Study on transient hydrodynamic performance and cavitation characteristic of high-speed mixed-flow pump

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Abstract. In order to analyse the hydrodynamic performance and cavitation characteristic of a high-speed mixed-flow pump during transient operations, experimental studies were carried out. The transient hydrodynamic performance and cavitation characteristics of the mixed-flow pump with guide vane during start-up operation processes were tested on the pump performance test-bed. Performance tests of the pump were carried out under various inlet pressures and speed-changing operations. The real-time instantaneous external characteristics such as rotational speed, hydraulic head, flow rate, suction pressure and discharge pressure of the pump were measured. Based on the experimental results, the effect of fluid acceleration on the hydrodynamic performances and cavitation characteristics of the mixed-flow pump were analysed and evaluated.

1. Introduction

In recent years pumps have been widely used in various fields as fluid transportation equipment. In most industrial applications, the pumps are always working at steady-state. The rotational speed and hydrodynamic parameters of the pump would not change or varied within a small range in running process. Such pump performance is expressed under steady and noncavitating operating condition, and is called steady-state performance. However, with the increasing of pump system complexity, more applications require controlling pump starting, stopping and other transient operation. During these complex operation processes of pumps, fluid flow structure changed quickly which always involved energy transformations. As one of the most sensitive phenomenon with energy, cavitation in those transient processes must be considered.

The steady-state performance of pumps have been predicted and analysed in many studies. Pumps with satisfied performance can be designed by using steady-state theory. However, there was not a suitable method to be used to study the transient performance. In recent years, much more studies about transient performance of pumps have been carried out because of the growing engineering application needs. Experimental and numerical study which investigated transient characteristics of a centrifugal pump during starting and stopping period has been carried out by Tsukamoto et al. [1, 2]. Thanapandi [3, 4] experimentally investigated a volute pump during transient starting and shut down with different discharge valve settings. Results showed that the transient head characteristics closely follow the steady-state system head curve and the change of operating point is quasi-steady during normal starting and stopping transients. Lefebvre [5] studied hydrodynamic performance of a
centrifugal pump impeller during transient operation by using experimental method. The results indicated that the quasi-steady assumptions commonly used for the design of impellers that operate under high transient conditions are not suitable. Wang and Wu [6-8] conducted a series of experimental and numerical studies on transient performance of the centrifugal pump. It’s showed that obvious transient effect existed in the transient process of the large-scale pump.

Besides, cavitation characteristics are important performance indicators of the pump and mostly cavitation was not allowed. The existing studies about pump cavitation characteristics essentially focus on the steady-state operations [9, 10]. Cavitation of the pump under transient operation was rarely investigated. However cavitation under transient operation is important. Based on the investigation of the transient characteristics of non-cavitating centrifugal pumps, Tanaka and Tsukamoto [11-13] researched the transient behaviour of a cavitating centrifugal pump at the sudden opening/closure of discharge valve and in transient processes. The results showed that the transient performance related to the time-dependent cavitation behaviours.

In order to study the transient hydrodynamic performance of cavitating pump during transient operation, an experiment was carried out on cavitation characteristics of a transient operation pump in this paper. The effects of cavitation on transient performance of mixed-flow pump with guide vane during instantaneous start-up process.

2. Pump and the test rig system

2.1. Parameters of the pump

A horizontal high-speed mixed-flow pump was used for experiment and its principal specifications are summarized in Table 1. The main flow components of the pump including impeller, guide vane, shell, etc. And the structure is shown in Figure 1. Clearance fit is used between unshrouded impeller and import shell to ensure the smaller leakage flow and volume loss. Guide vane is axial-flow type and port is gradually broadly structure. The pump configuration including the piping installation and test facility are illustrated schematically in Figure 3. The inlet pipe from the inlet of the pump to the water tank is 3000 mm in length and 350 mm in diameter. The diameter of the discharge pipe is 500 mm. Axial-flow 90°bending tube is used to connect pump and the discharge pipe.

![Figure 1. Sectional view of the mixed-flow pump.](image1)

![Figure 2. Impeller structure of the test pump.](image2)

![Figure 3. Installation diagram of the test rig system.](image3)
Table 1. Specifications of mixed-flow pump.

| Geometric Specifications | Hydraulic Specifications |
|--------------------------|--------------------------|
| Suction diameter 350 (mm) | Flow rate 0.80 (m/s) |
| Impeller diameter 235 (mm) | Total head 16 (m) |
| Hub diameter 166 (mm) | Efficiency 84% |
| Number of vanes 5 | Rotate Speed 1500rpm |

2.2. Sensors and data acquisition system

The signal acquisition test system consists of pressure sensor, electromagnetic flow meters, torque/rotational speed sensor, signal conversion circuit, data acquisition card, test procedures and laptops, etc. The data acquisition card is NI 9205 which has 32 input. Sampling rate is 100 KHz, ADC resolution is 16 byte, and programmable input range is ±10 V, ±5 V, ±1 V and ±0.2 V. The absolute error is 3.230 μV when the range is ±5V. For the convenience of data acquisition, the signal of rotational speed, torque, flow rate and pressure is processing to standard pressure signal of 1-5V.

![Figure 4. Pressure sensors and torque/rotational speed transducer set up arrangement](image)

The proliferation silicon pressure sensors are used to measure the pressure of the different place of the pump. The range of these pressure sensors are 0-0.2MPa, 0-0.6MPa, and 0-1.0MPa. The 0-24V dc power is used. Pressure sensor and precision resistor in series up to get the voltage signal to the data acquisition card.

JN-338 torque/rotational speed sensor is used in speed and power test. The range are 0-2000N•m and 0-2500rpm. IFM4080k electromagnetic flow meters produced by SGAIC are used with 500mm in diameter and the range is between 0-5000 m3/h.

Overall the test pump is driven by a motor (Hv motor for 1500rpm test). Three different motors are used to adjust the rotational speed of the test pump. These drive systems can perform significant adjustment on rotational speed. Time intervals of data acquisition for all channels are 0.0005 s. The measure of grounding and signal isolation was adopted to reduce the signal noise of instrumentation and data acquisition system. The instantaneous flow rate was measured by an electromagnetic flow meter installed in the drain pipe line. The suction pressure and discharge pressure were measured by semiconductor type pressure transducers, which were installed in the pipe line. The instantaneous torque and rotational speed were measured by a torque/rotational speed sensor installed between the motor and pump shaft. A desired value was set for the manual adjusting valve in the discharge pipe line before transient operation, which was kept constant during the transient operation period.

3. Steady state test results

Steady state performance of mixed-flow pump with guide vane is test on the open pump performance test-bed under three different rotational speed of 750rpm, 1000rpm and 1500rpm. Some working points of big flow are not tested in the rotational speed of 750rpm because the line loss and pipeline layout such as high export pipe. The steady state hydraulic performance of mixed-flow pump is shown in Figure4. Because of the higher NPSH in the full speed, lead pump is series in the entrance of the
mixed-flow pump to pressurization in the rotational speed of 1500rpm and its principal specifications are summarized in Table 2.

Table 2. Specifications of lead pump.

| Specifications      | Value   |
|---------------------|---------|
| Suction diameter    | 500 (mm)|
| Outlet diameter     | 350 (mm)|
| Flow rate           | 0.88(m³/s)|
| Total head          | 22 (m)  |
| NPSHr               | 4(m)    |
| Efficiency          | 84%     |

The steady state performance curves of mixed-flow pump with guide vane under three different rotational speeds are shown in Figure5-Figure6. As it shows that the performance curve is gentle near the design flow. But the performance becomes lower obviously in the 1/4 to 1/2 the rated flow area such as the head sharply reduced and efficiency is low. NPSH of the mixed-flow pump with guide vane in three speeds is shown in Table 3.

Table 3. Steady state cavitation characteristic of mixed-flow pump.

| Rotating speed | NPSHr (m) |
|----------------|-----------|
| 1500rpm        | 15.5      |
| 1000rpm        | 5.5       |
| 750rpm         | 3.5       |

In the process of the test, because of the pressurization of lead pump in full speed test of 1500rpm, no cavitation is occurred. But flow separation and rotating stall lead to performance degradation in small flow area. Empirically NPSH of mixed-flow pump in partial condition is higher than in rated condition. In the test of 1000rpm without a lead pump, there are more apparent vibration noise and cavitation noise in the partial condition. Slight cavitation and the instability flow exist. However the hydraulic performance is not affected by general cavitation because the port in the mixed-flow pump with guide vane is very wide. And in the rated condition of the mixed-flow pump, the operation is more stable, no obvious vibration and noise occurred.

4. Transient process test results

The main content of this section is detail test research and data analysis about the influence to the hydraulic performance in transient operation, especially in fast start-up process of unstable phenomenon in small flow condition of the mixed-flow pump with guide vane.
The pump boot process is divided into multiple independent operating conditions by pump transient performance prediction method that based on the assumption of quasi-steady-state. In the process of change, the small flow operation condition in unstable region is experienced, so the influence of this flow operation condition to the transient performance of fast start-up cannot be ignored. Because flow structure is in dramatic changes in fast start-up process in the pump, energy transfer and dissipation are very complex, it is very worth study about the effect of unstable flow to the performance of the start-up process.

The fast start-up process performance curve of the mixed-flow pump with the different stable flow in 0.4m3/s, 0.55m3/s, and 0.6m3/s are shown in Figure7-Figure9. The reaction rate of the torque/rotational speed and pressure signal is fast and it is accurately reflect the changes of the pump performance in the test. But the signal of flow rate produces lag because the electromagnetic flow meter is far from the export of the pump.

As it is shown in Figure7-Figure9, the motor rotational speed accelerates to stability linearly and the fluctuation is small. The change of the pump head is divided into three stages. In the first stage the head uniformly increase linearly too; but in the second stage the head is rising volatility, the increase rate reduces significantly and bigger fluctuations appear in the later; in the last stage the head curve becomes flat and stable. The power curve also presents the coherent variation trend of the head. The startup behavior of the 0.92m3/s flow rate under 1500rpm is shown in Figure10. As Figure10 shows that head and power curve rise smooth in the whole startup process and no obviously oscillation and fluctuations exist.
From the above analysis, we can conclude that the steady state performance would not significantly reduce in the mild cavitation condition of mixed-flow pump with guide vane. Cavitation makes great influence to head and power in the startup process. It will produce instability phenomena such as head and power oscillation, slow rise and dramatically reduce close to stable.

5. Conclusions
Cavitation occurs when the suction pressure is 2-3m higher than the NPSHr in the mixed-flow pump with guide vane. But the influence of cavitation to steady state performance of the pump is not great, and the performance would not reduce.

The transient hydraulic performance of the mixed-flow pump during fast startup process with low suction pressure which may cause slight cavitation is quite different from noncavitating operation. The transient hydraulic performance with cavitation will involve oscillation rise and fall of head and power curves.

Study about unstable flow and cavitation characteristics in the small flow with partial conditions of the mixed-flow pump will contribute to grasp the transient characteristics change trend and mechanism, and provide references to improve the transient operation cavitation performance.

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