

Centrifugal Pumps

Problem 1

This is a small project having three parts: Parts (a), (b), and (c).

Part (a): Enlist the design parameters and performance parameters of a centrifugal pump. Explain, to the extent possible, the effects of variation of such parameters (for example, in the impeller, the width of the blade, B_2 , affects the flow rate; higher the width, higher is the flow rate; and hence higher power; also, it does not affect the head created).

Part (b): Prepare a table which shows the values of parameters (as in part (a) above) in the solved examples and the exercise problems of this chapter. If some values are not available in the problems (either as part of data or part of answers), calculate them wherever possible.

Part (c): Make an attempt to reinforce your explanations of part (a), citing the values in the table of part (b), wherever possible.

Solution : Part (a): Independent variation of any one single parameter is possible only in some cases. The effect of such variation can be discussed as follows.

1. Impeller diameter at outlet, D_2 : It has been seen that $Q \propto ND^3$; $H \propto N^2D^2$; $P \propto N^3D^5$. Hence, effects of variation of D_2 are as guided by the coefficient π_1 , π_2 , and π_3 .
 - (a) As D_2 increases, flow rate increases as the cubical power of D_2 .
 - (b) As D_2 increases, the head increases as the square of D_2 .
 - (c) As D_2 increases, the power increases as the 5th power of D_2 .
2. Impeller diameter at inlet, D_1 : For centrifugal pumps, D_1 is a subsidiary value of D_2 ; generally the variation of D_1 is as a fraction of D_2 only. But its independent variation is to be looked at, as it varies the overall size of the inlet velocity triangle. Thus, the flow velocity is proportional to D_1 . Further, because area of flow varies as D_1^2 , the flow rate varies as D_1^3 , just as it happens with D_2 .

Although D_1 may not directly enter the calculations of specific work and power, ($V_{u1} = 0$), one has to look at the role of D_1 in a qualitative way: as D_1 increases, the length of blade in the impeller decreases; the energy transfer per unit length of blade increases. This calls

for design of the blades with stronger materials; the blades have to be stronger and more stable. Lower values of D_1 increase the length of blades and the energy transfer per unit length of blade decreases; blades become more stable.

3. Speed of the impeller, N : The effects of variation of N can also be known by considering the coefficients π_1 , π_2 , π_3 (as was seen in the case of impeller diameter). Thus, as the speed increases, the flow rate increases proportionately, but head varies as square of speed and power varies as the third power of speed.
4. Outlet blade angle, β_2 : The effect of the increase of the β_2 is to increase the specific work. Also, as β_2 is increased, the output characteristic varies, the slope of the characteristic changes from higher negative values to lower negative values. Further increase of β_2 can even change the characteristic with undesirable slope with extended positive values.
5. Width of the blades, B_1 and B_2 : Increase in the values of B_2 directly increases the flow rate; and therefore the power also increases. However, there is no effect on the head created, when B_2 is varied.
6. Specific speed of the pump, N_s : This is a very important parameter. Its variation means the variation of the shape of the blades. It characterizes the blade (and the impeller). But size of the impeller does not depend on the specific speed. A huge prototype pump and a small model pump can have equal values of the specific speed, if the blade shapes are similar.
7. Head of the pump, H : This is a performance parameter. Head depends on the impeller diameter and the speed, as their squares. When higher values of head are aimed at, either of these (D_2 or N) or both can be increased.
8. Flow rate of the pump, Q : This is a performance parameter. Flow rate depends on the impeller diameter and speed and the width of the blades. While Q is proportional to the speed of the rotor and width of blades, it is proportional to the cube of the impeller diameter. Hence, even a small increase in diameter can increase the flow rate very much.
9. Power of the pump, P : This is a performance parameter. The power consumption of the pump has to be less; but instead of putting it in these words, it is more appropriate to say that for a specified flow rate Q and head H , the input power has to be as low as possible. Quantitatively, the power varies as N^3 and D_2^5 .
10. Efficiency of the pump: There are different types of efficiencies, the volumetric, hydraulic, or mechanical efficiencies. In general, the product of these efficiencies, that is, the overall efficiency is one, which is generally referred to. For a given duty of a pump, there is always an optimum value of specific speed. At this value of the specific speed, the efficiency of the pump is the maximum.

11. Specific work of the pump, W : Specific work of the pump is indication of the magnitude of energy added to every unit mass of the fluid. Although this is a function of almost all parameters, some of the parameters are more important than the rest: the speed and the diameter. Both these parameters vary over wide ranges. A third parameter is the blade outlet angle, but generally β_2 varies in a comparatively smaller range: about 50° – 70° .

Part (b): The values of the various parameters are recorded in the Table 7.1.

Table 7.1 Parameter values

Example or Problem	D_1	D_2	N	β_2	B_2	N_s	H	Q	P	W
7.1	0.03	0.06	1500	75°	0.0075	65.75	1.556	0.00476	0.0854	17.953
7.2 (a)	0.06	0.18	1000	70°	0.03	87	6.478	0.125	7.94	63.52
7.2 (b)	0.06	0.18	1500	70°	0.03	64.77	14.58	0.1875	20.23	107.9
7.3		0.2137	960	90°	0.0115	38.17	10	0.05	4.91	98.2
7.4		0.3	1440		0.015	30.18	39.72	0.11	50.0	454.2
7.5	0.3	0.8	600	65.62°	0.12		42	3.89	1885	484.5
7.9		0.25	1440	60°	0.015	32	24.46	0.06	19.18	320
7.10				65°			30	2.0	588	294
(a)	0.2078	0.4155	960		0.147	106				
(b)	0.2714	0.5427	735		0.1123	81				
(c)	0.338	0.676	590		0.09	65				
1	0.2	0.4	1440	40°	0.02	27	61.5	0.171	129.2	755
2		0.3	980	35°		15.747	15	0.015	2.4	160
3 (a)		0.28	1440			23.83	30	0.045	13.24	294.2
(b)		0.3962	960			23.83	26.69	0.085	22.26	261
4			1440			12.35	48.7	0.025	14.93	597.2
5	0.4	1.0	300	30°	0.05	78.25	6.0	1.00	64.94	64.94
6	0.2	0.4	744.5	40°	0.02	20	16.5	0.09	14.57	162
7		0.205	1500	55°	0.062	50.155	20	0.1	19.62	196
8		0.45	1440	38.86°	0.025	26.41	83	0.2547	265.6	1044

Part (c):

- One important observation in Table 7.1 is that the problems cover a wide range of values of parameters. However, the values of β_1 and B_1 seem to be of secondary importance, as they are “subsidiary” to other parameters.

2. The observations of part (a) can be checked with the variation of values of parameters, spread over the examples or problems. All the comments agree very well.
3. It may be particularly mentioned that the comment with reference to specific work, W , can once again be checked. The values of Table 7.1 almost “testify” the comments.

Problem 2

Two pumps are required to be designed: one for a fire hose and another for pumping water to a town water supply scheme in a remote place where electrical power supply is snapped.

Both require power supply from mobile units and therefore the power of the prime mover is limited to an upper value of 60 kW. Discuss the parameters which distinguish the design of the two pumps. Substantiate your discussion with some numerical values that you might use in the design.

Solution: The two pumps to be designed are totally different in their requirement; this can be explained as follows:

1. When a fire breaks out, the fire fighters have to be at a distance from the fire and still be able to douse the fire with water jets from a distance. Hence, the water jet has to have a very high velocity; the pump must be able to cater to this need. The mechanism of energy transfer to water must be (as far as possible) directly in the form of velocity; and the degree of reaction must be as low as possible. Also during the fire, the electrical power in the area would have been disconnected, so the prime mover to drive the pump may be some form of internal combustion engine. Hence, the speed of the pump is not bound by the criterion of synchronous speeds. As a consequence, to obtain higher velocity jets, the pump speed can be even beyond the 3000 rpm limit to about 4000 rpm. (Still higher rpm may be difficult for a diesel engine also.)
2. In the case of town water supply scheme, the source of water may be a remote place. Water supply schemes are generally arranged in such a way, that there are a number of stage-wise water tanks or reservoirs with pumping stations attached to each of such intermediate reservoirs. A pump is required to pump water from one tank to next tank, without the need of creating large heads, but certainly requiring the capacity for large flow rates. Although the power supply to the pumping stations is on a preferential basis because of the critical nature of services, the power supply to one such pumping station

may be disrupted due to unforeseen circumstances (not to all the pumping stations, simultaneously). The present problem is, therefore, of designing a pump for low head output but large flow rates, to be run by a source of power which is mobile. Again the mobile unit may supply electrical power and the existing motors may drive the pumps, or, alternately a new pump run by internal combustion engine may be pressed into service. It is this pump that is being discussed at present.

Keeping the above requirements in mind, it is now realized that:

- (1) As speed of pump increases, outlet velocity increases.
- (2) As outlet diameter of impeller increases, outlet velocity is increased.
- (3) As blade angle at outlet increases, the outlet velocity increases.

Now, for the pump for the fire hose, the following specifications are contemplated:

Speed, $N = 4000$ rpm, Diameter of impeller, $D_2 = 0.2$ m,

Blade width at outlet, $B_2 = 0.0075$ m (= 7.5 mm),

Flow velocity, $V_{f2} = 7.5$ m/s, Blade angle at outlet, $\beta_2 = 75^\circ$

Blade velocity at outlet, $U_2 = \frac{\pi D_2 N}{60} = \frac{\pi \times 0.2 \times 4000}{60} = 41.89$ m/s

Whirl component at outlet,

$$\begin{aligned} V_{u2} &= U_2 - \frac{V_{f2}}{\tan \beta_2} = 41.89 - \frac{7.5}{\tan 75} \\ &= 39.89 \text{ m/s} \end{aligned}$$

The specific work,

$$\begin{aligned} W &= U_2 V_{u2} \\ &= 41.89 \times 39.89 \\ &= 1.671 \text{ kJ/kg} \end{aligned}$$

The flow rate,

$$\begin{aligned}
 Q &= \pi D_2 B_2 V_{f2} \\
 &= \pi \times 0.2 \times 0.0075 \times 7.5 \\
 &= 0.035343 \text{ m}^3/\text{s}
 \end{aligned}$$

Therefore,

$$\dot{m} = 35.343 \text{ kg/s}$$

The power,

$$\begin{aligned}
 P &= W\dot{m} \\
 &= 1.671 \times 35.343 \\
 &= 59 \text{ kW}
 \end{aligned}$$

The exit velocity,

$$\begin{aligned}
 V_2 &= (39.89^2 + 7.5^2)^{0.5} \\
 &= 40.589 \text{ m/s}
 \end{aligned}$$

For the pump for the town water supply, the following specifications are contemplated:

Speed, $N = 2000$ rpm, Diameter of impeller, $D_2 = 0.2$ m,

Blade width at outlet, $B_2 = 0.0025$ m (= 2.5 mm),

Flow velocity, $V_{f2} = 10$ m/s, Blade angle at outlet, $\beta_2 = 75^\circ$

Blade velocity at outlet, $U_2 = \frac{\pi \times 0.2 \times 2000}{60} = 20.944 \text{ m/s}$

Whirl component at outlet,

$$\begin{aligned}
 V_{u2} &= 20.944 - \frac{10}{\tan 75} \\
 &= 18.264 \text{ m/s}
 \end{aligned}$$

The specific work,

$$\begin{aligned}
 W &= U_2 V_{u2} \\
 &= 20.944 \times 18.264 \\
 &= 0.3825 \text{ kJ/kg}
 \end{aligned}$$

The flow rate,

$$\begin{aligned}Q &= \pi \times 0.2 \times 0.025 \times 10 \\ &= 0.1571 \text{ m}^3/\text{s}\end{aligned}$$

Therefore,

$$\dot{m} = 157.1 \text{ kg/s}$$

The power,

$$\begin{aligned}P &= W\dot{m} \\ &= 0.3825 \times 157.1 \\ &= 60 \text{ kW}\end{aligned}$$

The exit velocity,

$$\begin{aligned}V_2 &= (18.264^2 + 10^2)^{0.5} \\ &= 20.822 \text{ m/s}\end{aligned}$$

The specific speed of the fire-hose pump, $N_s = 15.95$

The specific speed of the water-supply pump, $N_s = 50.81$

Further results may also be obtained, if the power supply could be raised to 90 kW, 120 kW, etc.

The specific speeds have been calculated to find the D_2/D_1 ratios; that is, the answers to include D_1 , β_1 , etc. (Again the $D_2 = 0.2$ m, $N = 4000$ rpm, etc. have been obtained only after some trials.)