PART IIA COMPRESSIBLE FLOW 3A3/B EXPERIMENT
Pump Experiment

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1 Introduction

The experiment compares the performance of two identical pumps operating with two different liquids: water and a glycerine-water mixture. The pressure rise is investigated for different flow rates, which are achieved with throttles and the effect on cavitation is also examined. The effect of the flow, the throttle position and the Reynolds number are all factors that affect the pump performance. Dimensional analysis is used to aid understanding and summarise results.

2 Experimental Method

Two centrifugal pumps were used, one operating with water and one with a water and glycerine mixture. The impeller used, shown in the Appendix, has the following dimensions:
Outer Radius: 40 mm
Inner Radius: 12 mm
Vane Height: 5 mm
Inlet angle: 53°
Outlet angle:42°

It should be noted that the water pump exhibited suspicious behaviour. More specifically, when the inlet was throttled at the lower speed, air leaked into the pipe and large air bubbles could be observed at the compressor inlet. This happened at a non-dimensional flow rate of around 0.050 and was present all the way to fully throttled inlet. The result was the pressure being kept constant.

3 Results and Discussion

3.1 Impeller characteristics

As shown in the Appendix, the flow is from the middle to the rim of the impeller. In addition, since the impeller rotates counter-clockwise and the motor torque is in that direction, the high pressure surface is the concave side of the blades and the low pressure surface is the convex side of the blades, which provide a torque opposite to the motor torque.

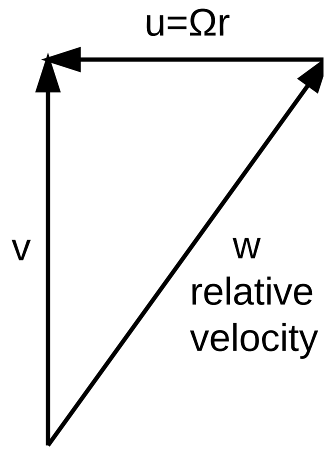

Figure 1: Velocity triangle showing flow speed, impeller speed and relative speed.

3.2 Impeller flow

The inlet area is assumed to be a cylinder, whose radius is the impeller inner radius and the height is equal to the vane height. This gives a value of $2\pi rh = 3.8 \times 10^{-4}$ m^2 . Using the water flow rate at the highest speed when both valves are fully open gives a velocity value of 2.9 m/s.

Figure 1 shows a velocity triangle, which is used to to calculate the relative velocity of the flow to the impeller, using Pythagoras' Theorem. This gives the value of $w = 4.7$ m/s. using this value, the inlet diameter of the impeller and the kinematic viscosity of water we can get the Reynolds number:

$$Re = 1.1 \times 10^5$$

3.3 Non-dimensional cavitation number

Cavitation occurs at the inlet of the compressor as the pressure there is lowest and it occurs when the inlet pressure falls below the water vapour pressure.

A remarkable observation is that cavitation starts on the inner side of the high pressure surface of the impeller vanes. This occurs because as the flow meets the beginning of the vane and has to turn to flow parallel to it, there is a recirculation bubble before the flow can attach to the vane surface. This causes a local low pressure, which is the first place to reach a pressure lower than the vapour pressure of water.

Since cavitation depends on how below the inlet pressure p_{in} is relative to the water vapour pressure p_v, their difference is significant. This difference can be non-dimensionalised by using the water density ρ, the compressor angular speed N and the impeller diameter D:

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

This non-dimensional cavitation number is plotted against non-dimensional flow rate $\frac{Q}{ND^3}$ in figure 2.

It can be seen that cavitation will occur only at the fast speed, which agreed with the observations. Cavitation only occurred when the inlet was significantly throttled at the high speed.

Since the discharge pressure of the compressor is known and the rise in pressure across the compressor is measured, the inlet pressure can be calculated. However, that value is correct only

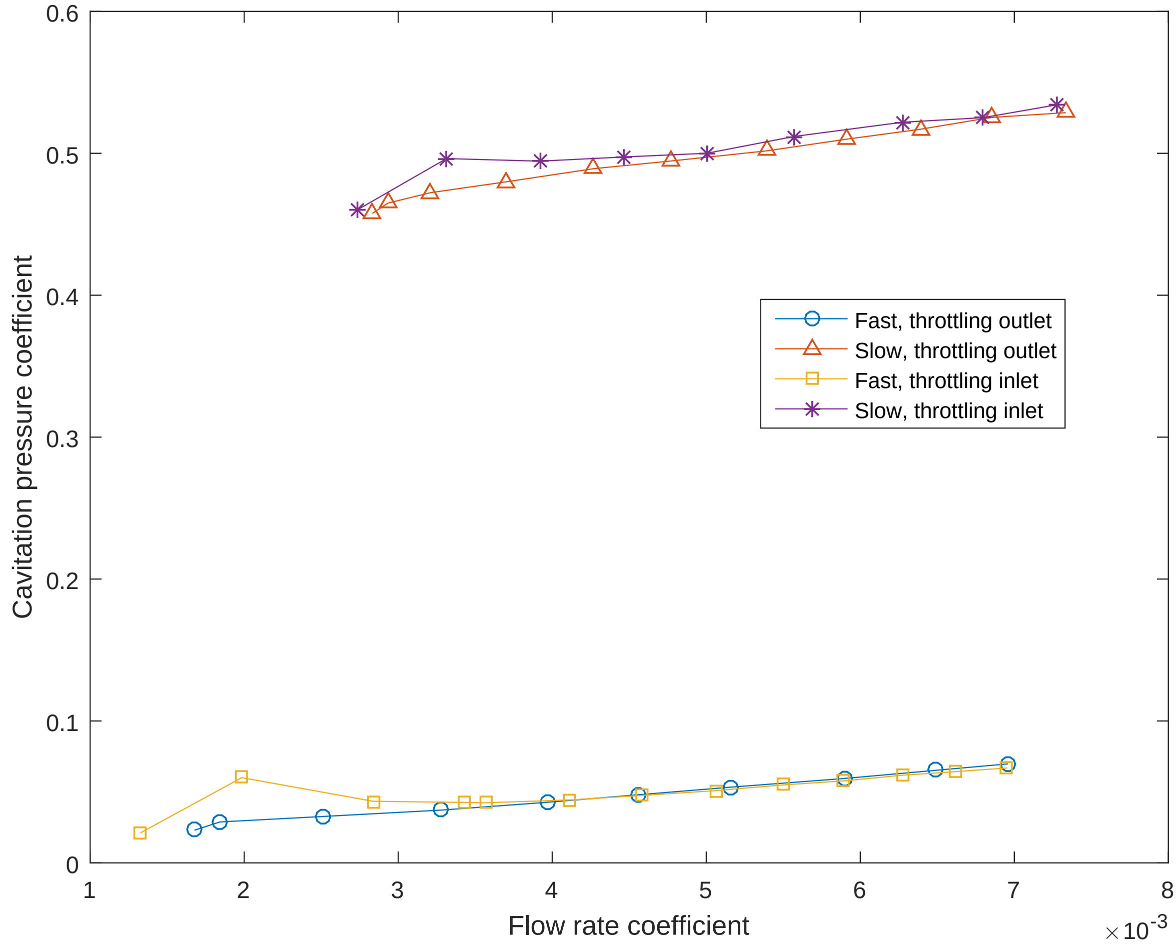

Figure 2: Cavitation pressure coefficient against flow coefficient for water pump.

for the tests where the inlet is throttled, as will be explained in section 3.5.

The line does not cross the x-axis because other pressure losses are neglected (eg. friction).

3.4 Performance curves

The five performance curves are plotted in figure 3

It evident that in general, the greater the throttling, i.e. the smaller the flow, the greater the pressure rise. The behaviour of the pump is very similar across all operating conditions. The effect of cavitation can be seen in the fast inlet throttled test, where the pressure rise drops significantly as cavitation takes place. This is due to the compressibility of the steam bubbles, changing the pumping efficiency dramatically.

As explained in section 2, the pressure was constant at the slow inlet throttled water test, due to air leakage. A kink is observed at the fully throttled point, because this measurement meant that there was no flow in and the compressor was not operating correctly.

3.5 The effect of throttling position on cavitation.

Figure 2 suggests that cavitation should occur both when the inlet is throttled and when the outlet is throttled at a high speed test. However, it was observed that cavitation occurred only when the outlet was throttled. This manifests itself in figure 3, as a drop in pressure with decreasing flow rate is only observed for the inlet throttled test.

This is the case because the method used to calculate the inlet pressure is only correct for when the inlet is throttled. The discharge pressure is known since the discharge head is known. The rise

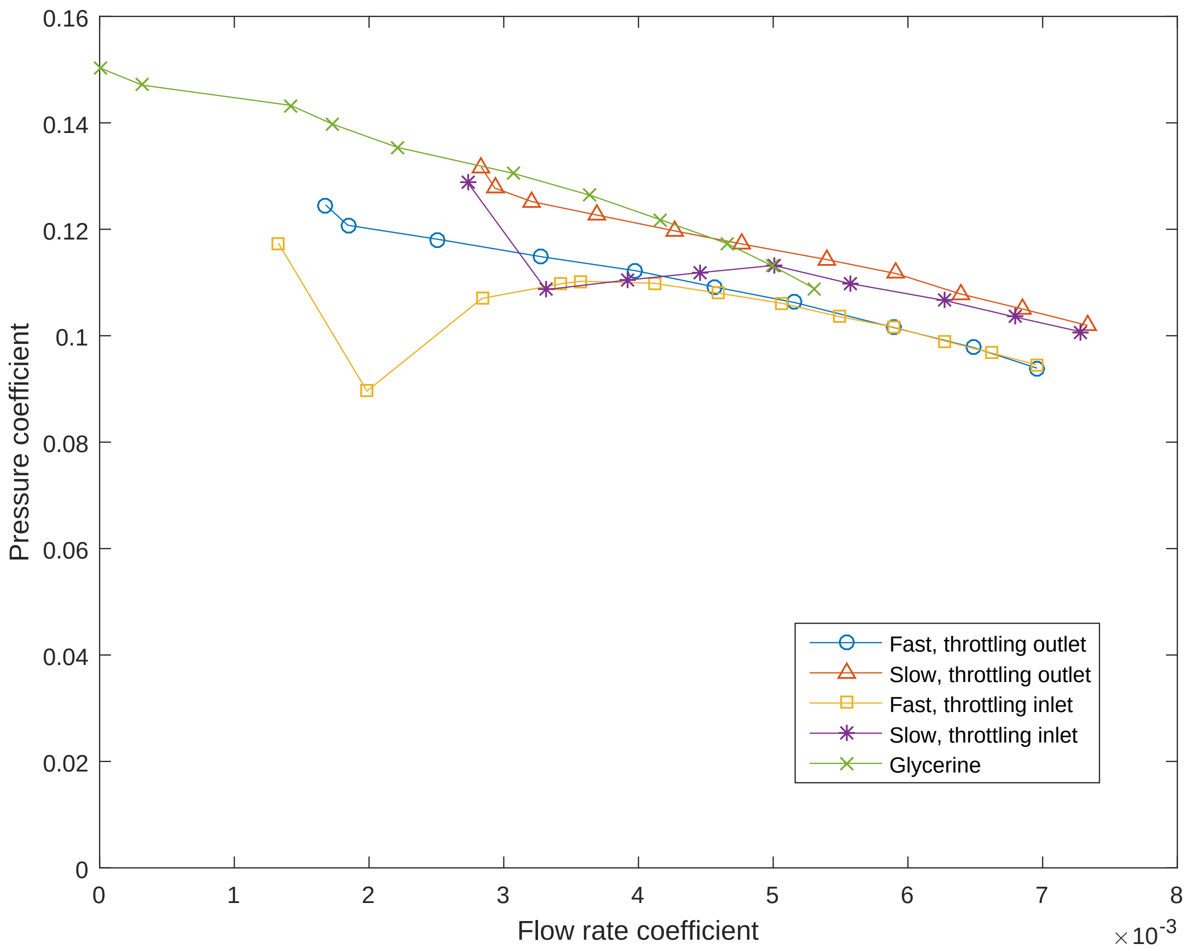

Figure 3: Performance curves for the glycerine pump and the water pump at different operating conditions.

in pressure due to the compressor is also measured. Thus, subtracting the compressor change in pressure from the discharge pressure should give the compressor inlet pressure.

Nevertheless, when the outlet is throttled, there is a drop in pressure between the compressor and the discharge, which is not taken into account. This means that the compressor inlet pressure is higher when the outlet is throttled, rather than the inlet being throttled.In other words, throttling the inlet causes a pressure drop which reduces the inlet pressure, whereas throttling the outlet does not have such an effect at the inlet.

3.6 Results validation

3.6.1 Change of pressure rise with flow

It is observed that the compressor pressure rise decreases with increasing flow rate. This is to be expected, since a low velocity leads to a higher pressure since the flow has a lower kinetic energy.

When the mass flow is greater, the same work input will lead to a smaller change in pressure, as the energy is transferred to "more fluid", thus the behaviour is sensible.

3.6.2 Change in pressure rise with Reynolds number

The Reynolds number calculated in section 3.2 depends on the flow rate and the angular speed for the same pump. Lowering the speed leads to a smaller inflow velocity, as well as a smaller Ωr component.

Figure 3 shows that at slow tests, where the Reynolds number is lower, the performance is slightly better. This can be explained using pipe flow theory.

In the lab handout it is seen that as the Reynolds number increases, the friction coefficient increases for a given roughness, as long as the flow is turbulent. For the Re calculated earlier, it is evident that the flow is fully turbulent. As a result, the impeller becomes less efficient at higher Re. This matches the observed behaviour.

3.6.3 Change in cavitation with rotor speed and throttle location

As seen in figure 2, cavitation occurs only when the impeller rotates at a high speed. This is the case because the pump pressure rise is greater. In figure 3 the non-dimensional pressure rises are close in value, but they are non-dimensionalised by $\rho N^2 D^2$, hence the fast tests produce a much greater Δp. This means that for the same discharge pressure, the inlet pressure is much lower at the fast tests.

In addition, cavitation occurs only when the inlet is throttled and the reason is explained in section 3.5.

The effect of flow rate is more complicated. Cavitation occurs at low flow rates, which is when the valves are more throttled. This is to be expected, since a more throttled valve is associated with a greater pressure loss across it. This means that the inlet pressure is lower when the flow rate is smaller, which leads to cavitation being a problem.

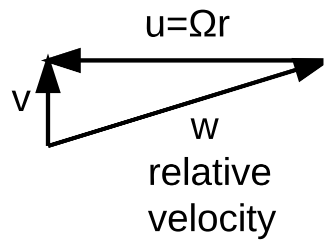

Figure 4: Velocity triangle showing flow speed, impeller speed and relative speed at a low flow rate.

Figure 1 shows the velocity triangle at nominal design conditions, whereas figure 4 shows the same triangle at a much smaller flow rate. At low flow rates, the relative velocity of the flow to the impeller decreases. More importantly, the incidence of the relative flow on the vanes increases. The vanes need to change this direction, thus local low pressure areas with lower pressures than nominal are formed. Therefore, cavitation is more likely to occur at low flow rates.

3.6.4 Differences

The two pumps have very similar behaviour but there are some key differences.

Firstly, the glycerine mixture is much more viscous than water. More specifically, the calibrated cylinders were used to calculate the ratio of viscosities of the two liquids. The glycerine mixture took 53 s to fall a distance of 5 mm, whereas water took only 32 s. This gave a glycerine mixture viscosity that is 9.7 times the viscosity of water.

Figure 3 shows that the performance of the glycerine pump is slightly better than the water pump and this is due to the difference in the Reynolds number. It has already been discussed how a low Re leads to a better performance. The high viscosity of the glycerine lowers the Reynolds number of the flow, even though the rotation speed is the same, hence the better performance.

In addition, the non-dimensionalised volumetric flow rates are lower for the glycerine pump, due to the glycerine's higher density. The mass flow rate might be very similar, but since $Q = \dot{m}/\rho$, Q is lower.

3.7 Venturi suitability

The Venturi is used to find a mass flow by measuring the pressure difference across it. The constrict the flow and thus accelerate it and the change in pressure is measured. This can be used to calculate the mass flow rate, but the calculations assume inviscid flow. The glycerine mixture has a much greater viscosity, thus a venturi meter is not an appropriate measurement device, as the viscosity would not allow the calculation of a relationship between the mass flow rate and the change in pressure.

4 Conclusions

1. Different sides of the impeller vanes experience different pressure.
2. Cavitation can be described by a non-dimensional number, which varies with flow rate.
3. The position of the throttle affects whether cavitation will actually occur.
4. Pumps perform better at lower flow rates.
5. Pumps perform better at lower Reynolds numbers due to friction.
6. Cavitation occurs at higher rotor speeds.
7. High viscosity liquids can be pumped with a greater pressure rise.
8. Venturi meters are not suitable for viscous liquids.