Experimental performance of a pump and the related vortices in a pump intake of a model pump station

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Abstract. In order to quantitatively study the relationship between the performance of a pump and the related hydraulic phenomena in a pump intake of a model pump station, a model test was carried out in the present paper. The results show that when the dimensionless water level (water level/diameter of the pipeline: W/d) $W_L^* \geq 5.46$, the influence of the water level on the performance of the pump can be ignored, and the operation of the pump is stable. When $W_L^* = 5.15$, the performance of the pump decreases deeply, the dimensionless flow rate (actual flow rate/reference flow rate under standard working condition) $Q^*$ can be as low as 0.79, and the pump becomes noisy. Finally, when $W_L^* < 5.15$, although the impeller is still rotating and the input power is unchanged, the pump no longer pumps water.

1. Introduction

The pump station is widely used in urban drainage and water supply, water resources dispatch, nuclear power station and other important industrial and agricultural fields [1-5], in which the pump intake and pump are the most important components. However, all kinds of complex hydraulic phenomena in the pump intake have an important influence on the performance of the pump [6-11].

At present, research on the complex flow pattern in the pump intake is mainly included in experimental research and numerical simulation investigation. Here, the experimental study mainly focuses on the observation of critical submergence and the capture of relevant vortex flow patterns, such as the study conducted by Rajendran V. P. and Patel V. C. [12], Eguchi Y. and Tanaka N. [13] and Kim C. G. et al. [14]. Moreover, the numerical simulation research is mainly about the prediction of vortex position and relevant vortex elimination strategies, such as the study carried out by Choi, J. W. et al [15], Ahmad Z. et al [16], Tang X. L. et al. [17] and Chuang W. L. et al. [18].

However, there are few quantitative studies on the complex hydraulic phenomena and flow performance of pump, such as the study conducted by Nagahara T. et al [19], it found that the diameter of the cavitation area of the submerged vortex correlated with the rate of increase in hydraulic forces when the vortex reached the pump impeller. The fluctuation of hydraulic forces was increasing in proportion to the diameter. The maximum value of fluctuation with submerged vortex cavitation was approximately 1.4 times higher than that measured without vortex cavitation. Therefore, based on the model test, high-speed photography (the capturing position is 200 mm away from the sidewall 1 of the pump intake model) and data acquisition technology, this paper researched the relationship between complex hydraulic phenomena in pump intake and the performance of the pump,
and has given the quantitative research results, which is of great significance for engineering reference based on normalization.

First, the construction of the test bench is presented, then the test process and working conditions are distributed, and finally, the experimental results and related analysis are given.

2. Experimental system

In the present paper, the experimental model applied the relevant design regulations [20-23] for reference, on the basis of guarantee the similarity of Reynolds approximation, Froude criterion, and other criteria, and finally, the geometric dimension ratio of prototype and model is 10:1.

2.1. Experimental setup and facilities

The test bench mainly includes a circulation tank, pipeline system before pump intake, pump intake, the pump, and its outlet pipeline, frequency converter controller system, ultrasonic flow meter, flow rate controlling valve, return pipeline and laser liquid-level measurement system, etc. The rotating speed and input power of the pump can be controlled and feedback by the frequency converter controller system. Schematic diagrams of the experimental loop as shown in Figure 1.

![Figure 1. Experimental loop.](image)

The pump intake and its pump system, relevant components are illustrated in Figure 2. Meanwhile, the distances $L_1$, $L_2$, $L_B$ and $L_H$ are applied to normalize the related parameters for further analysis, which are the distances from the centre of the pump bell to the sidewall 1, sidewall 2, back wall and floor, respectively. In the present experiment the dimensionless parameters $L_1^* = L_1/d = 1.20$, $L_2^* = L_2/d = 1.13$, $L_B^* = L_B/d = 1.06$ and $L_H^* = L_H/d = 1.33$ ($d$ is the inner diameter of the pipeline). Complex hydraulic phenomena such as free-surface vortex and various wall-attached vortex can form in pump intake. The sidewall 1 of the pump intake, the inlet and outlet pipes of the pump are made of Polymethyl Methacrylate (PMMA), to observe various complex flow patterns in the pump intake more conveniently.
Figure 2. Pump intake and pump.

In order to better compare and analyse various performance parameters of the pump, the factory setting parameters are listed in Table 1.

Table 1. Facilities of the test bench.

| Facility                        | Range    | Accuracy |
|---------------------------------|----------|----------|
| Pump                            | 0-22.3 m³/h |          |
| Ultrasonic flowmeter           | 0-50 m³/h    | 2%       |
| Laser Liquid-level Measurement System | 0-100 m     | 0.1%     |
| Frequency converter controller system | 50 Hz     | 1%       |

2.2. Experimental conditions

In order to comprehensive and accurately investigate the relationship between water level, various complex vortex flow patterns and pump performance in pump intake, five typical cases at least were carried out in the present experiment to capture phenomena accurately and data acquisition, which can be roughly divided into normal flow condition, transitional flow condition and no flow condition according to the flow rate. It should be noted that the input power parameters of the pump in pump intake were constant during this process, and the rotating speed was maintained at 1310 rpm. The performance parameters of the pump are listed in Table 2.

Table 2. Parameters of the test pump.

| Parameter    | Value    | Unit |
|--------------|----------|------|
| Flow rate $Q$ | 0-22.3   | m³/h |
| Power $P$    | 1.1      | kW   |
| Head $H$     | 10       | m    |
| Efficiency $\eta$ | 69% | -    |
| NPSHR        | 2.5      | m    |
| Rotating speed $n$ | 0-2900 | r/min |
| Voltage $U$  | 380      | V    |
| Frequency $f$ | 50       | Hz   |

On the other hand, in order to create a better reference, water level and flow rate are transformed into dimensionless parameters, water level $WL=H_1+H_2$, where $H_1$ is a constant value, $H_2$ is a variable of water level, which is obtained by the laser liquid-level measurement system. The relevant transformation rules as following

$$WL^* = \frac{WL}{d},$$

where $WL^*$ is the dimensionless water level, $WL$ is tested water level, and $d$ is the inner diameter of the pump pipe.

$$Q^* = \frac{Q}{Q'},$$

where $Q^*$ is the dimensionless measured flow rate, $Q'$ is the measured flow rate, and $Q$ is the reference standard flow rate, here $Q'$ is 10.08 m³/h. The experimental conditions are listed in table 3.
Table 3. Experimental conditions.

| Case | Dimensionless water level ($WL^*$) | Reference standard flowrate ($Q$ m$^3$/h) |
|------|-----------------------------------|------------------------------------------|
| 1    | 7.57                              |                                          |
| 2    | 5.46                              | 10.08                                    |
| 3    | 5.31                              |                                          |
| 4    | 5.15                              |                                          |
| 5    | <5.15                             |                                          |

2.3. Experimental procedure

In the experimental process, first, the water level was confirmed. After the water level reaches the interested value, the operational test should be 20 minutes at least. In this procedure, observe the experimental phenomenon, confirm its repeatability and reliability, then use high-speed photography technology to record the relevant hydraulic phenomena. Meanwhile, the flow rate, input power, rotating speed and other important operating parameters of the pump were collected. In order to verify the reliability and repeatability of each case of experimental phenomena and related parameters, the experiments under each case were run several times. The ultrasonic flowmeter, laser liquid-level measurement system, and the frequency converter controller system were applied in the present experiment, which measurement error is within 2%, 0.1%, and 1%, respectively. Besides, other experimental system errors can be controlled within the minimum range, which is deemed to be less than 2%.

3. Results and discussions

In this section, the curve of $Q^*$ with $WL^*$ is given first, which is intended to help the readers have an overall understanding of the performance of the pump under the overall framework. Then the three selected representative cases are analysed and explain the complex flow phenomena in pump intake and the pump inlet in detail.

3.1. Variation of $Q^*$ with $WL^*$

The evolution process of $Q^*$ of the pump with $WL^*$ is given in Fig. 3. When $WL^* \geq 5.46$, the flow parameters of the pump are the same as the reference flow parameters, i.e. $Q^*=1$, which indicated that the complex vortex flow patterns in pump intake have little impact on the performance of pump under these conditions, and it is not obvious through $Q^*$. When the lower the water level, $WL^*=5.31$, but the input power and rotating speed of the pump unchanged, the performance parameters of the pump begin to decrease. At the same time, $Q^*$ falls between 0.89 and 0.99, the operation of the pump starts to unstable, and the noise of the pump increase. Continue to reduce the water level, when $WL^*=5.15$, the performance parameters of the pump continue to decrease. Meanwhile, $Q^*$ drops between 0.79 and 0.90. The performance of the pump decreases deeply, the operation and the flow parameter instability rise sharply, the noise is noticeable, meanwhile, it can be identified that bubbles are sucked into the pump. Finally, when $WL^*<5.15$, the pump no longer successfully pumps the water, i.e. $Q^*=0$, although the impeller continues rotating, and the input power unchanged. Then, the tangible effect of the pump is zero.
3.2. Case 1: \( WL^* = 5.46 \)

When \( WL^* = 5.46 \), the complex flow patterns in pump intake and inlet pipeline of the pump are illustrated in Figure 4. It can be found that there are obviously free-surface vortices and sidewall-attached vortices (as shown in Fig. 4 (a)), which are related to the strong suction effect of the pump and the lower water level. For this case, a certain amount of air is sucked into the inlet of the pump, which is an obvious bubble flow in the inlet pipeline of the pump. These bubbles are sucked into the pump, which does not have a significant impact on the \( Q^* \), but have a certain negative impact on the internal rotating parts and other parts of the pump. Due to the high flow rate, the bubble is pulled into an ellipsoid and sucked into the inlet of the pump and these ellipsoidal bubbles volume accounts for about 1/540 of the total pipeline volume, as shown in Fig. 4 (b).

Figure 3. Variation of \( Q^* \) with \( WL^* \).

(a) Complex flow in pump intake for case 1.
(b) The flow in the pump inlet pipe with a certain amount of bubbles.

**Figure 4.** Flow patterns for case 1.

3.3. Case 2: $WL^* = 5.15$

As the water level is still dropping, and $WL^* = 5.15$. At this time, the water level fluctuates violently in pump intake, a large number of bubbles are sucked into the pipe bell, and two obvious wall-attached vortices are formed on the two side walls, which are also sucked into the pipe bell (as shown in Fig. 5 (a)). Under this condition, the obvious bubble flow and two spiral vortex ropes in the inlet pipeline of the pump are captured. They are sucked into the pump, which has a serious impact on the performance of the pump, resulting in the dimensionless flow $Q^*$ of pump sharply reduced to 0.79 (as shown in Fig. 5 (b)). Besides, these obvious bubbles volume accounts for about $1/7$ of the total pipeline volume.

![Image of complex flow in pump intake for case 2.](image)

(a) Complex flow in pump intake for case 2.

![Image showing flow direction and vortex ropes.](image)

(b) The flow in the pump inlet pipe with two spiral vortex ropes.

**Figure 5.** Flow patterns for case 2.

3.4. Case 3: $WL^* < 5.15$

When $WL^* < 5.15$, firstly, the water is sucked into the pipe bell gradually (as shown in Fig. 6 (a)), in this process, the water level gradually starts to decrease, and the free-surface vortex and sidewall-attached vortex are formed in pump intake (as showed in Fig. 6 (b)), furthermore, as the water level continues to drop, the fluctuation of the water level becomes more intense, resulting in a large number of bubbles being sucked into the pipe bell. At the same time, there are two more violent sidewall-attached vortices on both sidewalls, which are sucked into the pipe bell (as shown in Fig. 6 (c)). Subsequently, due to the increase of accumulated air volume in the pump, the flow parameters of the pump decreased significantly, and the water was no longer pumped, after then, the air reflux occurs, as shown in Figure 6 (d). Finally, after 3 to 4 rounds of the above process, the pump stops pumping water, the water in pump intake is stable, and the free surface returns to calm.
Figure 6. The evolution process of complex flow patterns in pump intake for case 3.

Finally, although the pump impeller rotates and the input power is constant, the pump no longer pumps the water. At the same time, a certain amount of air is staying in the inlet pipeline of the pump, and the air volume accounts for about 1/6 of the total pipeline volume, as shown in Figure 7.

Figure 7. Static flow in the inlet pipe with a large amount of air.

4. Conclusion

In the present paper, the relationship between water level, the performance of the pump and various complex hydraulic phenomena in pump intake is investigated by model test, and the relevant reasons are analyzed.

The results show that under the condition of $WL^*=5.46$ and higher, the influence of water level on the performance of the pump can be ignored, and the operation of the pump is stable. When the water level is reduced, $WL^*=5.31$, $Q^*$ decrease between 0.89 and 0.99, the performance of the pump becomes unstable, and the noise of the pump begins to increase. When $WL^*=5.15$, the performance of the pump decreases deeply, $Q^*$ drop between 0.79 and 0.90, and the noise is obvious. Finally, when $WL^*<5.15$, the water in pump intake is first sucked into the pipe bell, the water level is falling and accompanied by free-surface vortex and sub-surface vortex. At last, the performance of the pump is reduced, no longer pumping water, and the phenomenon of air reflux occurs, and the free surface is restored to be
calm. This evolution is repeated several times. Finally, a certain amount of air is stored in the inlet pipeline of the pump, and the gas volume accounts for about 1/6 of the entire pipeline volume.

The experimental results obtained in the present paper provide an important reference for the safe operation of the pump in pump intake in various pump stations.

5. References

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