**P3.149** The horizontal lawn sprinkler in Fig. P3.149 has a water flow rate of 4.0 gal/min introduced vertically through the center. Estimate (a) the retarding torque required to keep the arms from rotating and (b) the rotation rate (r/min) if there is no retarding torque.

![Diagram](image)

**Fig. P3.149**

**Solution:** The flow rate is 4 gal/min = 0.008912 ft³/s, and \( \rho = 1.94 \) slug/ft³. The velocity issuing from each arm is \( V_o = \frac{(0.008912/2)}{((\pi/4)(0.25/12 \text{ ft})^2)} \approx 13.1 \) ft/s. Then:

(a) From Example 3.15, \( \omega = \frac{V_o}{R} - \frac{T_o}{\rho QR^2} \) and, if there is no motion (\( \omega = 0 \)),

\[
T_o = \rho QRV_o = (1.94)(0.008912)(6/12)(13.1) \approx 0.113 \text{ ft-lbf} \quad \text{Ans. (a)}
\]

(b) If \( T_o = 0 \), then \( \omega_{\text{no friction}} = \frac{V_o}{R} = \frac{13.1 \text{ ft/s}}{6/12 \text{ ft}} = 26.14 \text{ rad/s} \approx 250 \text{ rev/min} \quad \text{Ans. (b)}
P3.154 Water at 20°C flows at 30 gal/min through the 0.75-in-diameter double pipe bend of Fig. P3.154. The pressures are $p_1 = 30$ lbf/in$^2$ and $p_2 = 24$ lbf/in$^2$. Compute the torque $T$ at point B necessary to keep the pipe from rotating.

Solution: This is similar to Example 3.13, of the text. The volume flow $Q = 30 \text{ gal/min} = 0.0668 \text{ ft}^3/\text{s}$, and $\rho = 1.94 \text{ slug/ft}^3$. Thus the mass flow $\rho Q = 0.130 \text{ slug/s}$. The velocity in the pipe is

$$V_1 = V_2 = \frac{Q}{A} = \frac{0.0668}{\left(\frac{\pi}{4}\right)(0.75/12)^2} = 21.8 \text{ ft/s}$$

If we take torques about point B, then the distance “h1,” from p. 143, = 0, and $h_2 = 3 \text{ ft}$. The final torque at point B, from “Ans. (a)” on p. 143 of the text, is

$$T_B = h_2(p_2A_2 + mV_2) = (3 \text{ ft})[(24 \text{ psi})\frac{\pi}{4}(0.75 \text{ in})^2 + (0.130)(21.8)] \approx 40 \text{ ft-lbf} \quad \text{Ans.}$$
**Problem 3.156**  A simple turbomachine is constructed from a disk with two internal ducts which exit tangentially through square holes, as in the figure. Water at 20°C enters the disk at the center, as shown. The disk must drive, at 250 rev/min, a small device whose retarding torque is 1.5 N·m. What is the proper mass flow of water, in kg/s?

**Solution:** This problem is a disguised version of the lawn-sprinkler arm in Example 3.15. For that problem, the steady rotating speed, with retarding torque \( T_0 \), was

\[
\omega = \frac{V_o}{R} - \frac{T_0}{\rho Q R^2}, \quad \text{where } V_o \text{ is the exit velocity and } R \text{ is the arm radius.}
\]

Enter the given data, noting that \( Q = 2V_o(\Delta L_{exit})^2 \) is the total volume flow from the two arms:

\[
\omega = 250 \left( \frac{2\pi}{60} \right) \frac{\text{rad}}{\text{s}} = \frac{V_o}{0.16 \text{ m}} - \frac{1.5 \text{ N·m}}{998(2V_o)(0.02 \text{ m})^2(0.16 \text{ m})^2}, \quad \text{solve } V_o = 6.11 \frac{\text{m}}{\text{s}}
\]

The required mass flow is thus,

\[
m = \rho Q = \left( 998 \frac{\text{kg}}{\text{m}^3} \right) \left( 2 \left( 6.11 \frac{\text{m}}{\text{s}} \right) \right) (0.02 \text{ m})^2 = 2.44 \frac{\text{kg}}{\text{s}} \quad \text{Ans.}
\]
**P3.169** When the pump in Fig. P3.169 draws 220 m$^3$/h of water at 20°C from the reservoir, the total friction head loss is 5 m. The flow discharges through a nozzle to the atmosphere. Estimate the pump power in kW delivered to the water.

**Solution:** Let “1” be at the reservoir surface and “2” be at the nozzle exit, as shown. We need to know the exit velocity:

\[ V_2 = \frac{Q}{A_2} = \frac{220/3600}{\pi(0.025)^2} = 31.12 \text{ m/s}, \text{ while } V_1 \approx 0 \text{ (reservoir surface)} \]

Now apply the steady flow energy equation from (1) to (2):

\[ \frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_f - h_p, \]

or: \( 0 + 0 + 0 = 0 + (31.12)^2/[2(9.81)] + 2 + 5 - h_p \), solve for \( h_p \approx 56.4 \text{ m} \).

The pump power \( P = \rho gQh_p = (998)(9.81)(220/3600)(56.4) \)

\[ = 33700 \text{ W} = 33.7 \text{ kW} \quad \text{Ans.} \]
P3.171 Consider a turbine extracting energy from a penstock in a dam, as in the figure. For turbulent flow (Chap. 6) the friction head loss is \( hf = CQ^2 \), where the constant \( C \) depends upon penstock dimensions and water physical properties. Show that, for a given penstock and river flow \( Q \), the maximum turbine power possible is \( P_{\text{max}} = 2 \rho g H Q/3 \) and occurs when \( Q = \sqrt{(H/3C)^2} \).

![Fig. P3.171](image)

**Solution:** Write the steady flow energy equation from point 1 on the upper surface to point 2 on the lower surface:

\[
\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + h = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + 0 + h_f + h_{\text{turbine}}
\]

But \( p_1 = p_2 = p_{\text{am}} \) and \( V_1 \approx V_2 \approx 0 \). Thus the turbine head is given by

\[ h_t = H - h_f = H - CQ^2, \]

or: \( \text{Power} = P = \rho g Q h_t = \rho g Q H - \rho g C Q^3 \)

Differentiate and set equal to zero for max power and appropriate flow rate:

\[
\frac{dP}{dQ} = \rho g H - 3 \rho g C Q^2 = 0 \quad \text{if} \quad Q = \sqrt{H/3C} \quad \text{Ans.}
\]

\[ \text{Insert } Q \text{ in } P \text{ to obtain} \quad P_{\text{max}} = \rho g Q \left( \frac{2H}{3} \right) \quad \text{Ans.} \]
**P3.176** A fireboat draws seawater (SG = 1.025) from a submerged pipe and discharges it through a nozzle, as in Fig. P3.176. The total head loss is 6.5 ft. If the pump efficiency is 75 percent, what horsepower motor is required to drive it?

![Fig. P3.176](image)

**Solution:** For seawater, \( \gamma = 1.025(62.4) = 63.96 \text{ lbf/ft}^3 \). The energy equation becomes

\[
\frac{p_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_f - h_p
\]

or:

\[
0 + 0 + 0 = 0 + \frac{(120)^2}{2(32.2)} + 10 + 6.5 - h_p
\]

Solve for \( h_p = 240 \text{ ft} \). The flow rate is \( Q = V_2A_2 = (120)(\pi/4)(2/12)^2 = 2.62 \text{ ft}^3/\text{s} \). Then

\[
P_{\text{pump}} \overset{\text{efficiency}}{=} \frac{\gamma Q h_p}{0.75} \approx \frac{(63.96)(2.62)(240)}{53600} \approx 97 \text{ hp} \quad \text{Ans.}
\]