Investigation of internal flow pattern of a multiphase axial pump

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Abstract. Due to recent advances in computational techniques, single phase performances of pumps can be easily estimated using CFD. However, when the working fluid is a mixture of liquid and gas (multi-phase flow) computations may struggle to capture the more complex physical phenomena that occurs, and the precision of the prediction worsen as the gas volume fraction at pump inlet is increased. To provide reliable benchmark for the improvement of simulations, in this study we experimentally investigated the internal flow pattern of a multiphase pump using high speed camera and high frequency pressure measurements, so as to obtain the data of pressure distribution inside of impeller, or to obtain blade loading, for several gas concentration conditions. Unsteady phenomena were identified at low flow rate conditions, and an explanation of their nature has been attempted.

1. Introduction

Liquid and air multiphase pumps have been widely used in various industrial fields for many years. For example, in the oil and gas industry multiphase transportation has recently become very popular, because of the remarkable economic benefit compared to conventional separated transportation method [1, 2]. Since liquid and air phases are generally separated when strong centrifugal force acts on the mixture, centrifugal pumps are not suitable for these applications. Instead axial mixed-flow pumps are preferred [3], while the so-called helico-axial pump type has been specifically developed to have good multiphase handling performances [4, 5]. However, the head per stage of these types of machines are low compared to centrifugal pumps, and many stages are therefore required to achieve high head. This in turns means that the pumps are affected by the issues typical of multistage machines. A main problem is represented by the shaft vibrations. Especially in the case of multiphase pumps, unsynchronized fluid force due to gas contents affects rotor dynamic characteristics, and may increase the deterioration of internal bearing or bushes. To avoid these issues, the pump head per stage should be increased while avoiding phase separation, requiring detailed investigations of pump internal flow pattern under multiphase flow conditions.

In this study, the flow patterns under air and water multiphase flow condition were investigated to understand the effect of flowrate, speed and gas volume fraction (GVF) on bubbles behavior, for a multistage axial pump model with splitter impeller blades. As a result, the onset conditions of unsynchronized pressure fluctuation were identified, and their mechanism was estimated by detailed investigation of the pressure field and high speed videos.
2. Experimental setup and evaluation method

2.1. Test rig and measurement method

In this study a 3-stage axial pump, with impeller diameter of 150mm, 4 main and 4 splitter blades was used. The design flow rate is fixed at 70m³/h when rotating at the nominal speed of 2950rpm. As shown in figure 1, part of pump casing is made of acrylic resin to allow optical visualization by high speed camera, while 5 pressure transducers were mounted on the casing surface of the third stage impeller. The sensors were mounted with 45 degrees of circumferential distance between each other, equally spaced from the leading to the trailing edge, as shown in figure 2.

The test rig configuration is shown in figure 3. Working fluid is a mixture of water and air. Air is injected upstream of the test pump, the mixture then passes through the pump before being separated in the ventilation tank, which is open to the atmosphere and where the air is removed and the water is transferred (by gravity) to another closed tank. Finally, the water is remixed with air in a closed loop. Suction head and liquid flowrate are controlled by three valves in this conduit, while the air flowrate is controlled by a valve downstream of air tank. Water and air volumetric flowrates are measured by electromagnetic flowmeter and float flowmeter respectively, and total flowrate and GVF is adjusted by those valves.

The pump performances were measured by pressure gauges at the inlet and outlet of the pump, torque meter and rotational speed sensor. Internal flow pattern was evaluated by high speed video camera and pressure sensors. The high speed camera recorded the flow pattern of the 2nd stage impeller (2R) while at the same time the pressure fluctuations of the 3rd stage impeller (3R) was measured. Due to the effect of gas compression, the stage characteristics are highly affected by the inlet pressure. Therefore, the flow pattern of the 2nd and 3rd stages may be slightly different. However, since the tested pump is axial type with relatively low head, we considered that the flow patterns to be close and comparable.

![Image](image_url)

**Figure 1.** Test pump, 3-stage axial flow pump.
2.2. Post-processing of the pressure signal

During the test, the pressure fluctuations from the 5 transducers were recorded for 30 seconds, with sampling frequency of 10,240 Hz. At first, this time signal was transformed into position (angle), according to the rotational speed. Then, the signal of each sensor is “folded” several time over a complete revolution (0 to 360 deg), as shown in figure 4, taking into account their different angular position. Moreover, for an easier evaluation of the internal flow pattern, an angle $\theta_i$ is included for each location, as shown in figure 2 to convert the blade shape into a simple straight shape. The signal thus obtained is then phase averaged, and the standard deviation of each averaging angular range is evaluated as well, as shown in figure 5, right. Finally, taking into account of phase averaged data from the 5 pressure transducers, contour maps of static pressure on the shroud surface can be established as shown in figure 6. Same kind of internal flow pattern visualization had been conducted for inducer, by Yoshida, et., al [6].
3. Results and discussions

Figure 7 shows the pump head curves for various inlet GVF, as lines (left) or as head contours (right). While detailed analysis of the performances result is given in a separate paper [7], it can be seen that the head decreases with increasing GVF as expected. However, at flow rates equal and above the design value (Q/Qd=1) the head is not degraded for inlet SVF up to 10-15%.
Figure 7. Left: Head performances of the pump as a function of the flow rate for various GVF. Right: pump head performances map as a function of the flow rate and inlet GVF. The black dots represent measured test cases while the colours have been linearly interpolated between the measurements to create the map.

Figure 8. Measured pressure distribution and its standard deviation on the tip surface of 3rd impeller, for QL=60m³/h. Flow direction in each figure is from top to bottom.
This result confirm the ability of the pump to handle multiphase flows.

The contour maps of the tangentially averaged pressure and of the standard deviation associated with its averaging for various gas and water flowrates are shown in figure 8. In each small figure, the flow is from top to bottom. In these images as well it is possible to see that the pressure in the impeller channel increases as the flowrate is decreased, and decreases with increasing the GVF, as can be expected from usual pump operation.

High levels of standard deviation are observed in conditions of high flowrate (around 90m$^3$/h), or low flow rate (around 40m$^3$/h), where the standard deviation is quite high, especially from SVF 15 to 40%. Further visualizations of this phenomenon are done in figure 9 where the pressure signals for sensor 1 to 5 are shown. While the blade passing is the dominant phenomena in the signal from sensor 1 (close to the leading edge of the main blade, 4 blades passages), and sensor 3 (close to the leading edge of splitter blade, 8 blades passages), the other sensors, mounted between the blade passages, show very high amplitude of pressure fluctuation, especially for SVF between 15 and 40%.

These fluctuations may be explained by the formation of horse-shoe vortex at the leading edge, or tip leakage vortex, which traps the gas bubble at their cores, generating unsteady and unsynchronized behaviours. This in turn will generate very high forcing of the structure. This analysis is partially supported by high speed images of the flow inside of the pump, which show a highly segregated flow in the region upstream and near the leading edge of the splitter blades (sensors 2 and 3), as shown in figure 10. This is the region where vortices formed at the main blade leading edge will develop their unsteady motion.
Figure 10. Snapshots of the flow within the impeller of the last stage, for QL=40m³/h, and GVF = 5, 17.5 and 25%. The flow moves from right to left, and the impeller rotates in top to bottom direction.

4. Conclusion

As a result of visualization and evaluation of pressure fluctuation, high amplitude fluctuations of the pressure signals were observed in low liquid flowrate, with moderate gas flow rate conditions. This is due to the existence of unsteady leading edge vortex, and as increasing gas volume fraction, vortex tends to capture gas more and more. This may cause asynchronous fluid force, may affect to the rotor dynamic characteristics. Additional research is necessary to clarify the reason and mechanism of leading edge vortex, to obtain more wider operating range.

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