14.1: PROBLEM DEFINITION

Situation: Thrust of a fixed pitch propeller

Find: Reason the thrust decreases with forward speed.

SOLUTION

The angle of attack for the propeller blade is the difference between the pitch angle and angle of flow due to forward motion,

$$\alpha = \beta - \tan^{-1}\left(\frac{V_0}{r\omega}\right)$$

As the forward speed, V_o, increases, the argument of the arc tangent increases and the angle of attack decreases. The lift and thrust decrease correspondingly.

14.2: PROBLEM DEFINITION

Situation: Rotational speed of propeller.

Find: Limit on rotational speed.

SOLUTION

As the rotational speed increases, the tip speed increases to the point where compressibility effects become important. As the tip Mach number approaches unity, the drag goes, the torque increases and the power requirements becomes excessive.

14.3: PROBLEM DEFINITION

Situation: A 3 m propeller operates at 1100 rpm with no forward speed.

Find: Thrust force.

Properties: ρ =1.05 kg/m^3.

PLAN

Use propeller characteristics in Fig. 14.3 (EFM 10e).

SOLUTION

From Fig. 14.3 (EFM 10e) for advance ratio equal to zero.

$$C_T = 0.048.$$

Propeller thrust force equation

$$\begin{aligned} F_T &= C_T \rho D^4 n^2 \\ &= 0.048 \times 1.05 \text{ kg/m}^3 \times (3 \text{ m})^4 \times \left(\frac{1,100 \text{ rev/min}}{60 \text{ s/min}}\right)^2 \\ &\boxed{F_T = 1372\,\text{N}} \end{aligned}$$

14.4: PROBLEM DEFINITION

Situation: A 3 m propeller operates at 1400 rpm with forward speed of 80 km/hr.

Find: (a) Thrust. (b) Power.

Properties: ρ =1.05 kg/m^3

PLAN

Use propeller characteristics in Fig. 14.3 (EFM 10e).

SOLUTION

Advance ratio

$$\begin{aligned}\frac{V_o}{nD} &= \frac{80 \text{ km/hr} \times \frac{1000 \text{ m}}{1 \text{ km}} \times \frac{1 \text{ hr}}{3600 \text{ s}}}{1400 \text{ rev/min} \times \frac{1 \text{ min}}{60 \text{ s}} \times 3 \text{ m}} \\ &= 0.317\end{aligned}$$

From Fig. 14.3 (EFM 10e)

$$C_T = 0.020$$

Propeller thrust force equation

$$\begin{aligned}F &= C_T \rho D^4 n_T^2 \\ &= 0.020 \times 1.05 \text{ kg/m}^3 \times (3 \text{ m})^4 \times (\frac{1,400 \text{ rev/min}}{60 \text{ s/min}})^2 \\ & (a) \quad \boxed{F_T = 926 \text{ N}}\end{aligned}$$

From Fig. 14.3 (EFM 10e)

$$C_p = 0.011$$

Propeller power equation

$$\begin{aligned}P &= C_p \rho n^3 D^5 \\ &= 0.011 \times 1.05 \text{ kg/m}^3 \times (3 \text{ m})^5 \times (\frac{1,400 \text{ rev/min}}{60 \text{ s/min}})^3 \\ & (b) \quad \boxed{P = 35.7 \text{ kW}}\end{aligned}$$

14.5: PROBLEM DEFINITION

Situation: An 2.4 m propeller rotates at 1200 rpm with forward speed of 48 km/h.

Find: (a) Thrust for $V_0 = 48$ km/h.
(b) Power for (a).
(c) Thrust for $V_0 = 0$.

Properties: $\rho = 1.24 \text{ kg/m}^3$

PLAN

Find advance ratio and use characteristics from Fig. 14.3 (EFM 10e). Apply the propeller thrust force equation and the propeller power equation.

SOLUTION

Rotational speed and forward velocity.

$$\begin{aligned} n &= \frac{1200 \text{ rev/min}}{60 \text{ s/min}} = 20 \text{ rev/sec} \\ V_0 &= 48 \text{ km/h} \times \frac{1000 \text{ m}}{1 \text{ km}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 13.3 \text{ m/s} \end{aligned}$$

Advance ratio

$$\begin{aligned} \frac{V_0}{nD} &= \frac{13.3 \text{ m/s}}{20 \text{ rev/s} \times 2.4 \text{ m}} \\ &= 0.277 \end{aligned}$$

Coefficient of thrust and power (from Fig. 14.3 (EFM 10e))

$$\begin{aligned} C_T &= 0.023 \\ C_p &= 0.011 \end{aligned}$$

Propeller thrust force equation

$$\begin{aligned} F &= C_T \rho D^4 n^2 \\ &= 0.023 \times 1.24 \times 2.4^4 \times 20^2 \\ &\boxed{F_T = 378.5 \, \text{N}} \end{aligned}$$

Propeller power equation

$$\begin{aligned} P &= C_p \rho n^3 D^5 \\ &= 0.011 \times 1.24 \times 20^3 \times 2.4^5 \\ &= 8689.2 \text{ N-m/s} \\ &\boxed{P = 8689 \, \text{W}} \end{aligned}$$

When the forward speed is 0 ($V_0 = 0$) ,then the thrust coefficient (Fig. 14.3 (EFM 10e)) is

$$C_T = 0.0475$$

Propeller thrust force equation

$$\begin{aligned} F_T &= C_T \rho D^4 n_T^2 \\ &= 0.0475 \times 1.24 \times 2.4^4 \times 20^2 \\ & \boxed{F_T = 782\,\mathrm{N}} \end{aligned}$$

14.6: PROBLEM DEFINITION

Situation: A 2.4 m propeller on a swamp boat moving at 48 km/h operates at maximum efficiency.

Find: Rotational speed of propeller, rpm

PLAN

Use Fig 14.3 (EFM 10e) to find the advance diameter ratio at maximum efficiency.

SOLUTION

$$V_0 = 48 \text{ km/h} = 13.3 \text{ m/s}$$

From Fig. 14.3 (EFM 10e), at maximum efficiency $V_0/(nD) = 0.285$ so

$$\begin{aligned} n &= V_0/(0.285D) \\ n &= 13.3 \text{ m/s}/(0.285 \times 2.4 \text{ m}) \\ &= 19.30 \text{ rps} \\ & \boxed{N = 1160 \text{ rpm}} \end{aligned}$$

14.7: PROBLEM DEFINITION

Situation: A 2.4 m propeller on a swamp boat moving at 48 km/h operates at maximum efficiency where rotational speed is 19.3 rps.

Find: (a) Thrust (b) Power output.

Properties: $\rho = 1.24$ kg/m^3.

PLAN

Apply the propeller thrust force equation and the propeller power equation. Use Fig 14.3 (EFM 10e) to find C_T and C_P at maximum efficiency.

SOLUTION

From Fig. 14.2

$$\begin{aligned} C_T &= 0.023 \\ C_p &= 0.012 \end{aligned}$$

Propeller thrust force equation

$$\begin{aligned} F_T &= C_T \rho D^4 n^2 \\ &= 0.023 \times 1.24 \text{ kg/m}^3 \times (2.4 \text{ m})^4 \times (19.3 \text{ rps})^2 \\ & \boxed{F_T = 352.5\,\text{N}} \end{aligned}$$

Propeller power equation

$$\begin{aligned} P &= C_p \rho n^3 D^5 \\ &= 0.012 \times 1.24 \text{ kg/m}^3 \times (2.4 \text{ m})^5 \times (19.3 \text{ rps})^3 \\ &= 8518 \text{ N-m/s} \\ & \boxed{P = 8518\,\text{W}} \end{aligned}$$

14.8: PROBLEM DEFINITION

Situation: A propeller is selected for an 1200 kg airplane operating at 60 kPa and 10°C. Lift to drag ratio of 30:1 with lift coefficient of 0.4 and plan form area of 10 m^2. Engine rpm is 3000. At optimum efficiency thrust coefficient is 0.025.

Find: (a) Diameter of propeller (b) Speed of aircraft.

PLAN

Apply the Ideal gas law to get the density for the propeller thrust force equation to calculate the diameter. Then apply the lift force equation to calculate the speed.

SOLUTION

Ideal gas law

$$\begin{aligned} \rho &= p/RT \\ &= 60 \times 10^3/((287)(283)) \\ &= 0.734 \text{ kg/m}^3 \end{aligned}$$

Propeller thrust force equation

$$\begin{aligned} F_T &= C_T \rho n^2 D^4 \\ F_T &= \text{Drag} = \text{Lift}/30 = \text{Weight}/30 = (1,200 \text{ kg})(9.81 \text{ m/s}^2)/(30) = 392 \text{ N} \\ 392 \text{ N} &= (0.025)(0.734 \text{ kg/m}^3)(3,000 \text{ rpm}/60 \text{ s/min})^2 D^4 \\ & \boxed{D = 1.71\,\text{m}} \end{aligned}$$

Lift force

$$\begin{aligned} L &= W = C_L(1/2)\rho V_0^2 S \\ (\rho V_0^2/2) &= W/(C_L S) \\ (\rho V_0^2/2) &= (1,200 \text{ kg})(9.81 \text{ m/s}^2)/(0.40 \times 10 \text{ m}^2) = 2,943 \text{ N/m}^2 \\ V_0^2 &= 2,943 \text{ N/m}^2 \times 2/0.734 \text{ kg/m}^3 = 7,994 \text{ m}^2/\text{s}^2 \\ & \boxed{V_0 = 89.4 \text{ m/s}} \end{aligned}$$

14.9: PROBLEM DEFINITION

Situation: A propeller tip speed must be less than 0.8 of sound speed.

Find: Maximum allowable angular speed for 2 m, 3 m and 4 m propeller.

Properties: $c = 335$ m/s

SOLUTION

$$\begin{aligned} V_{\text{tip}} &= 0.8c = 0.8 \times 335 = 268 \text{ m/s} \\ V_{\text{tip}} &= \omega r = n(2\pi)r \\ n &= V_{\text{tip}}/(2\pi r) = 268/(\pi D) \text{ rev/s} \\ N &= 60 \times n \text{ rpm} \end{aligned}$$

D (m)	N (rpm)
2	2,559
3	1,706
4	1,280

14.10: PROBLEM DEFINITION

Situation: A 2 m propeller used on a swamp boat moving at 40 km/hr and operates at maximum efficiency.

Find: Angular speed of propeller.

PLAN

Use Fig 14.3 (EFM 10e) to find the advance diameter ratio at maximum efficiency.

SOLUTION

Advance ratio (from Fig. 14.3 (EFM 10e))

$$V_0/(nD) = 0.285$$

Rotation speed

$$\begin{aligned} n &= V_0/(0.285D) \\ &= (40,000 \text{ m/hr}/3,600 \text{ s/hr})/(0.285 \times 2 \text{ m}) \\ &= 19.5 \text{ rev/s} \\ N &= 19.5 \times 60 \text{ s/min} \\ & \boxed{N = 1170 \text{ rpm}} \end{aligned}$$

14.11: PROBLEM DEFINITION

Situation: A 2 m propeller used on a swamp boat moving at 40 km/hr and operates at maximum efficiency. Rotational speed is 19.5 rps.

Find: (a) Thrust. (b) Power input.

Properties: $\rho = 1.2$ kg/m^3.

PLAN

Apply the propeller thrust force equation and the propeller power equation. Use Fig 14.3 (EFM 10e) to find C_T and C_P at maximum efficiency.

SOLUTION

From Fig. 14.3 (EFM 10e),

$$\begin{aligned} C_T &= 0.023 \\ C_p &= 0.012 \end{aligned}$$

Propeller thrust force equation

$$\begin{aligned} F &= C_T \rho D^4 n_T^2 \\ &= 0.023 \times 1.2 \text{ kg/m}^3 \times (2 \text{ m})^4 \times (19.5 \text{ rps})^2 \\ & \boxed{F_T = 168\,\text{N}} \end{aligned}$$

Propeller power equation

$$\begin{aligned} P &= C_p \rho n^3 D^5 \\ &= 0.012 \times 1.2 \text{ kg/m}^3 \times (2 \text{ m})^5 \times (19.5 \text{ rps})^3 \\ & \boxed{P = 3.42\,\text{kW}} \end{aligned}$$

14.12: PROBLEM DEFINITION

Situation: A 2 m propeller used on swamp boat. Angular speed is 1000 rpm and mass of boat and passengers is 300 kg.

Find: Initial acceleration.

Properties: $\rho = 1.1\ \text{kg/m}^3$.

PLAN

Apply the propeller thrust force equation. Use Fig 14.3 (EFM 10e) to find C_T.

SOLUTION

From Fig. 14.3 (EFM 10e)

$$C_T = 0.048$$

Propeller thrust force equation

$$\begin{aligned} F_T &= C_T \rho D^4 n^2 \\ &= 0.048 \times 1.1\ \text{kg/m}^3 \times (2\ \text{m})^4 \times (1,000\ \text{rpm}/60\ \text{s/min})^2 \\ &= 235\ \text{N} \end{aligned}$$

Calculate acceleration

$$\begin{aligned} a &= F/m \\ &= 235\ \text{N}/300\ \text{kg} \\ & \boxed{a = 0.783\ \text{m/s}^2} \end{aligned}$$

14.13: PROBLEM DEFINITION

Part (a)

Situation: Application of axial fans.

Find: Suited best for what conditions?

SOLUTION

The axial fan is best suited for high discharge, low head conditions.

Part (b)

Situation: Head produced and power required by axial pump.

Find: Variation of head produced and power required with discharge.

SOLUTION

Head produced and power required both decrease with increasing discharge through the pump.

14.14: PROBLEM DEFINITION

Situation: A 40 cm diameter pump operates at 1000 rpm against a 3-m head.

Find: Discharge.

PLAN

Apply discharge coefficient. Calculate the head coefficient to find the corresponding discharge coefficient from Fig. 14.7 (EFM10e).

SOLUTION

$$\begin{aligned} n &= 1,000/60 \\ &= 16.67 \text{ rev/s} \end{aligned}$$

Head coefficient

$$\begin{aligned} C_H &= \Delta H g/D^2 n^2 \\ &= 3 \text{ m} \times 9.81 \text{ m/s}^2/((0.4 \text{ m})^2 \times (16.67 \text{ rps})^2) \\ &= 0.662 \end{aligned}$$

From Fig. 14.7 (EFM10e), Discharge coefficient, $C_Q = Q/(nD^3) = 0.625$.

$$\begin{aligned} Q &= 0.625 \times 16.67 \text{ rps} \times (0.4 \text{ m})^3 \\ & \boxed{Q = 0.667\,\text{m}^3/\text{s}} \end{aligned}$$

14.15: PROBLEM DEFINITION

Situation: A pump is used to pump water between two reservoirs.

Find: (a) Discharge (b) Power required.

PLAN

Plot the system curve and the pump curve. Apply the energy equation from the reservoir surface to the center of the pipe at the outlet to solve the head of the pump in terms of Q. Apply head coefficient to solve for the head of the pump in terms of C_H. Apply discharge coefficient to solve for C_Q in terms of Q–then use Figure 14.7 (EFM10e) to find the corresponding C_H. Find the power by using Fig. 14.8 (EFM10e).

SOLUTION

$$\begin{aligned} D &= 35.6 \text{ cm} \\ n &= 11.5 \text{ rev/s} \end{aligned}$$

Energy equation from the reservoir surface to the center of the pipe at the outlet,

$$p_1/\gamma + V_1^2/(2g) + z_1 + h_p = p_2/\gamma + V_2^2/(2g) + z_2 + \sum h_L$$
$$h_p = z_2 - z_1 + [Q^2/(A^2 2g)](1 + fL/D + k_e + k_b)$$
$$L = 64 \text{ m}$$

Assume $f = 0.014$ (for completely rough steel pipe), $r_b/D = 1$. From Table 10.5 (EFM10e), $k_b = 0.35,\ k_e = 0.1$

$$\begin{aligned} h_p &= 1.5 + [Q^2((0.014 \times 64 \text{ m})/0.356 \text{ m}) + 0.35 + 0.1 + 1)] \\ &\quad /[2(9.81 \text{ m/s}^2)(\pi/4)^2(0.356 \text{ m})^4] \\ &= 1.5 + 20.42Q^2 \\ C_Q &= Q/(nD^3) = Q/[(11.5 \text{ rps})(0.356 \text{ m})^3] = 1.93Q \\ h_p &= C_H n^2 D^2/g = C_H(11.5 \text{ rps})^2(0.356 \text{ m})^2/9.81 \text{ m/s}^2 = 1.71\text{m} \times C_H \end{aligned}$$

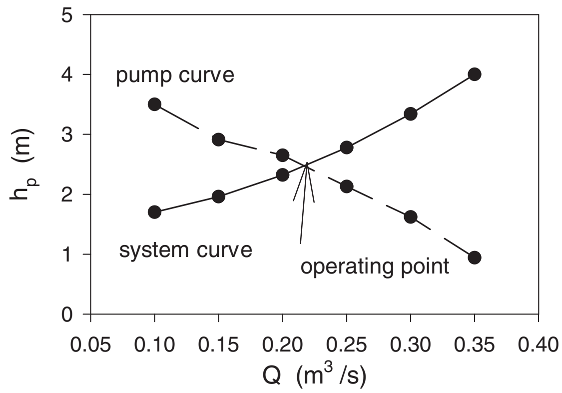
Q(m^3/s)	C_Q	C_H	h_{p1} (m)	h_{p2} (m)
0.10	0.193	2.05	1.70	3.50
0.15	0.289	1.70	1.96	2.91
0.20	0.385	1.55	2.32	2.65
0.25	0.482	1.25	2.78	2.13
0.30	0.578	0.95	3.34	1.62
0.35	0.675	0.55	4.00	0.94

Then plotting the system curve and the pump curve, we obtain the operating condition:

$$\boxed{Q = 0.22 \text{ m}^3/\text{s}}$$

From Fig. 14.8 (EFM10e)

$$\boxed{P = 6.5\,\text{kW}}$$



14.16: PROBLEM DEFINITION

Situation: A pump is used to pump water between two reservoirs and rpm increased to 900 rpm.

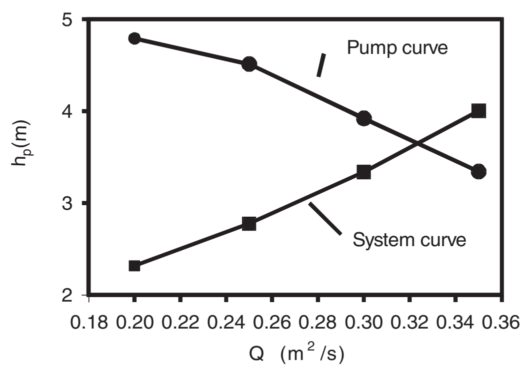
Find: (a) Discharge (b) Power required.

SOLUTION

The system curve will be the same as in Prob. 14.15 (EFM 10e) but rotational rate increased to 900 rpm/60 s/min=15 rps. Assume water density is 1000 kg/m^3.

$$\begin{aligned} C_Q &= Q/[nD^3] = Q/[15 \text{ rps} \times (0.356 \text{ m})^3] = 1.48Q \\ h_p &= C_H n^2 D^2/g = C_H (15 \text{ rps})^2 (0.356 \text{ m})^2/9.81 \text{ m/s}^2 = 2.91 \text{ m} \times C_H \end{aligned}$$

Q	C_Q	C_H	h_p
0.20	0.296	1.65	4.79
0.25	0.370	1.55	4.51
0.30	0.444	1.35	3.92
0.35	0.518	1.15	3.34



Plotting the pump curve with the system curve gives the operating condition;

$$\boxed{Q = 0.32 \text{ m}^3/\text{s}}$$

$$C_Q = 1.48(0.32) = 0.474$$

Then from Fig. 14.7 (EFM10e), $C_p = 0.70$
Power coefficient

$$\begin{aligned} P &= C_p n^3 D^3 \rho \\ &= 0.70(15 \text{ rps})^3 (0.356 \text{ m})^5 \times 1,000 \text{ kg/m}^3 \\ & \boxed{P = 13.5 \text{ kW}} \end{aligned}$$

14.17: PROBLEM DEFINITION

Situation: A 50 cm pump operating at 1100 rpm is used at maximum efficiency.

Find: (a) Discharge.
(b) Head.
(c) Power required.

PLAN

Apply discharge, head, and power coefficients. Use Fig. 14.7 (EFM10e) to find the discharge, power, and head coefficients at maximum efficiency. Assume density is 1000 kg/m^3.

SOLUTION

From Fig. 14.7 (EFM10e) at maximum efficiency, $C_Q = 0.64; C_p = 0.60$; and $C_H = 0.75$

$$\begin{aligned} D &= 0.5 \text{ m} \\ n &= 1100 \text{ rpm}/60 \text{ s/min} = 18.33 \text{ rev/s} \end{aligned}$$

Discharge coefficient

$$\begin{aligned} Q &= C_Q n D^3 \\ &= 0.64 \times 18.33 \text{ rps} \times (0.5 \text{ m})^3 \\ & \boxed{Q = 1.47 \text{ m}^3/\text{s}} \end{aligned}$$

Head coefficient

$$\begin{aligned} \Delta H &= C_H n^2 D^2 / g \\ &= 0.75 \times (18.33 \text{ rps})^2 \times (0.5 \text{ m})^2 / 9.81 \text{ m/s}^2 \\ & \boxed{\Delta H = 6.42 \, \text{m}} \end{aligned}$$

Power coefficient

$$\begin{aligned} P &= C_p \rho D^5 n^3 \\ &= 0.60 \times 1000 \text{ kg/m}^3 \times (0.5 \text{ m})^5 \times (18.33 \text{ rps})^3 \\ &= 115,475 \text{ N-m/s} \\ & \boxed{P = 115.5 \, \text{kW}} \end{aligned}$$

14.18: PROBLEM DEFINITION

Situation: A 50 cm pump operates at maximum efficiency at 45 rps pumping water at 10°C.

Find: (a) Discharge.
(b) Head.
(c) Power required.

Properties: From Table A.5 $\rho = 1000$ kg/m^3

PLAN

Apply discharge, head, and power coefficients. Use Fig. 14.7 (EFM10e) to find the discharge, power, and head coefficients at maximum efficiency.

SOLUTION

At maximum efficiency, from Fig. 14.7 (EFM10e), $C_Q = 0.64$; $C_p = 0.60$; $C_H = 0.75$
Discharge coefficient

$$\begin{aligned} Q &= C_Q n D^3 \\ &= 0.64 \times 45 \text{ rps} \times (0.5 \text{ m})^3 \\ & \boxed{Q = 3.60\,\mathrm{m}^3/\,\mathrm{s}} \end{aligned}$$

Head coefficient

$$\begin{aligned} \Delta H &= C_H n^2 D^2 / g \\ &= 0.75 \times (45 \text{ rps})^2 \times (0.5 \text{ m})^2 / 9.81 \text{ m/s}^2 \\ & \boxed{\Delta H = 38.7\,\mathrm{m}} \end{aligned}$$

Power coefficient

$$\begin{aligned} P &= C_p \rho D^5 n^3 \\ &= 0.60 \times 1,000 \text{ kg/m}^3 \times (0.5 \text{ m})^5 \times (45 \text{ rps})^3 \\ & \boxed{P = 1710 \text{ kW}} \end{aligned}$$

14.19: PROBLEM DEFINITION

Situation: A 35 cm diameter pump operates at 1000 rpm.

Find: Plot the head-discharge curve.

PLAN

Apply the discharge and head coefficient equations at a series of coefficients corresponding to each other from Fig. 14.7 (EFM10e).

SOLUTION

$$\begin{aligned} D &= 35 \text{ cm} = 0.35 \text{ m} \\ n &= 1000 \text{ rpm}/60 \text{ s/min} = 16.7 \text{ rev/s} \end{aligned}$$

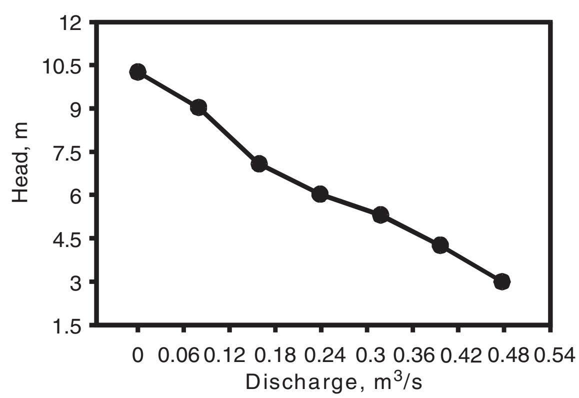
Head coefficient

$$\begin{aligned} \Delta H &= C_H n^2 D^2/g \\ &= C_H (16.7 \text{ rps})^2 (0.35 \text{ m})^2 / 9.81 \text{ m/s}^2 \\ &= 3.48 C_H \text{ m} \end{aligned}$$

Discharge coefficient

$$\begin{aligned} Q &= C_Q n D^3 \\ &= C_Q 16.7 \text{ rps} \times (0.35 \text{ m})^3 \\ &= 0.72 C_Q \text{ m}^3/\text{s} \end{aligned}$$

C_Q	C_H	$Q(\text{m}^3/\text{s})$	$\Delta H(\text{m})$
0.0	2.9	0	10.1
0.1	2.55	0.072	8.9
0.2	2.0	0.144	6.9
0.3	1.7	0.22	5.9
0.4	1.5	0.29	5.2
0.5	1.2	0.36	4.2
0.6	0.85	0.43	3



14.20: PROBLEM DEFINITION

Situation: A 60 cm pump operates at 690 rpm.

Find: Plot the head-discharge curve.

PLAN

Apply the discharge and head coefficient equations at a series of coefficients corresponding to each other from Fig. 14.7 (EFM10e).

SOLUTION

$$\begin{aligned} D &= 60 \text{ cm} = 0.60 \text{ m} \\ N &= 690 \text{ rpm} \\ n &= 11.5 \text{ rps} \end{aligned}$$

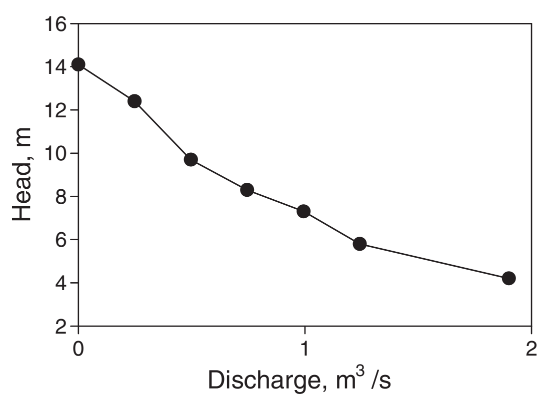
Head coefficient

$$\begin{aligned} \Delta h &= C_H D^2 n^2 / g \\ &= C_H \times (0.6 \text{ m})^2 \times (11.5 \text{ rps})^2 / 9.81 \text{ m/s}^2 \\ &= 4.85 \text{ m} \times C_H \end{aligned}$$

Discharge coefficient

$$\begin{aligned} Q &= C_Q n D^3 \\ &= 11.5 \text{ rps} \times (0.6 \text{ m})^3 \\ &= 2.48 \text{ m}^3/\text{s} \times C_Q \end{aligned}$$

C_Q	C_H	$Q(\text{m}^3/\text{s})$	$H(\text{m})$
0.0	2.90	0.0	14.1
0.1	2.55	0.248	12.4
0.2	2.00	0.497	9.7
0.3	1.70	0.745	8.3
0.4	1.50	0.994	7.3
0.5	1.20	1.242	5.8
0.6	0.85	1.490	4.2



14.21: PROBLEM DEFINITION

Situation: An axial blower for a 60 cm by 60 cm wind tunnel with velocity of 40 m/s. Blower to operate at 2000 rpm.

Find: (a) Diameter.
(b) Power requirements.

Properties: $\rho = 1.2$ kg/m^3

PLAN

Apply the discharge and power coefficient equations. Use Fig. 14.7 (EFM10e) to find the discharge and head coefficients at maximum efficiency. Apply the flow rate equation to get the Q to calculate the diameter with discharge coefficient.

SOLUTION

Flow rate equation

$$\begin{aligned} Q &= V \times A \\ &= 40.0 \times 0.36 \\ &= 14.4 \text{ m}^3/\text{s} \end{aligned}$$

From Fig. 14.7 (EFM10e), at maximum efficiency, $C_Q = 0.63$ and $C_p = 0.60$.Rotational speed, $n = \frac{2000 \text{ rpm}}{60 \text{ s/min}} = 33.3$ rps
Diameter, from Discharge coefficient:

$$\begin{aligned} D^3 &= Q/(nC_Q) \\ &= 14.4 \text{ m}^3/\text{s}/(33.3 \text{ rps} \times 0.63) \\ &= 0.686 \text{ m}^3 \\ & \boxed{D = 0.882 \text{ m}} \end{aligned}$$

Power, from Power coefficient:

$$\begin{aligned} P &= C_p \rho n^3 D^5 \\ &= 0.6(1.2 \text{ kg/m}^3)(33.3 \text{ rps})^3(0.882 \text{ m})^5 \\ & \boxed{P = 14.2 \text{ kW}} \end{aligned}$$

14.22: PROBLEM DEFINITION

Situation: A blower for air conditioning a 10^5 m^3 building replacing air every 15 min. Air temperature is 15 °C. Blower operates at 600 rpm.

Find: (a) Diameter.
(b) Power requirements.

PLAN

Apply the discharge and power coefficient equations. Use Fig. 14.7 (EFM10e) to find the discharge and head coefficients at maximum efficiency. Apply the flow rate equation to get the Q to calculate the diameter with discharge coefficient.

SOLUTION

Discharge is

$$Q = \frac{10^5 \text{ m}^3}{15 \text{ min} \times 60 \text{ s/min}} = 111.1 \text{ m}^3/\text{s}$$

$$\begin{aligned} N &= 600 \text{ rpm} = 10 \text{ rps} \\ \rho &= 1.22 \text{ kg/m}^3 \text{ at } 15\,^\circ\text{C} \end{aligned}$$

From Fig. 14.7 (EFM10e), at maximum efficiency, $C_Q = 0.63$; $C_p = 0.60$

For two blowers operating in parallel, the discharge per blower will be one half so

$$Q = 55.55 \text{ m}^3/\text{sec}$$

Diameter, from Discharge coefficient:

$$\begin{aligned} D^3 &= Q/nC_Q = (55.55 \text{ m}^3/\text{s})/[10 \text{ rps} \times 0.63] = 8.815 \\ & \boxed{D = 2.07 \text{ m}} \end{aligned}$$

Power, from Power coefficient:

$$\begin{aligned} P &= C_p \rho D^5 n^3 \\ &= (0.6)(1.22 \text{ kg/m})(2.07 \text{ m})^5 (10 \text{ rps})^3 \\ & \boxed{P = 27.8 \text{ kW}} \text{ per blower} \end{aligned}$$

14.23: PROBLEM DEFINITION

Situation: An 2 m axial fan used to run a 1.2 m diameter wind tunnel at 60 m/s. Rotational speed of blower is 1800 rpm.

Find: Power needed to operate fan.

Properties: $\rho = 1.05\ \text{kg/m}^3$

PLAN

Apply power coefficient. Calculate the discharge coefficient (apply the flow rate equation to find Q) to find the corresponding power coefficient from Fig. 14.7 (EFM10e).

SOLUTION

Flow rate equation

$$\begin{aligned} Q &= VA \\ &= (60\ \text{m/s})(\pi/4)(1.2\ \text{m})^2 \\ &= 67.8\ \text{m}^3/\text{s} \end{aligned}$$

Discharge coefficient

$$\begin{aligned} C_Q &= Q/(nD^3) \\ &= (67.8\ \text{m}^3/\text{s})/(\frac{1,800\ \text{rev/min}}{60\ \text{s/min}} \times (2\ \text{m})^3) \\ &= 0.282 \end{aligned}$$

From Fig. 14.7 (EFM10e) $C_p = 0.8$. Then power can be determined from power coefficient:

$$\begin{aligned} P &= C_p \rho D^5 n^3 \\ &= (0.8)(1.05\ \text{kg/m}^3)(2\ \text{m})^5(30\ \text{m})^3 \\ & \boxed{P = 726\ \text{kW}} \end{aligned}$$

14.24: PROBLEM DEFINITION

Situation: Radial flow pumps

Find: Best conditions for operation.

SOLUTION

The radial flow pump is best suited for high-head, low-discharge applications.

14.25: PROBLEM DEFINITION

Situation: Radial pump used to pump from reservoir.

Find: What limits depth of operation.

SOLUTION

The operational depth is limited by cavitation. In order to achieve flow the pressure at the pump inlet must be low and conducive to cavitation.

14.26: PROBLEM DEFINITION

Situation: A pump is doubled in size and halved in speed.

Find: (a)Head at maximum efficiency.
(b) Discharge at maximum efficiency.

PLAN

Apply discharge and head coefficients. Use Fig. 14.11 (EFM 10e) to find the discharge and head coefficients at maximum efficiency.

SOLUTION

$$D = 0.371 \text{ m} \times 2 = 0.742 \text{ m}$$
$$n = 2,133.5 \text{ rpm}/(2 \times 60 \text{ s/min}) = 17.77 \text{ rps}$$

From Fig. 14.11 (EFM 10e), at peak efficiency $C_Q = 0.121,\ C_H = 5.15.$
Head coefficient

$$\begin{aligned} \Delta H &= C_H n^2 D^2/g \\ &= 5.15(17.77 \text{ rps})^2(0.742 \text{ m})^2/9.81 \text{ m/s}^2 \\ &\boxed{\Delta H = 91.3\,\text{m}} \end{aligned}$$

Discharge coefficient

$$\begin{aligned} Q &= C_Q n D^3 \\ &= 0.121(17.77 \text{ rps})(0.742 \text{ m})^3 \\ &\boxed{Q = 0.878\ \text{m}^3/\text{s}} \end{aligned}$$

14.27: PROBLEM DEFINITION

Situation: A pump for water from 366 m elevation to 450 m elevation through 610 m of 36 cm steel pipe.

Find: Discharge through pipe.

Properties: From Table A5, $\rho = 998$ kg/m^3, $\nu = 10^{-6}$ m^2/s

PLAN

Guess the pump head and iterate using Fig. 14.10 (EFM10e) to get the corresponding flow rate and the Reynolds number. Find the Darcy-Weisbach friction factor to determine frictional loss in the pipe. Then write the energy equation between the two reservoirs and generate the system curve. The operating point is where the system and pump curve intersect.

SOLUTION

$$\Delta z = 450 - 366 = 84 \text{ m}$$

Assume $\Delta h = 90$ m ($>\Delta z$), then from Fig. 14.10 (EFM10e), $Q = 0.24$ m^3/s
Flow rate equation

$$\begin{aligned} V &= Q/A \\ &= 0.24 \text{ m}^3\text{/s}/[(\pi/4)(0.36 \text{ m})^2] \\ &= 2.36 \text{ m/s} \end{aligned}$$

Reynolds number

$$\begin{aligned} \text{Re} &= VD/\nu \\ &= 2.36 \text{ m/s} \times 0.36 \text{ m}/10^{-6} \text{ m}^2\text{/s} \\ &= 8.5 \times 10^5 \end{aligned}$$

Frictional head loss. For steel pipe, $k_s = 0.046$ mm from Table 10.4 (EFM 10e). Thus $k_s/D = 0.046$ mm/360 mm$= 1.2 \times 10^{-4}$.From Fig. 10.14 (EFM10e), $f = 0.014$
Writing the energy equation between the two reservoirs

$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} + h_p = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} + h_t + h_L$$

The pressures are the same at both reservoirs and the velocities are zero. Thus

$$h_p = z_2 - z_1 + h_L$$

Neglect inlet and bend losses. The losses are the frictional losses and the sudden expansion losses so

$$\begin{aligned} h_L &= \frac{V^2}{2g}\left(1 + \frac{fL}{D}\right) \\ &= \frac{Q^2}{2A^2 g}\left(1 + \frac{fL}{D}\right) \end{aligned}$$

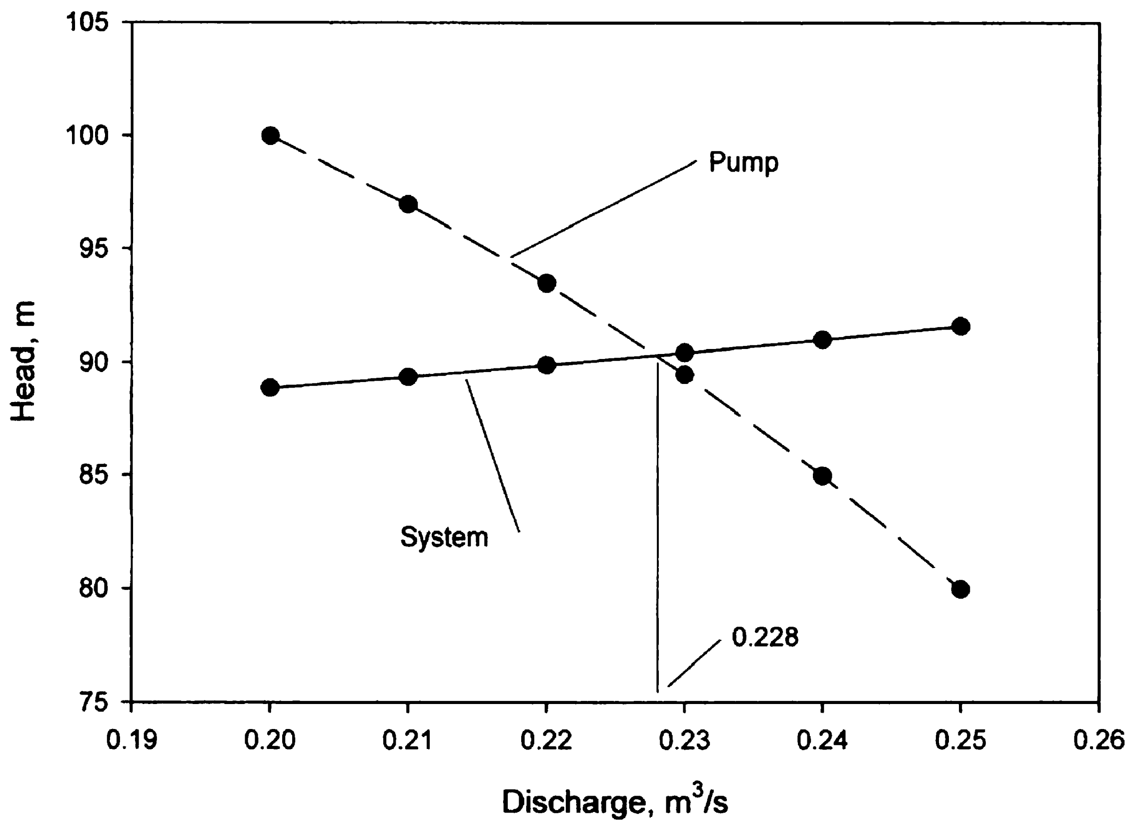


Figure 1:

The system curve is

$$
\begin{aligned}
h_p &= z_2 - z_1 + h_L \\
&= 450 - 366 + \frac{Q^2}{2 \times \left(\frac{\pi}{4} \times 0.36^2 \text{ m}^2\right)^2 \times 9.81 \text{ m/s}^2} \left(1 + \frac{0.014 \times 610 \text{ m}}{0.36 \text{ m}}\right) \\
&= 84 \text{ m} + 122 \times Q^2
\end{aligned}
$$

Plotting pump and system curve

$$
\boxed{\text{Q} = 0.228 \text{ m}^3/\text{s}}
$$

14.28: PROBLEM DEFINITION

Situation: A pump operated at 1600 rpm.

Find: Discharge when head is 41 m.

PLAN

Apply discharge coefficient. Calculate the head coefficient to find the corresponding discharge coefficient from Fig. 14.11 (EFM10e).

SOLUTION

$$\begin{aligned} \text{Pump in figure has } D &= 0.371 \text{ m} \\ n &= 1600/60 = 26.7 \text{ rps} \end{aligned}$$

Head coefficient

$$\begin{aligned} \Delta H &= C_H n^2 D^2 / g \\ C_H &= \frac{\Delta H g}{n^2 D^2} \\ C_H &= \frac{41 \text{ m} \times 9.81 \text{ m/s}^2}{(26.7 \text{ rps})^2 \times (0.371 \text{ m})^2} \\ &= 4.1 \end{aligned}$$

from Fig. 14.11 (EFM10e)

$$C_Q = 0.16$$

Use discharge coefficient to find Q

$$\begin{aligned} Q &= C_Q n D^3 \\ &= 0.16 \times 26.7 \text{ rps} \times (0.371 \text{ m})^3 \\ &\boxed{Q = 0.18 \text{ m}^3/\text{s}} \end{aligned}$$

14.29: PROBLEM DEFINITION

Situation: A pump operating at 1600 rpm.

Find: Maximum possible head developed.

PLAN

Apply head coefficient.

SOLUTION

Head coefficient

$$C_H = \Delta Hg/D^2n^2$$

Since C_H will be the same for the maximum head condition, then

$$\Delta H = \alpha \times n^2$$

or

$$H_{1600} = H_{1000} \times (1600/1000)^2$$

$$\begin{aligned} H_{1600} &= 30.6 \times 2.56 \\ &\boxed{H_{1600} = 78.3 \text{ m}} \end{aligned}$$

14.30: PROBLEM DEFINITION

Situation: A pump operated at 30 rps.

Find: Shutoff head.

PLAN

Apply head coefficient.

SOLUTION

$$H = \alpha \times n^2$$

so

$$H_{30}/H_{35.6} = (30/35.6)^2$$

or

$$\begin{aligned} H_{30} &= 104 \times (30/35.6)^2 \\ &\boxed{H_{30} = 73.8 \text{ m}} \end{aligned}$$

14.31: PROBLEM DEFINITION

Situation: A 40 cm diameter pump operated at 25 rps.

Find: Discharge when head is 50 m.

PLAN

Apply discharge coefficient. Calculate the head coefficient to find the corresponding discharge coefficient from Fig. 14.11 (EFM10e).

SOLUTION

Head coefficient

$$\begin{aligned} C_H &= \Delta H g/(n^2 D^2) \\ &= 50 \text{ m} \times 9.81 \text{ m/s}^2/[(25 \text{ rps})^2 \times (0.40 \text{ m})^2] \\ &= 4.91 \end{aligned}$$

from Fig. 14.11 (EFM10e) $C_Q = 0.136$
Discharge coefficient

$$\begin{aligned} Q &= C_Q n D^3 \\ &= 0.136 \times 25 \text{ rps} \times (0.40\text{m})^3 \\ & \boxed{Q = 0.218 \text{ m}^3/\text{s}} \end{aligned}$$

14.32: PROBLEM DEFINITION

Situation: A 20 cm pump for kerosene operates at 5000 rpm. is described in the problem statement.

Find: (a) Flow rate.
(b) Pressure rise across pump.
(c) Power required.

Properties: From Table A.4 $\rho = 814$ kg/m^3.

PLAN

Apply the discharge, head, and power coefficient equations. Use Fig. 14.11 (EFM10e) to find the discharge, power, and head coefficients at maximum efficiency.

SOLUTION

$$N = 5,000 \text{ rpm} = 83.33 \text{ rps}$$

From Fig. 14.11 (EFM10e) at maximum efficiency $C_Q = 0.125$; $C_H = 5.15$; $C_p = 0.69$
Discharge coefficient

$$\begin{aligned} Q &= C_Q n D^3 \\ &= 0.125 \times 83.33\text{rps} \times (0.20 \text{ m})^3 \\ & \boxed{Q = 0.0833 \text{ m}^3/\text{s}} \end{aligned}$$

Head coefficient

$$\begin{aligned} \Delta h &= C_H D^2 n^2 / g \\ &= 5.15 \times (0.20 \text{ m})^2 \times (83.33 \text{ rps})^2 / 9.81 \text{ m/s}^2 \\ & \boxed{\Delta h = 146 \text{ m}} \end{aligned}$$

Power coefficient

$$\begin{aligned} P &= C_p \rho D^5 n^3 \\ &= 0.69 \times 814 \text{ kg/m}^3 \times (0.20 \text{ m})^5 \times (83.33 \text{ rps})^3 \\ & \boxed{P = 104 \text{ kW}} \end{aligned}$$

14.33: PROBLEM DEFINITION

Part (a)

Find: Difference between system and pump curves.

SOLUTION

The pump curve provides the head supplied by the pump while the system curve is the head required to operate the system.

Part (b)

Find: Define the operating point.

SOLUTION

The operating point is the discharge at which the pump and system curves intersect.

14.34: PROBLEM DEFINITION

Situation: Significance of specific speed.

Find: The best pump corresponding to high specific speed.

SOLUTION

A high specific speed suggests the use of an axial flow pump.

14.35: PROBLEM DEFINITION

Situation: Pumps, with characteristics $h_{p,\text{pump}} = 20[1 - (Q/100)^2]$ are connected in series and parallel to operate a fluid system with system curve $h_{p,\text{sys}} = 5 + 0.002Q^2$.

Find: Operating point with a) one pump, b) two pumps connected in series and c) two pumps connected in parallel.

PLAN

Equate the head provided by the pump and the head required by the system.

SOLUTION

a) For one pump

$$\begin{aligned} 20[1 - \left(\frac{Q}{100}\right)^2] &= 5 + 0.002Q^2 \\ 20 - 0.002Q^2 &= 5 + 0.002Q^2 \\ 15 &= 0.004Q^2 \\ &\boxed{Q = 232 \text{ L/min}} \end{aligned}$$

b) For two pumps in series

$$\begin{aligned} 2 \times 20[1 - \left(\frac{Q}{100}\right)^2] &= 5 + 0.002Q^2 \\ 35 &= 0.006Q^2 \\ &\boxed{Q = 289 \text{ L/min}} \end{aligned}$$

c) For two pumps in parallel

$$\begin{aligned} 20[1 - \left(\frac{Q}{2 \times 100}\right)^2] &= 5 + 0.002Q^2 \\ 20 - 0.0005Q^2 &= 5 + 0.002Q^2 \\ 15 &= 0.0025Q^2 \\ &\boxed{Q = 293 \text{ L/min}} \end{aligned}$$

14.36: PROBLEM DEFINITION

Situation: The pump is described in Problem 14.15 (EFM10e) has a rotational speed of 690 rpm, a discharge of 0.22 m^3/s and pipe diameter of 35.6 cm.

Find: (a) Suction specific speed.
(b) Safety of operation with respect to cavitation.

Properties: From Table A.5 (EFM 10e), $p_v(10^oC)$=1230 Pa,

PLAN

Calculate the pressure and the net postive suction head (NSPH) at the pump inlet to get discharge. From discharge determine the suction specific speed. Then compare that with the critical value of $85,000$.

SOLUTION

From the energy equation, where point 1 is water surface and point 2 is entrance to pump

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

Neglecting entrance losses

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

The velocity at pump

$$V_2=\frac{Q}{A}=\frac{0.22\text{ m}^3/\text{s}}{\frac{\pi}{4}\times(0.356\text{ m})^2}=2.21\text{ m/s}$$

The head at the pump entrance is

$$\begin{aligned}\frac{p_2}{\gamma} &= \frac{101\text{ kPa}}{9810\text{ N/m}^3}+1\text{ m}-\frac{(2.21\text{ m/s})^2}{2\times 9.81\text{ m/s}^2}\\ &= 11.05\text{ m}\end{aligned}$$

The NSPH is

$$\text{NSPH}=11.05\text{ m}-\frac{1230\text{ Pa}}{9810\text{ N/m}^3}=11.04\text{ m}$$

The discharge in gpm

$$Q=0.22\text{ m}^3/\text{s}=13200\text{ L/min}$$

Suction specific speed

$$
\begin{aligned}
N_{ss} &= (NQ^{1/2})/(NPSH)^{3/4} \\
N &= 690 \text{ rpm} \\
N_{ss} &= 690 \text{ rpm} \times [13200 \text{ L/min}]^{1/2} \Big/ (11.04 \text{ m})^{3/4} \\
&\boxed{N_{ss} = 13089}
\end{aligned}
$$

$\boxed{N_{ss} \text{ is much below 85,000; therefore, it is in a safe operating range.}}$

14.37: PROBLEM DEFINITION

Situation: A pump is needed that rotates at 1500 rpm and has discharge of 0.3 m^3/s at 9 m.

Find: Type of water pump.

PLAN

Calculate the specific speed and use Fig. 14.15 (EFM 10e) to find the pump range to which it corresponds.

SOLUTION

The parameters are

$$n = \frac{1500 \text{ rpm}}{60 \text{ s/min}} = 25 \text{ rps}$$

Specific speed

$$\begin{aligned} n_s &= n\sqrt{Q}/[g^{3/4}h^{3/4}] \\ &= (25 \text{ rps})(0.3 \text{ m}^3/\text{s})^{1/2}/[(9.81 \text{ m/s}^2)^{3/4}(9 \text{ m})^{3/4}] \\ &= 0.48 \end{aligned}$$

Then from Fig. 14.13 (EFM10e), use a **mixed flow pump.**

14.38: PROBLEM DEFINITION

Situation: A pump is needed to pump water at 0.10 m^3/s at a head of 30 m with a rotational rate of 25 rps.

Find: Type of pump.

PLAN

Calculate the specific speed and use Fig. 14.13 (EFM10e) to find the pump range to which it corresponds.

SOLUTION

Specific speed

$$\begin{aligned} n &= 25 \text{ rps} \\ Q &= 0.10 \text{ m}^3/\text{sec} \\ h &= 30 \text{ meters} \\ n_s &= n\sqrt{Q}/[g^{3/4}h^{3/4}] \\ &= 25(0.1)^{1/2}/[(9.81)^{3/4}(30)^{3/4}] \\ &= 0.111 \end{aligned}$$

Then from Fig. 14.13 (EFM10e), $n_s < 0.150$ so use a **radial flow pump.**

14.39: PROBLEM DEFINITION

Situation: A pump is required to pump water at 0.40 m^3/s at head of 70 m and rotational speed of 1100 rpm.

Find: Type of pump.

PLAN

Calculate the specific speed and use Fig. 14.13 (EFM10e) to find the pump range to which it corresponds.

SOLUTION

Specific speed

$$
\begin{aligned}
N &= 1,100 \text{ rpm} = 18.33 \text{ rps} \\
Q &= 0.4 \text{ m}^3/\text{sec} \\
h &= 70 \text{ meters} \\
n_s &= n\sqrt{Q}/[g^{3/4}h^{3/4}] \\
&= (18.33 \text{ rps})(0.4 \text{ m}^3/\text{s})^{1/2}/[(9.81 \text{ m/s}^2)^{3/4}(70 \text{ m})^{3/4}] \\
&= 0.086
\end{aligned}
$$

Then from Fig. 14.13 (EFM10e) use a **radial flow pump.**

14.40: PROBLEM DEFINITION

Situation: An axial flow pump is used to pump water 15,000 lpm against a 4.5 m with a suction head of 1.5 m.

Find: Maximum speed.

Properties: From Table A.5, $p_v(15\,^\circ\mathrm{C}) = 1700\ \mathrm{N/m^2}$.

PLAN

Apply the suction specific speed equation setting the critical value for N_{ss} proposed by the Hydraulic Institute to 8500.

SOLUTION

Suction specific speed

$$8500 = NQ^{1/2}/(NPSH)^{3/4}$$

The suction head is given as 1.5 m. Then assuming that the atmospheric pressure is 101.3 kPa, and the vapor pressure is 1.77 kPa, the net positive suction head ($NPSH$) is

$$NPSH = 101.3\ \mathrm{kPa}\ \times 0.0001\ \mathrm{m/Pa} + 1.5\ \mathrm{m} - (h_{\mathrm{vap.press.}}) \times 0.0001\ \mathrm{m/Pa} = 11.5\ \mathrm{m}$$

Then

$$\begin{aligned} N &= \frac{8500 \times (NPSH)^{3/4}}{Q^{1/2}} \\ &= \frac{8500 \times (11.5\ \mathrm{m})^{3/4}}{(15,000\ \mathrm{lpm})^{1/2}} \\ & \boxed{N = 2070\ \mathrm{rpm}} \end{aligned}$$

14.41: PROBLEM DEFINITION

Situation: A pump with a rotational rate of 600 rpm is required to pump water at 0.2 m^3/s between two reservoirs with a 0.1 m diameter pipe.

Find: Type of pump

PLAN

Calculate the specific speed and use figure 14.13 (EFM10e) to find the pump range to which it corresponds.

SOLUTION

Apply energy equation between the two reservoir surfaces.

$$h_p = \Delta z + (1 + K_e + \frac{fL}{D})\frac{V^2}{2g}$$

Assume $f = 0.02$ and $K_e = 0.5$.The velocity is

$$V = \frac{Q}{A} = \frac{0.2 \text{ m}^3/\text{s}}{\frac{\pi}{4}(0.1 \text{ m})^2} = 25.5 \text{ m/s}$$

Head across pump.

$$\begin{aligned} h_p &= 3 + (1 + 0.5 + \frac{0.02 \times 20}{0.1})\frac{(25.5 \text{ m/s})^2}{2 \times 9.81 \text{ m/s}^2} \\ &= 185 \text{ m} \end{aligned}$$

Specific speed

$$\begin{aligned} n_s &= n\sqrt{Q}/(g^{3/4}h^{3/4}) \\ n &= 10 \text{ rps} \\ Q &= 0.2 \text{ m}^3/\text{s} \\ n_s &= \frac{10\text{rps} \times (0.2 \text{ m}^3/\text{s})^{1/2}}{(9.81 \text{ m/s}^2 \times 185 \text{ m})^{3/4}} \\ &= 0.016 \end{aligned}$$

From Fig. 14.13 (EFM10e), use **radial flow pump.**

14.42: PROBLEM DEFINITION

Situation: The performance curve for a centrifugal pump with different impeller diameters is shown in Fig 14.15 (EFM10e).

Find: Plot five performance curves for the different diameters in terms of head and discharge coefficients.

PLAN

Calculate the five discharge coefficients by applying the discharge coefficient equation, and the five head coefficients by the applying head coefficient equation.

SOLUTION

Discharge coefficient

$$C_Q = Q/nD^3$$

The rotational speed is 1750/60=29.2 rps. The diameter for each impeller is 0.13 m, 0.14 m, 0.15 m, 0.16 m and 0.17 m. One liter per minute is 0.0000668 m^3/s. So for each impeller, follow the form of this example calculation for the first impeller to get the conversion factors for all impellors:

$$\text{conversion factor} = \frac{\frac{0.0000668 \text{ m}^3/\text{s}}{\text{lpm}}}{29.2 \text{ rps} \times (0.13 \text{ m})^3} = .00106$$

the conversion factor to get the discharge coefficient is

13 cm	lpm	$\times$ 0.00106
14 cm	lpm	$\times$ 0.000794
15 cm	lpm	$\times$ 0.000610
16 cm	lpm	$\times$ 0.000479
17 cm	lpm	$\times$ 0.000385

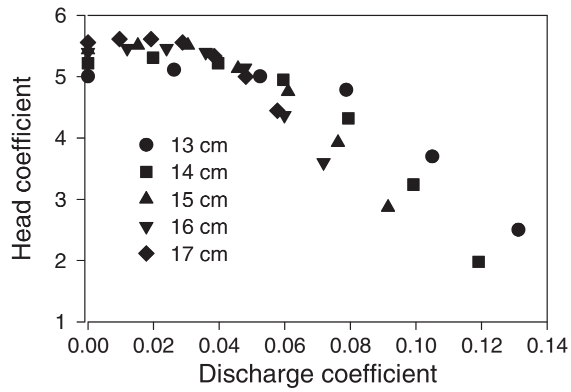
Head coefficient

$$C_H = \frac{\Delta H g}{n^2 D^2}$$

The conversion factors to get the head coefficient are

13 cm	m	$\times$ 0.2175
14 cm	m	$\times$ 0.1800
15 cm	m	$\times$ 0.1510
16 cm	m	$\times$ 0.1285
17 cm	m	$\times$ 0.1111

The performance in terms of the non-dimensional coefficients is shown on the graph.



14.43: PROBLEM DEFINITION

Situation: For gas flow through compressor, ratio of final temperature to initial temperature is less than ratio of final pressure to initial pressure.

Find: Ratio of final density to initial density.

SOLUTION

From ideal gas law

$$\frac{\rho_f}{\rho_i} = \frac{p_f}{p_i}\frac{T_i}{T_f} = \frac{p_f/p_i}{T_f/T_i}$$

For flow through compressor

$$\frac{T_f}{T_i} < \frac{p_f}{p_i}$$

Therefore

$$\frac{\rho_f}{\rho_i} > 1$$

So

$$\boxed{\rho_f > \rho_i}$$

14.44: PROBLEM DEFINITION

Situation:
Methane compressed from 100 to 165 kPa in non-cooled centrifugal compressor.
Mass flow rate of 1 kg/s.
Entering temperature 27°C.
Efficiency is 70%.

Find:
Shaft power to run compressor

Properties:
From Table A.2 for methane $R = 518$ J/kg/K and $k = 1.31$.

SOLUTION

$$\begin{aligned}
P &= \frac{k}{k-1} Q_1 p_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right] \\
&= \frac{k}{k-1} \dot{m} R T_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right] \\
&= \left(\frac{1.31}{1.31-1} \right) (1\,\mathrm{kg/\,s}) (518\,\mathrm{J/\,kg \cdot\ K}) (300\,\mathrm{K}) \left[\left(\frac{165\,\mathrm{kPa}}{100\,\mathrm{kPa}} \right)^{\frac{.31}{1.31}} - 1 \right] \\
&= 82.6 \text{ kW} \\
P_{\text{ref}} &= P_{th}/e \\
&= 82.6/0.7 \\
& \boxed{P_{\text{ref}} = 118 \text{ kW}}
\end{aligned}$$

14.45: PROBLEM DEFINITION

Situation: A 36 kW motor drives a non cooled 60 percent efficient compressor to compress CO_2 from 100 to 150 kPa.

Find: Volume flow rate into the compressor.

Properties: From Table A.2 for CO_2, $k = 1.3$

PLAN

Apply equation 14.19 (EFM 10e).

SOLUTION

$$\begin{aligned}
P_{th} &= 36 \text{ kW} \times 0.6 = 21.6 \text{ kW} \\
P_{th} &= (k/(k-1))Qp_1[(p_2/p_1)^{(k-1)/k} - 1] \\
&= (1.3/0.3)Q \times 1 \times 10^5 \text{ Pa}[(150 \text{ kPa}/100 \text{ kPa})^{0.3/1.3} - 1] \\
&= 4.25 \times 10^4 \text{ N/m}^2 \times Q \\
Q &= 21.6 \text{ kW}/42.5 \text{ kN/m}^2 \\
& \boxed{Q = 0.508 \text{ m}^3/\text{s}}
\end{aligned}$$

14.46: PROBLEM DEFINITION

Situation: A water-cooled centrifugal compressor compresses air from 100 kPa to 600 kPa at 2 kg/s. Inlet temperature is 15°C and efficiency is 50%.

Find: The shaft power.

Properties: From Table A.2 for air, $R = 287$ J/kg-K

PLAN

Apply equation 14.20 (EFM 10e).

SOLUTION

$$
\begin{aligned}
P_{th} &= p_1 Q_1 \ell n(p_2/p_1) \\
&= \dot{m} R T_1 \ell n(p_2/p_1) \\
&= 2 \text{ kg/s} \times 287 \text{ J/kg-K} \times 288 \text{ K} \times \ell n(600 \text{ kPa}/100 \text{ kPa}) \\
&= 296.2 \text{ kW} \\
P_{\text{ref}} &= 296.2 \text{ kW}/0.5 \\
& \boxed{P_{\text{ref}} = 592.4 \text{ kW}}
\end{aligned}
$$

14.47: PROBLEM DEFINITION

Situation: Impulse turbine.

Find: Explain why impulse turbine produces not power when jet velocity is equal to bucket velocity.

SOLUTION

When both speeds are the same, there is no change in momentum and, hence, no force and no torque.

14.48: PROBLEM DEFINITION

Situation: An impulse turbine is driven from a reservoir 650 m above jet outlet through a 10 km long 1 m diameter pipe connected to a 16 cm jet. Wheel speed is 360 rpm. Turbine efficiency $\eta_{turb} = 0.85$.

Find: (a) Power produced.
(b) Diameter of turbine wheel.

Assumptions: $T = 10°C$, $f = 0.016$

Properties: From Table A.5, $\rho = 1000$ kg/m^3

PLAN

Apply the energy equation from reservoir to turbine jet. Then apply the continuity principle and the power equation.

SOLUTION

Energy equation

$$\begin{aligned} p_1/\gamma + V_1^2/2g + z_1 &= p_2/\gamma + V_2^2/2g + z_2 + \sum h_L \\ 0 + 0 + 650 &= 0 + V_{\text{jet}}^2/2g + 0 + (fL/D)(V_{\text{pipe}}^2/2g) \end{aligned}$$

Continuity principle

$$\begin{aligned} V_{\text{pipe}} A_{\text{pipe}} &= V_{\text{jet}} A_{\text{jet}} \\ V_{\text{pipe}} &= V_{\text{jet}}(A_{\text{jet}}/A_{\text{pipe}}) = V_{\text{jet}}(0.16)^2 = 0.0256 V_{\text{jet}} \end{aligned}$$

so

$$(V_{\text{jet}}^2/2g)(1 + (fL/D) \times 0.0256^2) = 650$$

$$\begin{aligned} V_{\text{jet}}^2 &= \frac{2 \times 9.81 \text{ m/s}^2 \times 650 \text{ m}}{1 + (0.016 \times 10,000/1) \times 0.0256^2} \\ V_{\text{jet}} &= 107.3 \text{ m/s} \end{aligned}$$

Power equation

$$\begin{aligned} P &= \rho Q \frac{V_{\text{jet}}^2}{2} \eta_{turb} \\ &= \rho A_{\text{jet}} \frac{V_{\text{jet}}^3}{2} \eta_{turb} \\ &= 1000 \text{ kg/m}^3 \times \left(\frac{\pi}{4}\right) \times (0.16 \text{ m})^2 \times \frac{(107.3 \text{ m/s})^3}{2} \times 0.85 \\ &\boxed{P = 10.6 \text{ MW}} \\ V_{\text{bucket}} &= (1/2) V_{\text{jet}} \\ &= 53.7 \text{ m/s } = (D/2)\omega \\ D &= 53.7 \text{ m/s} \times 2/(360 \times (\pi/30) \text{ rad/s}) \\ &\boxed{D = 2.85 \text{ m}} \end{aligned}$$

14.49: PROBLEM DEFINITION

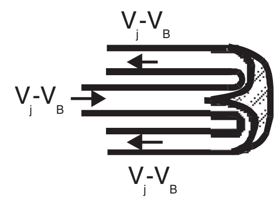
Situation: Bucket on impulse turbine turns water by 180 degrees.

Find: Show bucket speed should be 1/2 jet speed for maximum power.

PLAN

Apply the momentum principle.

SOLUTION



Momentum principle

$$\sum F_{\text{bucket on jet}} = \rho Q[-(V_j - V_B) - (V_j - V_B)]$$

Then

$$\sum F_{\text{on bucket}} = \rho V_j A_j 2(V_j - V_B)$$

assuming the combination of buckets to be intercepting flow at the rate of $V_j A_j$. Then

$$P = FV_B = 2\rho A_j[V_j^2 V_B - V_j V_B^2]$$

For maximum power production, $dP/dV_B = 0$, so

$$\begin{aligned} 0 &= 2\rho A(V_j^2 - V_j 2V_B) \\ 0 &= V_j - 2V_B \end{aligned}$$

or

$$\boxed{V_B = 1/2 V_j}$$

14.50: PROBLEM DEFINITION

Situation: A jet of water strikes the buckets of an impulse wheel and turns water by 180 degrees with bucket speed 1/2 of jet speed.

Find: (a) Jet force on the bucket.
(b) Resolve the discrepancy with Eq. 14.24 (EFM 10e).

PLAN

Apply the momentum principle.

SOLUTION

Consider the power developed from the force on a single bucket. Referencing velocities to the bucket gives
Momentum principle

$$\sum F_{\text{on bucket}} = \rho Q_{\text{rel. to bucket}}(-(1/2)V_j - (1/2)V_j)$$

Then

$$F_{\text{on bucket}} = \rho(V_j - V_B)A_j(V_j)$$

but

$$V_j - V_B = 1/2V_j$$

so

$$\boxed{\text{a) } F_{\text{on bucket}} = 1/2\rho AV_j^2}$$

Then

$$P = FV_B = (1/2)\rho QV_j^3/2$$

b) The power is 1/2 that given by Eq. (14.24 (EFM 10e)). The extra power comes from the operation of more than a single bucket at a time so that the wheel as a whole turns the full discharge; whereas, a single bucket intercepts flow at a rate of 1/2 V_jA_j.

14.51: PROBLEM DEFINITION

Part (a)
Situation: Compare reaction turbine and centrifugal pump.

Find: Difference between reaction turbine and centrifugal pump.

SOLUTION

The power is provided to the impeller of a centrifugal pump to increase pressure of fluid. The pressure on the runner of a reaction turbine causes rotating and power production.

Part (b)
Situation: Runner in reaction turbine.

Find: Meaning of "runner" in reaction turbine.

SOLUTION

The runners in a reaction turbine are the blades that turn the flow.

14.52: PROBLEM DEFINITION

Situation: A Francis turbine has an outside diameter of 5 m and inside diameter of 3 m, an inlet blade angle of 60° and an outlet angle of 90°. Runner width is 1 m and discharge is 126 m^3/s.

Find: (a) α_1 for non-separating flow conditions .
(b) Maximum attainable power.
(c) Changes to increase power production.

Properties: From Table A.5, $\rho = 1000$ kg/m^3 at 10°C

SOLUTION

Flow rate equation

$$\begin{aligned} V_{r_1} &= Q/(2\pi r_1 B) \\ &= 126 \text{ m}^3/\text{s}/(2\pi \times 5 \text{ m} \times 1 \text{ m}) \\ &= 4.01 \text{ m/s} \\ \omega &= 60 \times 2\pi/60 = 2\pi \text{ rad/s} \end{aligned}$$

a)

$$\begin{aligned} \alpha_1 &= \text{arc cot } ((r_1\omega/V_{r_1}) + \cot \beta_1) \\ &= \text{arc cot } ((5 \text{ m} \times 2\pi \text{ rad/s}/4.01 \text{ m/s}) + 0.577) \\ &\boxed{\alpha_1 = 6.78^\circ} \end{aligned}$$

The outlet radial velocity is

$$\begin{aligned} V_{r2} &= Q/(2\pi r_2 B) = \frac{5}{3} \times V_{r1} = 6.68 \text{ m/s} \\ \alpha_2 &= \text{arc tan } (V_{r_2}/\omega r_2) = \text{arc tan } ((6.68 \text{ m/s})/(3 \text{ m} \times 2\pi \text{ rad/s})) = \text{arc tan } 0.355 \\ &= 19.5^\circ \end{aligned}$$

b) From Eq. (14.27 (EFM 10e))

$$\begin{aligned} P &= \rho Q\omega(r_1 V_1 \cos\alpha_1 - r_2 V_2 \cos\alpha_2) \\ V_1 &= V_{r_1}/\sin\alpha_1 = 4.01/0.118 = 34.0 \text{ m/s} \\ V_2 &= V_{r_2}/\sin\alpha_2 = 20.0 \text{ m/s} \\ P &= 1000 \text{ kg/m}^3 \times 126 \text{ m}^3/\text{s} \times 2\pi \text{ rad/s} \\ &\quad \times (5 \text{ m} \times 34.0 \text{ m/s} \times \cos\ 6.78^\circ - 3 \times 20.0 \text{ m/s} \times \cos\ 19.5^\circ) \\ &\boxed{P = 88.9 \text{ MW}} \end{aligned}$$

c) $\boxed{\text{Increase } \beta_2}$

14.53: PROBLEM DEFINITION

Situation: A Francis turbine with a discharge of 3.3 m^3/s operates at 60 rpm, has outside and inside diameters of 1.5 and 1.2 m respectively, inlet and outlet blade angles of 85 and 165 degrees and a runner width of 33 cm.

Find: (a) α_1 for non-separating flow conditions.
(b) Power.
(c) Torque.

Properties: From Table A.5, $\rho = 1000$ kg/m^3 at 10°C

SOLUTION

$$\begin{aligned}
V &= Q/(2\pi * r * B) \\
V_{r_1} &= 3.3 \text{ m}^3/\text{s}/(2\pi \times 1.5 \text{ m} \times 0.33 \text{ m}) = 1.061 \text{ m/s} \\
V_{r_2} &= 3.3 \text{ m}^3/\text{s}/(2\pi \times 1.2 \text{ m} \times 0.33 \text{ m}) = 1.326 \text{ m/s}; \\
\omega &= (60/60)2\pi = 2\pi \text{ rad/s} \\
\alpha_1 &= \text{arc cot } ((r_1\omega/V_{r_1}) + \cot \beta_1) = \text{arc cot } [(1.5 \text{ m} \times 2\pi \text{ rad/s})/1.061 \text{ m/s} \\
&\quad +\cot 85^\circ] \\
&= \text{arc cot } (8.88 + 0.0875) \\
&\quad \boxed{\alpha_1 = 6.36^\text{o} = 6^\text{o}22'} \\
V_{\tan_1} &= r_1\omega + V_{r_1} \cot \beta_1 = 1.5 \text{ m} \times 2\pi \text{ rad/s} + 1.061 \text{ m/s} \times 0.0875 \\
&= 9.518 \text{ m/s} \\
V_{\tan_2} &= r_2\omega + V_{r_2} \cot \beta_2 \\
&= 2.591 \text{ m/s} \\
T &= \rho Q(r_1 V_{\tan_1} - r_2 V_{\tan_2}) \\
&= 1,000 \text{ kg/s} \times 3 \text{ m}^3/\text{s} \times (1.5 \text{ m} \times 9.518 \text{ m/s} - 1.2 \text{ m} \times 2.591 \text{ m/s}) \\
&\quad \boxed{T = 33,500 \text{ N-m}} \\
\text{Power} &= T\omega \\
&= 33,500 \text{ N-m} \times 2\pi \text{ rad/s} \\
&\quad \boxed{P = 210 \text{ kW}}
\end{aligned}$$

14.54: PROBLEM DEFINITION

Situation: A Francis turbine operates at 120 rpm with discharge of 200 m^3/s. The outer radius, vane angle and runner width are 3 m, 45° and 0.9 m respectively.

Find: α_1 for non-separating flow conditions.

SOLUTION

$$\begin{aligned}
\omega &= 120 \text{ rpm}/60 \text{ s/min} \times 2\pi \text{ rad/rev} = 12.6 \text{ s}^{-1} \\
V_{r_1} &= 200 \text{ m}^3/\text{s}/(2\pi \times 3 \text{ m} \times 0.9 \text{ m}) = 11.79 \text{ m/s} \\
\alpha_1 &= \text{arc cot } [(r_1\omega/V_{r_1}) + \cot \beta_1] \\
&= \text{arc cot } (\frac{3 \text{ m} \times 12.6\,\text{s}^{-1}}{11.79 \text{ m/s}} + \cot 45^\circ) \\
& \boxed{\alpha_1 = 13.6\,^\circ}
\end{aligned}$$

14.55: PROBLEM DEFINITION

Situation: A small hydroelectric project is fed by an elevation difference of 120 m by 300 m of 30 cm diameter steel pipe. Design calls for 0.23 m^3/s and 80% efficiency.

Find: (a) Power output.
(b) Draw the HGL and EGL.

Assumptions: $K_e = 0.50$; $K_E = 1.0$; $K_b = 0.2$; $\rho = 1000$ kg/m^3, $\nu = 1.14 \times 10^{-6}$ m^2/s. Assume two bends in system.

PLAN

To get power apply the energy equation. Apply the flow rate equation to get V for the head loss. Then apply the power equation.

SOLUTION

Assume there is an entry loss, sudden expansion loss and loss due to a bend.
Energy equation

$$\begin{aligned}
\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} + h_p &= \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} + h_t + \sum h_L \\
h_t &= z_1 - z_2 - \sum h_L \\
&= 900 \text{ m} - 800 \text{ m} - \sum h_L \\
h_L &= \frac{V^2}{2g}(\frac{fL}{D} + K_E + Ke_e + 2K_b)
\end{aligned}$$

-

Reynolds number.

$$\begin{aligned}
V &= Q/A = 0.23 \text{ m}^3/\text{s}/((\pi/4) \times (0.3 \text{ m})^2) = 3.3 \text{ m/s}; \\
\text{Re} &= VD/\nu = (3.3 \text{ m/s})(0.3 \text{ m})/(1.14 \times 10^{-6} \text{ m}^2/\text{s}) = 8.6 \times 10^5
\end{aligned}$$

From Table 10.4 (EFM 10e) for a steel pipe $k_s = 0.002$ in so relative roughness $k_s/D = 0.000167$. From Figure 10.14 (EFM 10e), $f = 0.014$

$$\begin{aligned}
\sum h_L &= \frac{(3.3 \text{ m/s})^2}{2 \times 9.81 \text{ m/s}^2}(\frac{0.014 \times 300 \text{ m}}{0.3 \text{ m}} + 1.0 + 0.5 + 2 \times 0.2) \\
\sum h_L &= 0.56 \text{ m} \times 15.9 = 8.9 \text{ m} \\
h_t &= 120 \text{ m} - 8.9 \text{ m} = 111.1 \text{ m}
\end{aligned}$$

Power equation

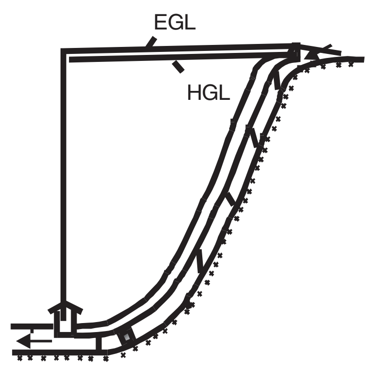
$$\begin{aligned}
P_{\text{in}} &= \gamma Q h_t \\
&= (0.23 \text{ m}^3/\text{s})(9810 \text{ N/m}^3)(111.1 \text{ m}) \\
& P_{\text{in}} = 250,675 \text{ W}
\end{aligned}$$

Power output from the turbine

$$\begin{aligned} P_{\text{out}} &= 250,675 \times \eta \\ &= 250,675 \times 0.8 \\ &= 200,540\,\text{W} \end{aligned}$$

$$\boxed{P_{\text{out}} = 201\,\text{kW}}$$

Plot of HGL & EGL



14.56: PROBLEM DEFINITION

Situation: Performance of wind turbines

Find: Factors determining maximum and minimum wind speed for turbine.

SOLUTION

At minimum speed, insufficient energy to run turbine. Maximum speed is determined by potential mechanical failure.

14.57: PROBLEM DEFINITION

Situation: Using the internet and other resources, identify at least four different types of wind turbines. For each type, discribe its distinguishing characteristics, and its relative advantages and disadvantages.

SOLUTION

No solution provided for this problem, answers will vary.

14.58: PROBLEM DEFINITION

Situation: Sizing a wind turbine given a power requirement and wind data.

Find: Minimum capture area

Properties: $\rho = 1.2\,\mathrm{kg/m^3}, V = 16$ km/h

PLAN

Use equations for maximum power of a windmill.

$$A = P_{\max}\frac{54}{16}\frac{1}{\rho V^3}$$

SOLUTION

Convert windspeed to m/s.

$$\begin{aligned} V &= \frac{16\,\mathrm{km}}{\mathrm{h}}\cdot\frac{1000\,\mathrm{m}}{\mathrm{km}}\cdot\frac{1\,\mathrm{h}}{3600\,\mathrm{s}} = 4.44\,\mathrm{m/s} \\ A &= \frac{2000\,\mathrm{N\cdot m}}{\mathrm{s}}\cdot\frac{54}{16}\cdot\frac{\mathrm{m^3}}{1.2\,\mathrm{kg}}\cdot\left(\frac{1\,\mathrm{s}}{4.44\,\mathrm{m}}\right)^3 \\ &= 64.3\cdot\frac{\mathrm{kg\cdot m\cdot m}}{\mathrm{s^3}}\cdot\frac{\mathrm{m^3}}{\mathrm{kg}}\cdot\frac{\mathrm{s^3}}{\mathrm{m^3}} \\ & \boxed{A = 64.3\,\mathrm{m^2}} \end{aligned}$$

14.59: PROBLEM DEFINITION

Situation: A conventional horizontal-axis wind turbine with 2.3 m diameter propeller in a 47 km/h wind.

Find: Maximum deliverable power.

Properties: $\rho = 1.2 \text{ kg/m}^3$.

PLAN

Use equation for theoretical maximum power.

SOLUTION

The wind speed in m/s

$$V = 47 \ \frac{\text{km}}{\text{h}} \times \frac{1000 \text{ m}}{1 \text{ km}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 13.1 \text{ m/s}$$

Maximum power

$$\begin{aligned} P_{\max} &= \frac{16}{27} \times \frac{1}{2}\rho V^3 A \\ &= \frac{8}{27}\rho V^3 A \\ &= \frac{8}{27} \times 1.2 \ \text{kg/m}^3 \times (13.1 \, \text{m/s})^3 \times \frac{\pi}{4} \times (2.3 \ \text{m})^2 \\ &\boxed{P_{\max} = 3.32 \text{ kW}} \end{aligned}$$

14.60: PROBLEM DEFINITION

Situation: Wind farm with 20 Darrieus wind turbines 15 m tall in 20 m/s wind to produce 2 MW power. Turbine has shape of circular arc.

Find: Width of wind turbine.

Properties: $\rho = 1.2$ kg/m^3.

PLAN

Apply the wind turbine maximum power equation and find capture area of each turbine.

SOLUTION

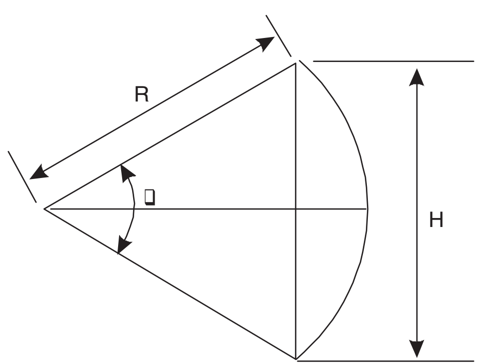
Each windmill must produce 2 MW/20 = 100,000 W.
Wind turbine maximum power

$$P_{\max} = \frac{8}{27}\rho V_o^3 A$$

In a 20 m/s wind with a density of 1.2 kg/m^3, the capture area is

$$A = \frac{27}{8}\frac{100000 \text{ W}}{1.2 \text{ kg/m}^3 \times (20 \text{ m/s})^3} = 35.2 \text{ m}^2$$

Consider the figure for the section of a circle.



The area of a sector is given by

$$A_s = \frac{1}{2}\theta R^2 - \frac{1}{2}RH\cos(\theta/2)$$

where θ is the angle subtended by the arc and H is the distance between the edges of the arc. But

$$R = \frac{H}{2\sin(\theta/2)}$$

so

$$
\begin{aligned}
A &= 2A_s = \frac{H^2}{4}[\frac{\theta}{\sin^2(\theta/2)} - 2\frac{\cos(\theta/2)}{\sin(\theta/2)}] \\
&= 56.2 \times [\frac{\theta}{\sin^2(\theta/2)} - 2\frac{\cos(\theta/2)}{\sin(\theta/2)}]
\end{aligned}
$$

Solving graphically gives $\theta = 52^o$. The width of the windmill is

$$
\begin{aligned}
W &= H[\frac{1}{\sin(\theta/2)} - \frac{1}{\tan(\theta/2)}] \\
&= 15 \text{ m} \times \left(\frac{1}{\sin 26^{\text{o}}} - \frac{1}{\tan 26^{\text{o}}} \right) \\
& \boxed{W = 3.46 \text{ m}}
\end{aligned}
$$

14.61: PROBLEM DEFINITION

Situation: A 3 m diameter windmill used to pump water from 3 m deep well in 48 km/h wind. Pump efficiency is 80%. There is 6 m of 0.05 m galvcanized iron pipe in system.

Find: Discharge of pump.

Properties: $\rho = 1.12$ kg/m^3.

Assumptions: Assume one 90 degree elbow in system and a fully rough galvanized pipe.

PLAN

Apply energy equation between well and exit to find system head in terms of Q. Apply the wind turbine maximum power equation to get P for the power equation and solve for Q.

SOLUTION

Wind speed

$$V = 48\frac{\text{km}}{\text{h}} \times \frac{1000 \text{ m}}{1 \text{ km}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 13.3 \text{ m}^3/\text{s}$$

Energy equation between well surface and outlet.

$$\begin{aligned} \frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_p &= \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_p + h_L \\ h_p &= (z_2 - z_1) + \frac{V^2}{2g}(\frac{fL}{D} + 1 + K_e + K_b) \end{aligned}$$

The roughness for galvanized iron is 0.015 cm, so relative roughness is 0.015 cm/ 5 cm = 0.003. From Fig 10.14 (EFM 10e), the fully rough Darcy Weisback friction factor is 0.027. The system head is

$$\begin{aligned} h_p &= 3 \text{ m} + \frac{V^2}{2g}\left(\frac{0.027 \times 6 \text{ m}}{0.05 \text{ m}} + 1 + 0.5 + 0.9\right) \\ &= 3 + 0.287V^2 \end{aligned}$$

The velocity is

$$V = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4} \times (0.05 \text{ m})^2} = 510Q$$

The system head is

$$\begin{aligned} h_p &= 3 \text{ m} + 0.287 \times (510Q)^2 \\ &= 3 \text{ m} + 74,649Q^2 \end{aligned}$$

Wind turbine maximum power

$$\begin{aligned} P &= \frac{16}{27} \times \frac{1}{2}\rho A V^3 \\ &= \frac{8}{27} \times 1.12 \text{ kg/m}^3 \times \frac{\pi}{4}(3 \text{ m})^2 \times (13.3 \text{ m}^3\text{/s})^3 \\ &= 5585 \text{ N-m/s} \end{aligned}$$

Power equation

$$\begin{aligned} 0.80 \times P &= \gamma Q h_p \\ h_p &= \frac{0.8 \times P}{\gamma Q} \\ &= \frac{0.8 \times 5585 \text{ N-m/s}}{9810 \text{ N/m}^3 \times Q} \\ &= \frac{0.46}{Q} \end{aligned}$$

Equating the heads

$$0.46 = \left(3 \text{ m} + 74,649 Q^2\right) Q$$

Solving for discharge gives $Q = 0.091 \text{ m}^3\text{/s}$

$$\begin{aligned} Q &= 0.091 \text{ m}^3\text{/s} \times 60 \text{ s/min} \\ &\boxed{Q = 5460 \text{ L/min}} \end{aligned}$$