Experiment 3A3/B: Fluid Mechanics - Pump Experiment

Aldwyn Eyres
Emmanuel College
ae349

February 14, 2016

1 Summary

In this experiment, the performance characteristics were determined for two pumps - one pumping water and one pumping a solution of water and glycerine. It is important to understand pump characteristics because they have a vast number of applications in engineering, and designing them to be efficient and correctly specified is of paramount importance. It was discovered that cavitation only occurred when throttling the inlet to the water pump when it was at full speed - only this combination of low stagnation pressure and high local fluid velocity lead to low enough static pressures.

2 Introduction

In this experiment, the performance of two pumps - one pumping glycerine and the other pumping water - was investigated. The flow rates of both pumps were varied and the pressure rise across the pumps measured. For the water pump, the pressure rise was recorded for both full and half rotational speeds, and for throttling both upstream and downstream of the pump.

Dimensional analysis can be used to express the non-dimensional pressure rise across the pump as a function of two other dimensionless groups:

$$\frac{\Delta p}{\rho N^2 D^2} = \left\{ \frac{Q}{ND^3}, \frac{\rho N D^2}{\mu} \right\} \tag{1}$$

where $\frac{\Delta p}{\rho N^2 D^2}$ is the non-dimensional pressure rise. A quick unit check reveals it is indeed dimensionless:

$$\frac{\frac{M}{L \cdot T^2}}{\frac{M}{L^3} \cdot T^{-2} \cdot L^2} = 1$$

$\frac{Q}{ND^3}$ and $\frac{\rho N D^2}{\mu}$ are the <u>dimensionless flow ratio</u> and a <u>characteristic Reynolds number</u> (the ratio of inertial to viscous forces for the fluid). These are also both non-dimensional:

$$\frac{\frac{L^3}{T}}{T^{-1} \cdot L^3} = 1 \; ; \quad \frac{\frac{M}{L^3} \cdot T^{-1} \cdot L^2}{\frac{M}{L \cdot T}} = 1$$

3 Discussion

As can be seen in Figure 1 *a)*, the convex side of the impeller is the pressure surface. This can be deduced by observing that the fluid must be accelerated tangentially by the vanes in the direction that the impeller is rotating. In order for this to happen, for the direction of rotation shown in the figure, the pressure must be higher on the right of the fluid than on the left, or in other words, the pressure must be higher on the left-hand face of the vane.

It was possible to derive a non-dimensional group, Ca, which indicates when cavitation is likely to occur:

$$Ca = \frac{p_{in} - p_v}{\rho N^2 D^2}$$

This cavitation number was calculated at a temperature of 20°C, therefore using a vapour pressure, p_v, of 2339 Pa. Figure 5 shows Ca plotted against non-dimensional flow rate for the water pump at full speed while throttling the inlet.

It was possible to calculate the Reynolds number based on inlet diameter and the velocity of the fluid at inlet relative to the impeller. As can be seen from Figure 3 *a)*, $V_{radial} = \frac{\dot{m}}{\rho A}$ and from *b)*, $V_{relative} = \frac{V_{radial}}{\cos 65°}$. For the water pump at maximum speed and flow rate, this gives a Reynolds number of:

$$Re = \frac{V_{relative} D_{inlet}}{\nu} = \frac{4.42 \times 30 \times 10^{-3}}{1 \times 10^{-6}} = 1.326 \times 10^5$$

For the glycerine pump, Re was found to be 5.55×10^3, and for the water pump at half speed it was found to be 6.66×10^4.

Cavitation occurs when the local static pressure becomes lower than the vapour pressure of the fluid. From applying Bernoulli's equation, it can be seen that a low static pressure can arise from either a low stagnation pressure or a high absolute velocity:

$$p_{static} = p_0 - \frac{1}{2}\rho V^2$$

It was observed that cavitation only occurred when throttling the water pump at its inlet for low flow rates, when the pump was operating at full speed. Throttling the inlet caused a loss in stagnation pressure loss across the throttle, and thus a low static pressure (as seen from Bernoulli above) in the pump for the same absolute velocity of the flow.

Also, lowering the mass flow rate increased the absolute velocity of the fluid at inlet, as well as its angle of incidence, as shown in Figure 3 *c)*. Operating the pump at full rotational speed (as opposed to half speed) also ensured the local velocities were high at inlet. This high velocity also ensured a low static pressure, as seen from Bernoulli above. The combination of a low stagnation pressure and high local velocity caused a low enough static pressure for cavitation to occur.

Throttling the pump outlet did not cause cavitation because although the mass flow rate is low (and hence the absolute fluid velocities high, as discussed above), the drop in stagnation pressure is downstream of the pump, so the stagnation pressure at inlet to the pump remained high. This means that the local fluid velocities at inlet were not high enough on their own, without any stagnation pressure loss, to cause cavitation.

The pressure rise across the pump was largely independent of the throttle location - this because the pressures were only determined by the local fluid velocities (which were themselves functions of the pump flow rate), and not the stagnation pressure at inlet (which was controlled by the throttle location).

As the flow turns from axial to radial upon entry to the pump, one would expect the lowest pressure to occur as shown in Figure 2. This is where one would expect cavitation to initiate, and this is confirmed from observation. One would also expect the cavitation to be nearer the suction surface (Figure 1, *a)*) but this was not observed, possibly because there was not enough difference in pressure between the pressure and suction surfaces, while the difference in pressure between inlet and outlet of the pump was substantial.

The venturi might not be suitable for measuring the flow rate of the glycerine solution because the subsequent method of calculation assumes the fluid is inviscid. For the glycerine solution it may not be appropriate to neglect its viscosity.

The reduction in pressure rise as flow rate increases (as shown in Figure 4) is as expected - the pressure rise is a measure of the energy imparted to the flow by the pump per unit volume of fluid. At higher flow rates, the pressure rise will be lower for a given pump power, and this is what is observed.

Figure 6 shows how the pressure rises vary with the Reynolds numbers calculated above, for the water pump at both full and half speeds, and the glycerine pump - again it varies in a similar fashion to that of flow rate. At higher Reynolds numbers the pressure rise is lower because the pump is able to impart less energy per unit volume of flow.

Figure 5 shows how cavitation number varies with non-dimensional flow rate. It suggests that cavitation occurs at a critical number of 0.06 and that above this number cavitation is unlikely. As flow rate increases, the absolute velocity of the flow at inlet decreases (shown in Figure 3 *b)* and *c)*) and this means that the local static pressure rises, so is less likely to be less than the local vapour pressure (the condition needed for cavitation to occur).

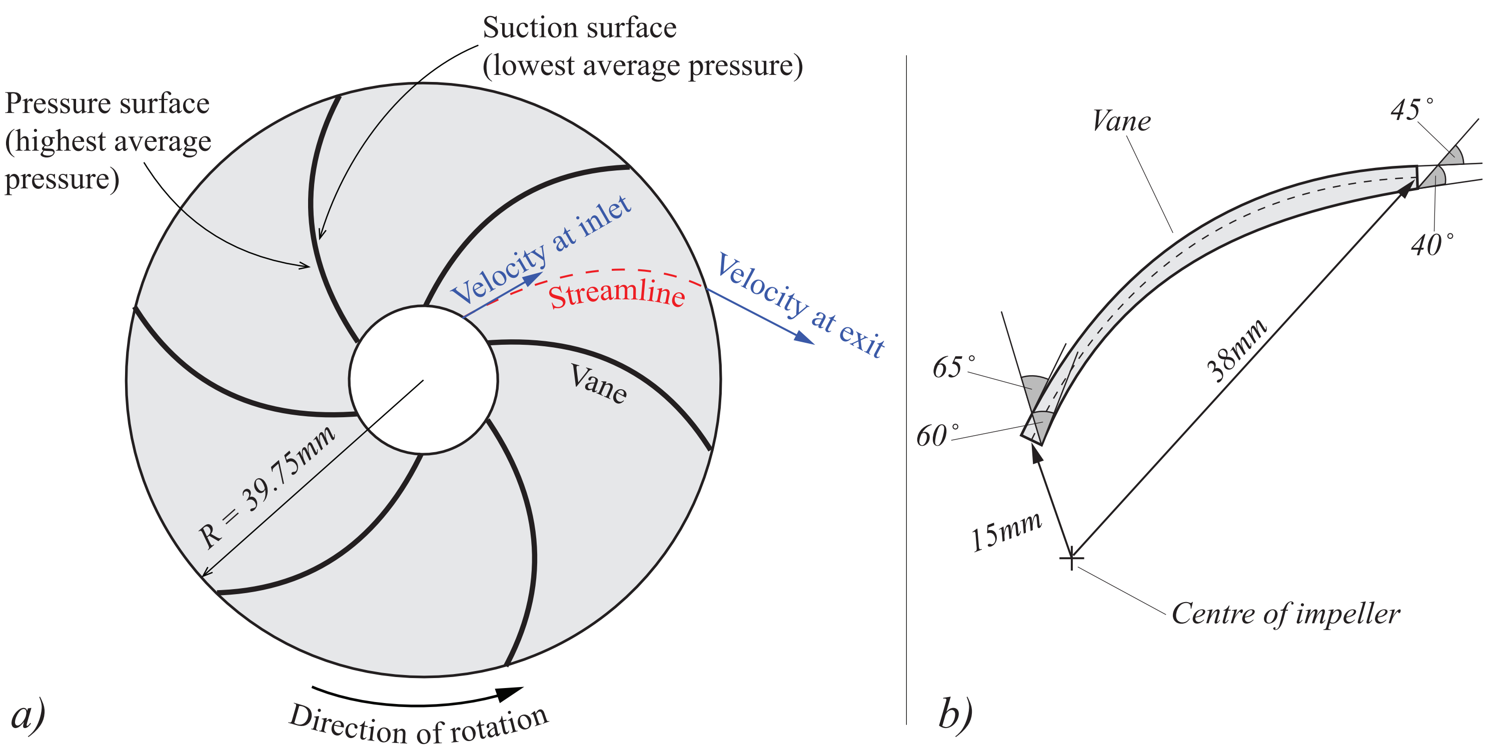

Figure 1: A diagram of: *a)* the whole impeller, and *b)* an individual vane on the impeller, showing the inlet and outlet angles of both the leading and trailing edges.

4 Conclusion

To conclude:

- it was found that the pressure surface of the impeller was the convex side of the vane.

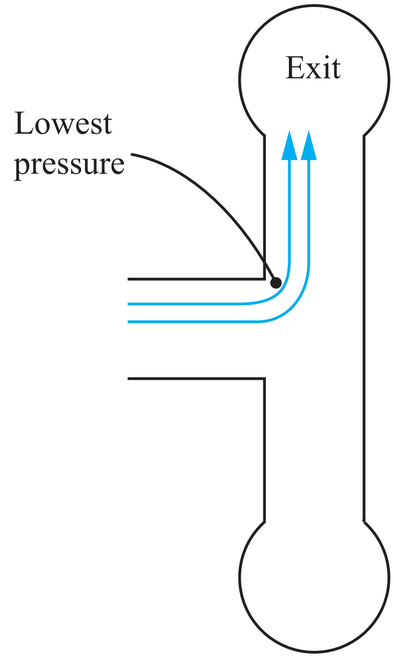

Figure 2: A side view of the pump housing, showing where the lowest pressure will occur as the flow turns from axial to radial.

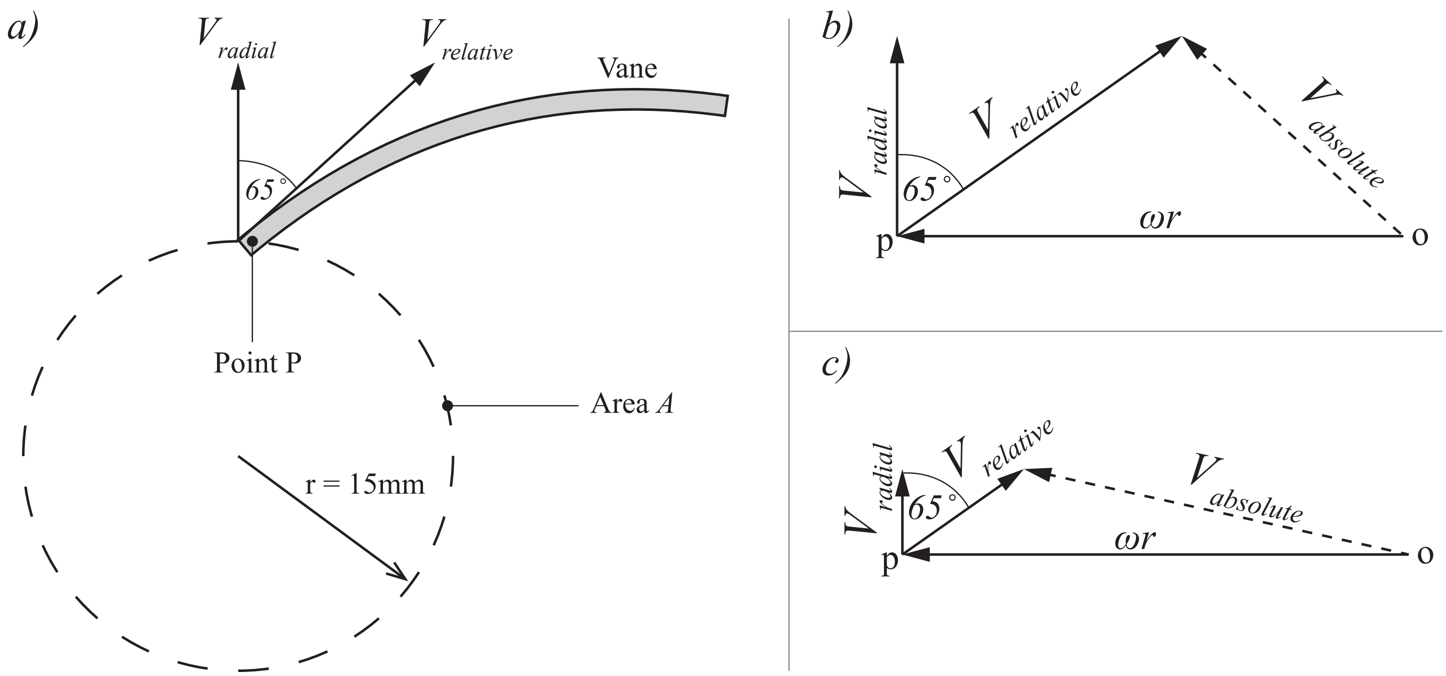

Figure 3: *a)* A space diagram,*b)* the corresponding velocity diagram at nominal design conditions (nominal flow rate), for the fluid at the inlet, and *c)* the corresponding velocity diagram when the flow rate is much lower than this.

- velocity diagrams of the fluid at inlet allowed the Reynolds numbers of the pumps at their maximum flow condition to be determined, and also explained why reducing the flow rate lowered the static pressure enough for cavitation.
- cavitation only occurred when throttling the inlet to the water pump at its maximum rotational speed. These conditions resulted in a low stagnation pressure at pump inlet and a high local fluid velocity, which lowered the local static pressure to below the vapour pressure.
- it was possible to define a cavitation number, $Ca = \frac{p_{in} - p_v}{\rho N^2 D^2}$, that had a critical value of 0.06. Above this value

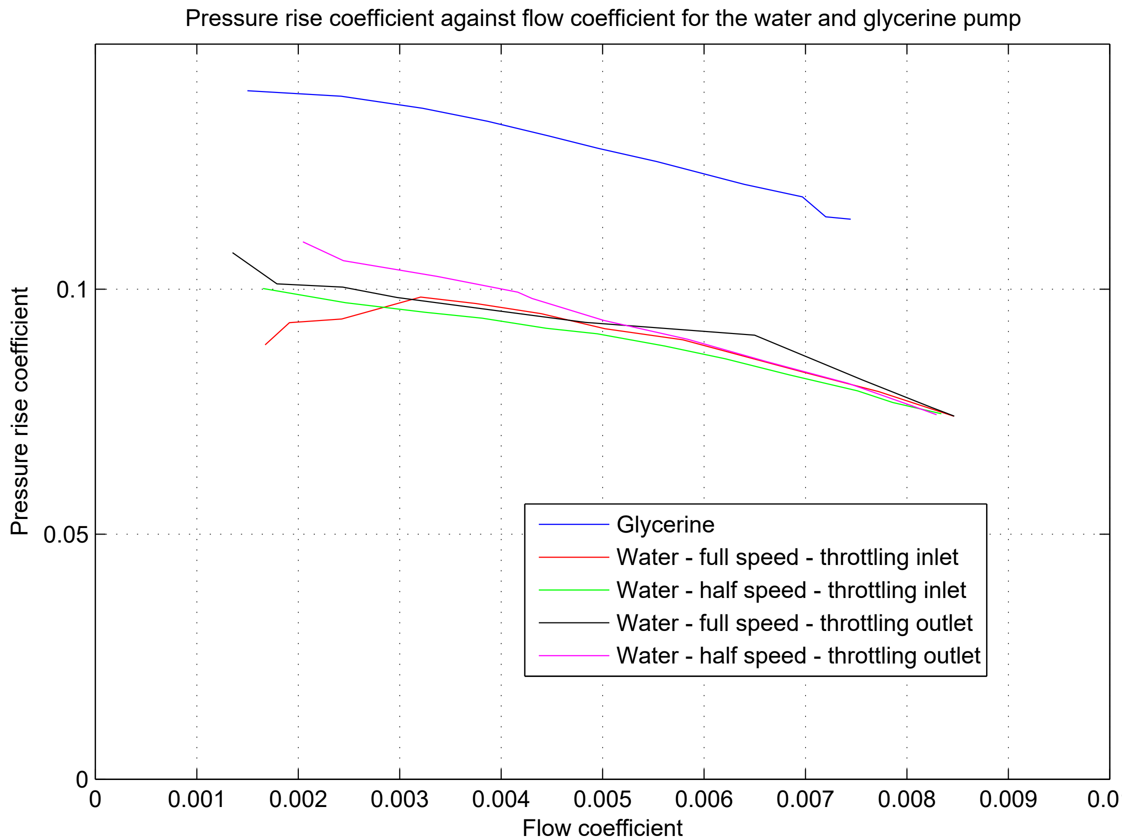

Figure 4: Graphs of non-dimensional pressure rise against non-dimensional flow coefficient for the glycerine pump, and the water pump running at full/half speed while throttling the inlet/outlet.

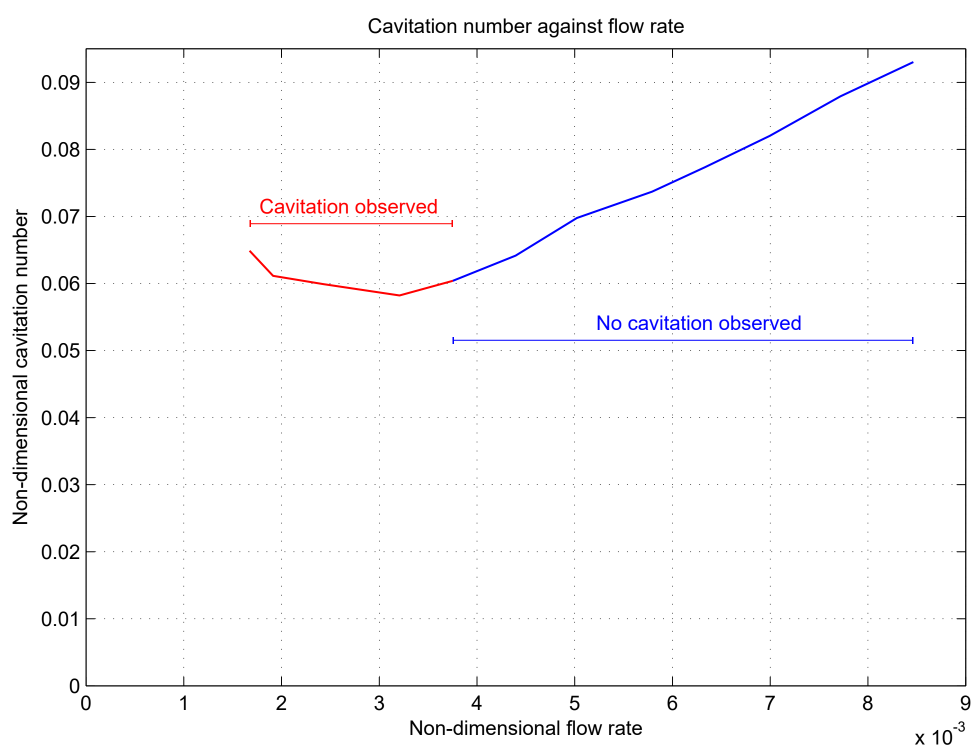

Figure 5: A graph of non-dimensional cavitation number against non-dimensional flow rate.

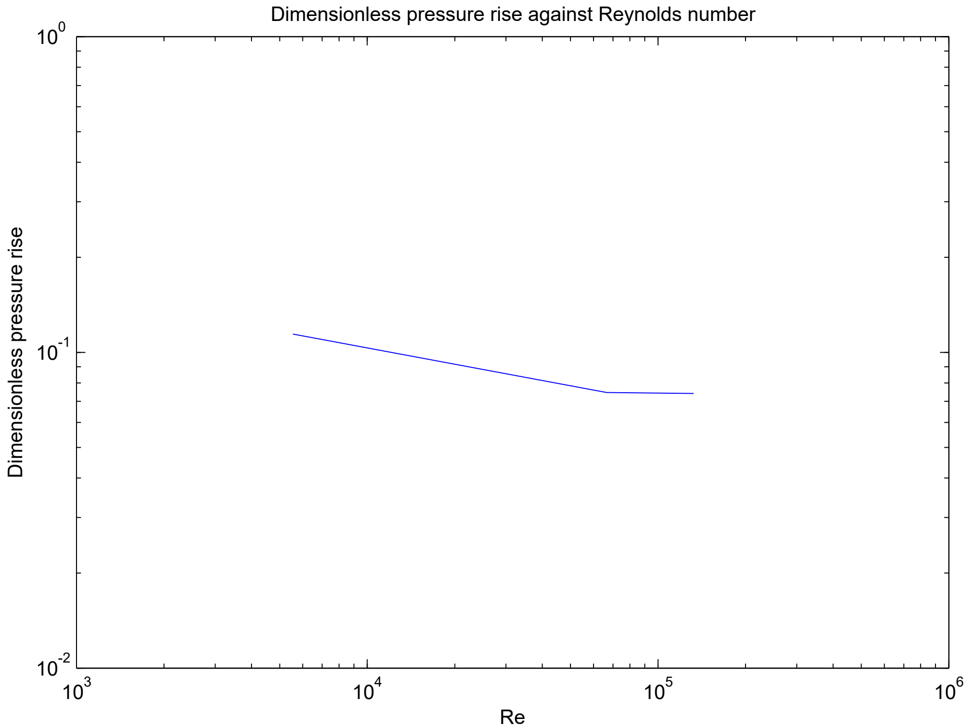

Figure 6: A graph of non-dimensional pressure rise against Reynolds number.

cavitation was unlikely.

- the pressure rise across the pump was independent of throttle location, because the throttle location only changes the stagnation pressure and this does not determine the static pressure differences across the pump.
- the pressure rise across the pump was observed to fall with both increasing flow rate and Reynolds number. This was expected because as flow rate increases, the pump is able to impart less energy to the fluid per unit volume.
- Only high rotor speeds produced high enough velocities and correspondingly low static pressures for cavitation to occur. The loss in stagnation pressure required for cavitation could only be produced by a throttle at the inlet to the pump, and not at the outlet.
- the venturi could not be used to measure the flow rate of the glycerine solution because it only works for fluids where the viscosity is low enough to be ignored.