P11.7 A piston PDP has a 5-in diameter and a 2-in stroke and operates at 750 rpm with 92% volumetric efficiency. (a) What is the delivery, in gal/min? (b) If the pump delivers SAE 10W oil at 20°C against a head of 50 ft, what horsepower is required when the overall efficiency is 84%?

Solution: For SAE 10W oil, take $\rho \approx 870\ \text{kg/m}^3 \approx 1.69\ \text{slug/ft}^3$. The volume displaced is

$$\upsilon = \frac{\pi}{4}(5)^2(2) = 39.3\ \text{in}^3,$$

$$\therefore\quad Q = \left(39.3\ \frac{\text{in}^3}{\text{stroke}}\right)\left(\frac{1\ \text{gal}}{231\ \text{in}^3}\right)\left(750\ \frac{\text{strokes}}{\text{min}}\right)(0.92\ \text{efficiency})$$

$$\text{or:}\quad Q \approx \mathbf{117\ gal/min}\quad \textit{Ans.}\ \text{(a)}$$

$$\text{Power} = \frac{\rho g Q H}{\eta} = \frac{1.69(32.2)\left(\frac{117}{449}\ \text{ft}^3/\text{s}\right)(50)}{0.84} = 846\ \frac{\text{ft}\cdot\text{lbf}}{\text{s}} \div 550 \approx \mathbf{1.54\ hp}\quad \textit{Ans.}\ \text{(b)}$$

P11.11 A pump delivers 1500 L/min of water at 20°C against a pressure rise of 270 kPa. Kinetic and potential energy changes are negligible. If the driving motor supplies 9 kW, what is the overall efficiency?

Solution: With pressure rise given, we don't need density. Compute "water" power:

$$P_{water} = \rho g Q H = Q\,\Delta p = \left(\frac{1.5}{60}\ \frac{\text{m}^3}{\text{s}}\right)\left(270\ \frac{\text{kN}}{\text{m}^2}\right) = 6.75\ \text{kW},\quad \therefore\ \eta = \frac{6.75}{9.0} = \mathbf{75\%}\quad \textit{Ans.}$$

P11.12 In a test of the pump in the figure, the data are: p_1 = 100 mmHg (vacuum), p_2 = 500 mmHg (gage), D_1 = 12 cm, and D_2 = 5 cm. The flow rate is 180 gal/min of light oil (SG = 0.91). Estimate (a) the head developed; and (b) the input power at 75% efficiency.

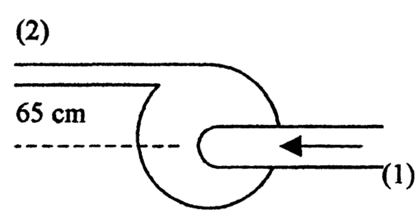

Fig. P11.12

Solution: Convert 100 mmHg = 13332 Pa, 500 mmHg = 66661 Pa, 180 gal/min = 0.01136 m³/s. Compute $V_1 = Q/A_1 = 0.01136/[(\pi/4)(0.12)^2] = 1.00$ m/s. Also, $V_2 = Q/A_2 = 5.79$ m/s. Calculate $\gamma_{oil} = 0.91(9790) = 8909\ \text{N/m}^3$. Then the head is

$$H = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 - \frac{p_1}{\gamma} - \frac{V_1^2}{2g} - z_1$$

$$= \frac{66661}{8909} + \frac{(5.79)^2}{2(9.81)} + 0.65 - \frac{-13332}{8909} - \frac{(1.00)^2}{2(9.81)} - 0,\quad \text{or:}\quad \mathbf{H = 11.3\ m}\quad \textit{Ans.}\ \text{(a)}$$

$$Power = \frac{\gamma QH}{\eta} = \frac{8909(0.01136)(11.3)}{0.75} = \mathbf{1520\ W} \quad \textit{Ans.}\ \text{(b)}$$

P11.28 Tests by the Byron Jackson Co. of a 14.62-in centrifugal water pump at 2134 rpm yield the data below. What is the BEP? What is the specific speed? Estimate the maximum discharge possible.

Q, ft^3/s:	0	2	4	6	8	10
H, ft:	340	340	340	330	300	220
bhp:	135	160	205	255	330	330

Solution: The efficiencies are computed from $\eta = \rho gQH/(550\text{ bhp})$ and are as follows:

Q:	0	2	4	**6**	8	10
η:	0	0.482	0.753	**0.881**	0.825	0.756

Thus the BEP is, even without a plot, close to **Q ≈ 6 ft³/s**. *Ans.* The specific speed is

$$N_s \approx \frac{nQ^{*1/2}}{H^{*3/4}} = \frac{2134[(6)(449)]^{1/2}}{(330)^{3/4}} \approx \mathbf{1430} \quad \textit{Ans.}$$

For estimating Q_{max}, the last three points fit a Power-law to within ±0.5%:

$$H \approx 340 - 0.00168Q^{4.85} = 0 \quad \text{if} \quad Q \approx \mathbf{12.4\ \frac{ft^3}{s}} = Q_{max} \quad \textit{Ans.}$$

P11.30 A pump, geometrically similar to the 12.95-in model in Fig. P11.24, has a diameter of 24 in and is to develop 30 hp at BEP when pumping *gasoline* (not water). Determine (*a*) the appropriate speed, in r/min; (*b*) the BEP head, in ft; and (*c*) the BEP flow rate, in gal/min.

Solution: For gasoline, from Table A.3, ρ = 680 kg/m^3 = 1.32 slug/ft^3. Read Fig. P11.24 for the BEP values: $H_1^* = 72\ ft$, $Q = 525\ gal/min$, $\eta_1^* = 0.80$. Compute the power from this data:

$$P_1 = \frac{\rho g Q H}{\eta} = \frac{(1.94)(32.2)(525/449)(72)}{0.80} = 6570\frac{ft\cdot lbf}{s} = 11.95\,hp$$

Use the scaling laws to find the new speed, head, and flow rate:

$$\frac{P_2}{P_1} = \frac{30}{11.95} = \frac{\rho_2}{\rho_1}\left(\frac{n_2}{n_1}\right)^3\left(\frac{D_2}{D_1}\right)^5 = \left(\frac{1.32}{1.94}\right)\left(\frac{n_2}{1160}\right)^3\left(\frac{24}{12.95}\right)^5,\ solve\ n_2 \approx \mathbf{640\frac{r}{min}} \quad Ans.(a)$$

$$\frac{H_2}{H_1} = \frac{H_2}{72} = \left(\frac{n_2}{n_1}\right)^2\left(\frac{D_2}{D_1}\right)^2 = \left(\frac{640}{1160}\right)^2\left(\frac{24}{12.95}\right)^2,\ solve\ H_2 \approx \mathbf{75\,ft} \quad Ans.(b)$$

$$\frac{Q_2}{Q_1} = \frac{Q_2}{525} = \left(\frac{n_2}{n_1}\right)\left(\frac{D_2}{D_1}\right)^3 = \left(\frac{640}{1160}\right)\left(\frac{24}{12.95}\right)^3,\quad solve\ Q_2 \approx \mathbf{1840\,\frac{gal}{min}} \quad Ans.(c)$$

P11.36 The pump of Prob. P11.35 has a maximum efficiency of 88% at 8000 gal/min. (*a*) Can we use this pump, at the same diameter but a different speed, to generate a BEP head of 150 ft and a BEP flow rate of 10,000 gal/min? (*b*) If not, what diameter is appropriate?

Solution: We are still pumping *water*, $\rho = 1.94$ slug/ft^3. Try scaling laws for head and then for flow:

$$H_1 = 68\,ft \ ; \ Q_1 = 8000\,\frac{gal}{min} = 17.8\,\frac{ft^3}{s} \ ; \ P_1 = 156\,bhp \ ; \ D_1 = 1.5\,ft \ ; \ n_1 = 880\,rpm = 14.7\,\frac{r}{s}$$

$$D_1 = D_2: \ \frac{H_2}{H_1} = \frac{150}{68} = \left(\frac{n_2}{14.7}\right)^2 , \ n_2 = 21.8\,\frac{r}{s} = 1307\,\frac{r}{min} \ \text{(from the head)}$$

$$D_1 = D_2: \ \frac{Q_2}{Q_1} = \frac{10000}{8000} = \left(\frac{n_2}{14.7}\right) , \ n_2 = 18.3\,\frac{r}{s} = 1100\,\frac{r}{min} \ \text{(from the flow rate)}$$

These rotation rates are not the same. **Therefore we must change the diameter**. Ans.(*a*)
(*b*) Allow for a different diameter in both head and flow rate scaling:

$$\frac{H_2}{H_1} = \frac{150\,ft}{68\,ft} = \left(\frac{n_2}{n_1}\right)^2 \left(\frac{D_2}{D_1}\right)^2 = \left(\frac{n_2}{14.67\,r/s}\right)^2 \left(\frac{D_2}{1.5\,ft}\right)^2 , \quad or: \ n_2^2 D_2^2 = 1068$$

$$\frac{Q_2}{Q_1} = \frac{10{,}000\,gpm}{8{,}000\,gpm} = \frac{n_2}{n_1}\left(\frac{D_2}{D_1}\right)^3 = \left(\frac{n_2}{14.67}\right)\left(\frac{D_2}{1.5\,ft}\right)^3 , \quad or: \ n_2 D_2^3 = 61.88$$

Solve simultaneously to obtain

$n_2 = 16.0\ r/s =$ **960 rpm** ; $D_2 = 2.04\,ft =$ **24.5 inches** *Ans*(*b*)

The power required increases to 380 bhp.

P11.76 Two 32-inch pumps are combined in parallel to deliver water at 20°C through 1500 ft of horizontal pipe. If $f = 0.025$, what pipe diameter will ensure a flow rate of 35,000 gal/min at 1170 rpm?

Solution: For water at 20°C, take $\rho = 1.94$ slug/ft^3 and $\mu = 2.09E{-}5$ slug/ft·s. As in Prob. 11.74, a reasonable curve-fit to the pump head is taken from Fig. 11.7*a*: $H_p(ft) \approx 500 - 0.3Q^2$, with Q in kgal/min. Each pump takes half the flow, 17,500 gal/min, for which

$$H_p \approx 500 - 0.3(17.5)^2 \approx 408 \text{ ft.} \quad \text{Then } Q_{pipe} = \frac{35000}{449} = 78\ \frac{ft^3}{s} \text{ and the pipe loss is}$$

$$H_{syst} = 0.025\left(\frac{1500}{d}\right)\frac{[78/(\pi d^2/4)]^2}{2(32.2)} = \frac{5740}{d^5} = 408 \text{ ft,} \quad \text{solve for } \mathbf{d \approx 1.70\ ft} \quad \textit{Ans.}$$

P11.80 Determine if either (*a*) the smallest, or (*b*) the largest of the seven Taco pumps in Fig.P11.24, running in series at 1160 r/min, can efficiently pump water at 20°C through 1 km of horizontal 12-cm-diameter commercial steel pipe.

Solution: For water at 20°C, take $\rho = 998$ kg/m^3 and $\mu = 0.001$ kg/m-s. For commercial steel pipe, from Table 6.1, $\varepsilon = 0.046$ mm. Then $\varepsilon/D = 0.046$ mm/120 mm = 0.000383.

(*a*) For the smallest pump in Fig. P11.24, the BEP is at about 400 gal/min, with a head of about 41 ft. See what friction head loss results from this flow rate:

$$V = \frac{Q}{A} = \frac{(400\times 6.309E-5)m^3/s}{(\pi/4)(0.12m)^2} = 2.23\frac{m}{s};\ \mathrm{Re}_D = \frac{\rho VD}{\mu} = \frac{(998)(2.23)(0.12)}{0.001} = 267{,}000$$

$$\frac{\varepsilon}{D} = 0.000383; \quad Eq.(6.48): \ f_{Moody} \approx 0.0177 \ ,$$

$$h_f = f\frac{L}{D}\frac{V^2}{2g} = (0.0177)(\frac{1000}{0.12})\frac{(2.23)^2}{2(9.81)} = 37.4m = 123ft$$

So **three small pumps in series**, each with 41 ft of head, would be an efficient system. *Ans*. (*a*)

(*b*) For the largest pump in Fig. P11.24, the BEP is at about 525 gal/min, with a head of about 72 ft. See what friction head loss results from this flow rate:

$$V = \frac{Q}{A} = \frac{(525\times 6.309E-5)m^3/s}{(\pi/4)(0.12m)^2} = 2.98\frac{m}{s}; \mathrm{Re}_D = \frac{\rho VD}{\mu} = \frac{(998)(2.98)(0.12)}{0.001} = 357{,}000$$

$$\frac{\varepsilon}{D} = 0.000383; \quad Eq.\ (6.48): \quad f_{Moody} \approx 0.0173,$$

$$h_f = f\frac{L}{D}\frac{V^2}{2g} = (0.0173)(\frac{1000}{0.12})\frac{(2.98)^2}{2(9.81)} = 65.4m = 214\ ft$$

So **three large pumps in series**, each with 71 ft of head, would be an efficient system. *Ans*. (*b*) The largest pump is a better solution because of its higher efficiency (80% compared to 65%).

P11.102 An American 6-ft diameter multiblade HAWT is used to pump water to a height of 10 ft through 3-in-diameter cast-iron pipe. If the winds are 12 mi/h, estimate the rate of water flow in gal/min.

Solution: For air in "America" (?), take $\rho \approx 0.0023$ slug/ft^3. Convert 12 mi/h = 17.6 ft/s. For water, take ρ = 1.94 slug/ft^3 and μ = 2.09E–5 slug/(ft·s). From Fig. 11.34 for the American multiblade HAWT, read optimum C_P and speed ratio:

$$C_{P,max} \approx 0.29 \text{ at } \frac{\omega r}{V_1} \approx 0.9: \quad P_{max} \approx 0.29\left(\frac{1}{2}\right)(0.0023)\frac{\pi}{4}(6)^2(17.6)^3 \approx 51.4\ \frac{\text{ft·lbf}}{\text{s}}$$

$$\text{If } \eta_{pump} \approx 80\%, \quad P_{pump} \approx 0.8(51.4) = \rho_{water} g Q H_{syst} = 62.4Q\left(\Delta z + f\frac{L}{D}\frac{V_{pipe}^2}{2g}\right)$$

$$\text{where} \quad V_{pipe} = \frac{Q}{(\pi/4)(3/12)^2}, \quad \frac{L}{D} = \frac{10}{3/12} = 40, \quad \frac{\varepsilon}{D} = \frac{0.00085}{3/12} \approx 0.0034$$

$$\text{Clean up to:} \quad 0.659 = Q(10 + 258 f_{Moody} Q^2), \text{ with Q in ft}^3\text{/s.} \quad \text{Iterate to obtain}$$

$$f \approx 0.0305, \ V_{pipe} \approx 1.34\ \frac{ft}{s}, \ \mathrm{Re} \approx 31000, \ Q \approx 0.0657\ \frac{ft^3}{s} \approx \mathbf{29\ gal/min} \quad \textit{Ans.}$$

P11.108 To avoid the bulky tower and impeller and generator in the HAWT of the chapter-opener photo, we could instead build a number of Darrieus turbines of height 4 m and diameter 3 m. (a) How many of these would we need to match the HAWT's 100 kW output for 15 m/s wind speed and maximum power? (b) How fast would they rotate? Assume the area swept out by a Darrieus turbine is two-thirds the height times the diameter.

Solution: Again take $\rho = 1.2\ kg/m^3$. From Fig. 11.32, for a Darrieus turbine, $C_{P,max} =$ 0.42 at $\omega r/V = 4.2$. The total power generated by one turbine is thus

$$P_{Darrieus} = C_P(\frac{1}{2})\rho A V^3 = (0.42)(\frac{1}{2})(1.2)[\frac{2}{3}(4)(3)](15)^3 = 6800\ W$$

To match the big 3-blade HAWT, we would need 100,000/6800 ≈ **15 Darrieus turbines**. *Ans.*

The rotation speed at this maximum-power condition is

$$\frac{\omega r}{V} = 4.2 = \frac{\omega(1.5m)}{15\,m/s}, \text{ solve } \omega \approx 42\frac{rad}{s} \approx \mathbf{400\ \frac{r}{min}} \quad \textit{Ans.}$$