# 6

# Hydraulic Turbines

**Problem 1**

There are 10 solved examples and 7 exercise problems (exclude Problems 1, 2, and 10) in this chapter. Prepare a table to mention the values of all the parameters, such as head, flow rate, speed, diameter, specific speed, power, and efficiency (whether these parameters are part of the data or part of the answers), so that one can have an overall view of the variety of the machines. Do they fit into the values prescribed in Figs. 6.1 and 6.2? A site has a head of 130 m of water and the flow rate of 3.5 m$^3$/s. From the table which you have prepared, or otherwise, select and design a suitable turbine for the site. Assume suitable coefficients for the design.

**Solution:** The various parameters of all the hydraulic turbines of the solved examples and exercise problems are recorded in Table 6.1.

**Table 6.1** Parameters of hydraulic turbines

| Example or Problem | Head $H$ (m) | Flow Rate $Q$ (m$^3$/s) | Speed $N$ (rpm) | Power $P$ (kW) | Specific Speed $N_s$ | Rotor Diameter $D$ (m) | Machine |
|---|---|---|---|---|---|---|---|
| 6.1 | 510 | 0.03 | 1500 | 130.13 | 7.06 | 0.577 | Pelton |
| 6.2 | 260 | 2.00 | 600 | 4911 | 39.15 | 1.025 | Pelton |
| 6.3 | 336 | 0.8574 | 600 | 2600 | 21.26 | 1.19 | Pelton |
| 6.4 | 500 | 3.5 | 330 | 16652 | 18 | 2.6 | Pelton |
| 6.5 | 10 | 2.0 | 300 | 156.96 | 211.36 | 0.713 | Francis |
| 6.6 | 60 | 1.7 | 500 | 1000.62 | 94.7 | 0.93 | Francis |
| 6.7 | 70 | 8.0 | 300 | 4670 | 101.25 | 1.51 | Francis |
| 6.9 | 4 | 239.85 | 44.29 | 8000 | 700 | 7.63 | Kaplan |
| 6.10 (a) | 18 | 150 | 375 | 23044 | 1535 | – | Kaplan |
| (b) | 18 | 5 | 375 | 7681 | 886 | 2.393 | Kaplan (3 units) |
| 3 | 260 | 4.8 | 500 | 10406 | 28.2 | 1.2 | Pelton (3 jets) |
| 4 | 340 | 1.66 | 600 | 4986 | 28.73 | 1.18 | Pelton |
| 5 | 65 | 2.8 | 540 | 1464 | 112 | 0.92 | Francis |
| 6 | 85 | 0.635 | 1000 | 450 | 82.2 | 0.4922 | Francis |
| 7 | 12.5 | 0.35 | 500 | 36.48 | 128.5 | 0.39 | Francis |
| 8 | 5.5 | 95 | 100 | 4460 | 793 | 4.2 | Kaplan |
| 9 | 40 | 7.7 | 600 | 2600 | 304 | 1.115 | Kaplan |

It is observed that the values of head and specific speeds of all the machines agree very well with those mentioned in Figs. 6.1 and 6.2.

To design a turbine with head, $H$ = 130 m and flow rate, $Q$ = 3.5 $m^3/s$, we proceed as follows:

1. To find the power that can be developed, we assume an overall efficiency of 0.85.

$$\text{Power,} \quad P = \frac{\omega Q H \eta}{1000}$$
$$= \frac{9810 \times 3.5 \times 130 \times 0.85}{1000}$$
$$= 3794 \, \text{kW}$$

2. The speed of the machine is to be selected out of the synchronous speeds such as 500, 600, 750, or 1000 rpm.
3. Then we proceed to calculate the specific speed and the corresponding speed ratio, $\phi$, of the machine. The specific speed suggests that the turbine is of Francis type.
4. From the value of $\phi$, the blade velocity is calculated.
5. Blade velocity, then, gives rise to the diameter of rotor.

   The results of the above steps are tabulated as in Table 6.2.

**Table 6.2** Different parameters

| **Speed** $N$ | **Specific Speed** $N_s = \frac{N\sqrt{P}}{H^{1.25}}$ | $\phi$ | $U = \phi.\sqrt{2gH}$ | **Diameter** $D = \frac{U \times 60}{\pi N}$ | $\psi$ | $V_{f1} = V_{f2}$ $\psi.\sqrt{2gH}$ |
|---|---|---|---|---|---|---|
| 500 | 70.16 | 0.63 | 31.815 | 1.215 | 0.16 | 8.08 |
| 600 | 84.2 | 0.64 | 32.57 | 1.037 | 0.17 | 8.585 |
| 750 | 105.24 | 0.66 | 33.33 | 0.849 | 0.18 | 9.09 |
| 1000 | 140.32 | 0.69 | 34.845 | 0.6655 | 0.23 | 11.615 |

6. When the diameter of the rotor is known, its width can be determined by having its flow velocity, and then getting the area of flow.

As seen in the table, the four speeds and the corresponding diameters are calculated. The higher speeds and lower diameters are preferred designs, because of the lower costs. However, at the next higher speed of 1500 rpm, the diameter is too small. In fact, the speed can be either 600 rpm or 750 rpm. Presently, the selection is 600 rpm and the diameter is 1.037 m, with $N_s$ = 84.2, $U_1$ = 32.57 m/s. The flow velocity is $V_{f1}$ = 8.585 m/s.

Further, we have $\pi D_1 B_1 V_{f1} = Q$

Therefore,

$$
\begin{aligned}
B_1 &= \frac{Q}{\pi D_1 V_{f1}} \\
&= \frac{3.5}{\pi \times 1.037 \times 8.585} \\
&= 0.12514 \, \text{m} \\
&= 12.5 \, \text{cm}
\end{aligned}
$$

We can now find the blade angles and remaining parameters.

The specific work is given by

$$
\begin{aligned}
W &= \frac{P}{\dot{m}} \\
&= \frac{3794}{3500} \\
&= 1.084 \, \text{kJ/kg}
\end{aligned}
$$

But $W = U_1 V_{u1}$, because $V_{u2} = 0$, $\alpha_2 = 90°$.

Therefore,

$$
\begin{aligned}
U_1 V_{u1} &= 1084 \\
V_{u1} &= \frac{1084}{32.57} \\
&= 33.282 \text{ m/s}
\end{aligned}
$$

The velocity triangles are drawn, as in Fig. 6.3.

At $N_s$ = 84.2, the $\frac{D_2}{D_1}$ is selected as 0.55.

Therefore,

$$
\begin{aligned}
D_2 &= D_1 \times 0.55 \\
&= 1.037 \times 0.55 \\
&= 0.57\,\text{m} \\
&= 57\,\text{cm}
\end{aligned}
$$

Blade velocity at outlet,

$$
\begin{aligned}
U_2 &= U_1 \times 0.55 \\
&= 32.57 \times 0.55 \\
&= 17.91\,\text{m/s}
\end{aligned}
$$

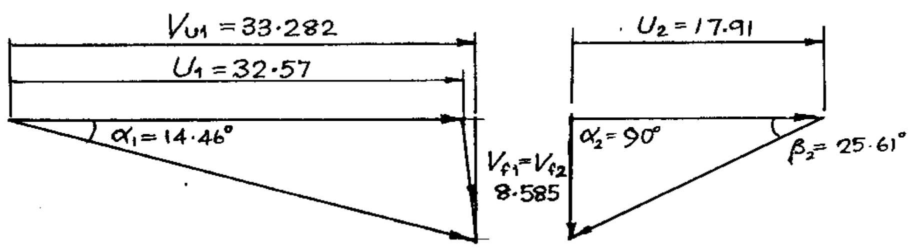


**Figure 6.3** Inlet and outlet velocity triangles.

Inlet velocity angle,

$$
\begin{aligned}
\alpha_1 &= \tan^{-1}\left[\frac{V_{f1}}{V_{u1}}\right] \\
&= \tan^{-1}\left[\frac{8.585}{33.282}\right] \\
&= 14.46°
\end{aligned}
$$

Blade inlet angle,

$$
\begin{aligned}
\beta_1 &= \tan^{-1}\left[\frac{V_{f1}}{V_{u1} - U_1}\right] \\
&= \tan^{-1}\left[\frac{8.585}{33.282 - 32.57}\right] \\
&= 85.26
\end{aligned}
$$

Blade outlet angle,

 

$$\beta_2 = \tan^{-1}\left[\frac{V_{f2}}{U_2}\right]$$
$$= \tan^{-1}\left[\frac{8.585}{17.91}\right]$$
$$= 25.61°$$

Guide Vane details:

Diameter of guide vane ring,

$$D_0 = D_1 + 0.013\,\text{m}$$
$$= 1.037 + 0.013\,\text{m}$$
$$= 1.05\,\text{m}$$

Width of guide vane ring,

$$B_0 = B_1 + 0.5\,\text{cm}$$
$$= 13\,\text{cm}$$

Length of guide vanes,

$$L_0 = 0.3 \times D_0$$
$$= 0.315\,\text{m}$$

The penstock diameter can be determined with a velocity of water, which is approximately 80% of $V_f$, that is, 7 m/s.

Hence,

$$\left(\frac{\pi D_{\mathrm{p}}^2}{4}\right)\times 7 = 3.5$$

$$D_{\mathrm{p}} = \left[\frac{3.5\times 4}{\pi\times 7}\right]^{0.5}$$
$$= 0.8\,\mathrm{m}$$

**Problem 2**

At a project site, the head available is 160 m of water at a flow rate of 0.005 $m^3$/s. Select and design a suitable turbine to generate power, assuming the required coefficients with justification and stating all the relevant parameters.

**Solution:** A suitable turbine is to be designed for a site where the available head is 160 m and flow rate is 0.005 $m^3$/s.

1. This is a case of design of Pelton turbine.
2. The loss in the pipeline is taken as 10%. This makes the net head available at the nozzle as 160 – 16 = 144 m.
3. The overall efficiency of energy conversion is assumed as 95%.
4. The power, that can be developed, is therefore

$$P = \frac{\omega QH\eta}{1000} = \frac{9810\times 0.005\times 144\times 0.95}{1000}$$
$$= 6.71\,\mathrm{kW}$$

For the hydropower development, this power is too small. However, the procedure of the design can be continued.

5. The jet velocity is calculated as

$$V_1 = c_{\mathrm{v}}\sqrt{2gH}, \text{where } c_{\mathrm{v}} = 0.98$$
$$= 0.98\sqrt{2\times 9.81\times 144}$$
$$= 52.09\,\mathrm{m/s}$$

6. To calculate the jet diameter, $d$, we have

$$\frac{\pi d^2}{4} V_1 = Q$$

Therefore,

$$d = \left[\frac{Q \times 4}{\pi \times V_1}\right]^{0.5} = \left[\frac{0.005 \times 4}{\pi \times 52.09}\right]^{0.5}$$
$$= 0.01097\,\text{m}$$
$$= 1.1\,\text{cm}$$

7. The speed ratio is taken as 0.46.

8. The peripheral velocity of blades (Pelton buckets) is

$$U = 0.46 V_1 = 0.46 \times 52.09$$
$$= 23.96\,\text{m/s or } 24\,\text{m/s}$$

9. Now, the possible speeds of the rotor are synchronous speeds, that is, 3000, 1500, 1000, 750, 600, etc. We can choose each of the speed, to find the diameter, so that the peripheral velocity is *U*.

$$D = \frac{U \times 60}{\pi N}, U = 24\,\text{m/s}$$

| | | | | | |
|---|---|---|---|---|---|
| $N$ | 3000 | 1500 | 1000 | 750 | 600 |
| $D$ | 0.1528 | 0.3056 | 0.4584 | 0.611 | 0.764 |

10. At this juncture, the procedure is with respect to two cases of the speed, $N$ = 3000 rpm and $N$ = 1500 rpm.

11. (a) When $N$ = 3000 rpm, the specific speed is

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{3000 \times \sqrt{6.71}}{144^{1.25}} = 15.6$$

(b) When $N$ = 1500 rpm, the specific speed is

$$N_s = \frac{N\sqrt{P}}{H^{5/4}} = \frac{1500 \times \sqrt{6.71}}{144^{1.25}} = 7.789$$

It is possible to have both these values as alternate designs.

12. The jet diameter continues as 1.1 cm in either case.

The jet ratios are

(a) $\frac{D}{d} = \frac{15.28}{1.1} = 14.18$

(b) $\frac{D}{d} = \frac{30.56}{1.1} = 27.78$

13. The number of Pelton buckets are

(a) $Z = 7 + 15 = 22$

(b) $Z = 14 + 15 = 29$

14. Because jet diameter is 1.1 cm in both cases, the cup dimensions are same in the two cases.

| | |
|---|---|
| Length | $L = 2.3\, d = 2.53$ cm |
| Breadth | $B = 2.8\, d = 3.08$ cm |
| Depth | $D = 0.6\, d = 0.66$ cm |

15. The blade angles are $\beta_1 = 0°$ and $\beta_2 = 165°$.

This completes the designs.