1 = V_2 = 0, \ \Delta z = z_2 - z_1 = 10 \text{ ft}, \ f = 0.02, \ D = 6/12 \text{ ft}, \) and \( \ell = 200 \text{ ft}, \) Eq. 1 becomes

\[
h_u = 10 + \left[ \frac{0.02 \ (200 \text{ ft})}{(6/12 \text{ ft})} \right] \frac{V^2}{2(32.2 \text{ ft}/\text{s}^2)} + (0.5 + 1.5 + 1.0)
\]

(2)

where the given minor loss coefficients have been used. Since

\[
V = \frac{Q}{A} = \frac{Q(t^2/s)}{(\pi/4)(6/12 \text{ ft})^2}
\]

Eq. 2 can be expressed as

\[
h_u = 10 + 4.43 Q^2
\]

(3)

where \( Q \) is in \( \text{ft}^3/\text{s}, \) or with \( Q \) in gallons per minute

\[
h_u = 10 + 2.20 \times 10^{-2} Q^2
\]

(4)

Equation 3 or 4 represents the system equation for this particular system and reveals how much actual head the fluid will need to gain from the pump to maintain a certain flow rate. Performance data shown in Fig. E12.4b indicate the actual head the fluid will gain from this particular pump when it operates at a certain flow rate. Thus, when Eq. 4 is plotted on the same graph with performance data, the intersection of the two curves represents the operating point for the pump and the system. This combination is shown in Fig. E12.4c with the intersection (as obtained graphically) occurring at

\[
Q = 1600 \text{ gal/min}
\]

(Ans)

with the corresponding actual head gained equal to 66.5 ft.

Another concern is whether the pump is operating efficiently at the operating point. As can be seen from Fig. E12.4c, although this is not peak efficiency, which is about 86%, it is close (about 84%). Thus, this pump would be a satisfactory choice, assuming the 1600 gal/min flow rate is at or near the desired flow rate.
The amount of pump head needed at the pump shaft is 66.5 ft/0.84 = 79.2 ft. The power needed to drive the pump is

\[
W_{\text{shaft}} = \frac{\gamma Q h_s}{\eta} = \frac{(62.4 \text{ lb/ft}^3)(1600 \text{ gal/min})/(7.48 \text{ gal/ft}^3) (60 \text{ s/min}) (66.5 \text{ ft})}{0.84} = 17,600 \text{ ft-lb/s} = 32.0 \text{ hp}
\]

**COMMENT** By repeating the calculations for \( \Delta z = z_2 - z_1 = 80 \text{ ft} \) and 100 ft (rather than the given 10 ft), the results shown in Fig. E12.4d are obtained. Although the given pump could be used with \( \Delta z = 80 \text{ ft} \) (provided that the 500 gal/min flowrate produced is acceptable), it would not be an ideal pump for this application since its efficiency would be only 36%.

Energy could be saved by using a different pump with a performance curve that more nearly matches the new system requirements (i.e., higher efficiency at the operating condition). On the other hand, the given pump would not work at all for \( \Delta z = 100 \text{ ft} \) since its maximum head \( h_s = 88 \text{ ft} \) when \( Q = 0 \) is not enough to lift the water 100 ft, let alone overcome head losses. This is shown in Fig. E12.4d by the fact that for \( \Delta z = 100 \text{ ft} \) the system curve and the pump performance curve do not intersect.

Note that head loss within the pump itself was accounted for with the pump efficiency, \( \eta \). Thus, \( h = h_s/\eta \), where \( h_s \) is the pump shaft work head and \( h \) is the actual head rise experienced by the flowing fluid.

For two pumps in series, add heads; for two in parallel, add flowrates.

Pumps can be arranged in series or in parallel to provide for additional head or flow capacity. When two pumps are placed in series, the resulting pump performance curve is obtained by adding heads at the same flowrate. As illustrated in Fig. 12.16a, for two identical pumps in series, both the actual head gained by the fluid and the flowrate are increased, but neither will be doubled if the system curve remains the same. The operating point is at (A) for one pump and moves to (B) for two pumps in series. For two identical pumps in parallel, the combined performance curve is obtained by adding flowrates at the same head, as shown in Fig. 12.16b. As illustrated, the flowrate for the system will not be doubled with the addition of two pumps in parallel (if the same system