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PIV experiment of the unsteady flow field in mixed-flow pump under part loading condition

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ABSTRACT

In order to study the rotor-stator interaction mechanism in impeller and guide vanes of mixed-flow pump under part loading condition, the flow field between the impeller outlet and the guide vane inlet under part loading condition was measured based on Particle Image Velocimetry (PIV). Besides, the relative velocity distribution along the monitoring lines in the impeller inlet and outlet sections, the relative velocity distribution and the vorticity distribution of interference field were analyzed under 0.2 times of the design flow condition at different phases. The results showed that at 0.2 times of the design flow rate, the internal flow between impeller and guide blades is affected by the rotor-stator interaction and as a result, the internal flow is disordered, conspicuous backflow and vortex flow occurred at different phases. The positive vortex structure and the reverse vortex structure both exist in the interaction zones, but the former exists near the wall while the latter exists near the hub. With the change of phase angle from impeller blade leading edge to impeller blade trailing edge, the positive vortex structure strength increases while the reverse vortex structure strength is reduced first and then increased. The relative velocity distributions at different phases in the monitor line near the guide vane inlet, due to the rectifying action of guide vane, are similar and steady. The closer the monitoring line to the impeller inlet, the more disordered the relative velocity distribution at different phase is, and the more conspicuous the rotor-stator interaction is. The maximum relative velocity difference can reach about 5 m/s on the same place at different phases. All these phenomena indicate that the rotor-stator interaction is the major source of the unsteady flow field at the part loading condition. The research results provide significant reference value for revealing the internal flow characteristics under part loading condition as well as for optimization of mixed-flow pump.

1. Introduction

Mixed-flow pump, which integrates advantages of centrifugal pump and axial-flow pump, is widely applied in hydraulic engineering, agricultural irrigation, urban water supply and drainage system and other aspects [1–4]. With the continuous expansion of its application fields, mixed-flow pump is usually running at off-design conditions. When mix-flow pump is running at off-design conditions, especially when under part loading conditions, pump vibration and noise are significantly increased, which not only affects the performance of the pump, but also have an important impact on the safety and stability of the pump unit.

Unsteady flow inside fluid machines has been proved to have grate impact on the pump performance like the efficiency and the reliability of the hydraulic system. Fluid-dynamic impact may excite severe noise and vibration in the fluid machinery, and hence, researchers show great interest in the characteristic of the internal flow phenomena. The research in the past mainly focus on the performance under designed flow condition, either by experimental or numerical approaches, while the understanding of the unsteady flow under part-load conditions, especially about the influence of rotor-stator interaction on the pump performance, is still not enough. Zhang et al. [5] numerically studied the unsteady flow in a centrifugal pump impeller at off-design condition using particle image velocimetry (PIV) and a kind of hybrid RANS/LES turbulence modeling method. A “two channel” non-uniform flow structure was captured by both PIV and numerical simulation. Feng et al. [6] researched the unsteady flow in a radial diffuser pump at part-load conditions by PIV and CFD, it is found that a low-velocity region appears on impeller suction side at $0.75Q_{des}$ and the steady flow separation develops on the impeller suction side at $0.5Q_{des}$. Currently, several investigations on the impacts that rotor-stator interaction has on pump performance have been conducted over the years and have got some achievement. Arndt [7]

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Nomenclature

Value	Structure parameter	Value	Performance parameters
Q_{des}	the design flow rate, m^3/h	Z_g	blade number of guide vane
H	pump head, m	D_1	pump inlet section diameter, mm
n	rotate speed, r/min	D_4	pump outlet section diameter, mm
n_s	specific speed	T	shooting section phase
Z	Blade number of impeller	X	the horizontal coordinate value
Y	the longitudinal coordinate value		

conducted an experimental investigation of rotor-stator interaction within a centrifugal pump having several vaned diffusers, under conditions of different flow coefficients and different radial gaps between the impeller blade trailing edge and the diffuser vane leading edge. The largest pressure fluctuations on the diffuser vanes and the impeller blades were found to be of the same order of magnitude as the total pressure rise across the pump. Parrondo [8] presented an experimental investigation and analyzed the unsteady pressure distribution existing in the volute of a conventional centrifugal pump. The results clearly showed the leading role played by the tongue in the impeller-volute interaction and the strong increase in the magnitude of dynamic forces and dipole-like sound generation in off-design conditions. Zhang [9] developed the experimental and computational study for unsteady hydrodynamic forces on a diffuser pump impeller excited by the interaction between the impeller and the vane diffuser with the same number of vanes as impeller. It was demonstrated that the fluid forces on the impeller with the same number of vanes as the vane diffuser are smaller compared with other combinations of vane numbers. Zhang et al. [10] studied the instantaneous flow dynamics induced by rotor-stator interaction under the stable operation of centrifugal pumps using the Large Eddy Simulation (LES) method. The results showed that rotor-stator interaction is dominated by vortex shedding in the wake of the blade trailing edge and their impingement on the volute tongue with subsequent cut-ting and distortion. The influence that rotor-stator interaction between vane and blade has on flow field in axial flow pump was investigated by Zhang [11] through numerical simulation test and experiment. The results indicated that the direction is just from rim to hub, as is affected by the location of the intersection line of the shooting section and the impeller blade on the impeller as well as the angle between the intersection line and the rotating shaft. Also, Shi et al. [12] studied pressure fluctuations at different locations in mixed-flow pump and movement stability of apparatus analytically, as well as flow-induced vibration and noise under interference conditions. Batailly [13] introduced a numerical-experimental comparison in the simulation of rotor-stator interaction through blade-tip/abradable coating contact based on a numerical strategy developed previously. Numerical results suggested an alteration of the abradable mechanical properties in order to explain the outbreak of a divergent interaction. Javadi [14] carried out a series of numerical simulations to study a highly swirling turbulent flow generated by rotor-stator interaction and the results show the flow contains a strong disintegration of the vortex rope which is predicted well by the hybrid RANS-LES models. Due to the special configuration of mixed-flow pump, very few experiments have investigated its rotor-stator interaction flow field under part loading conditions [15,4,16].

Particle Image Velocimetry (PIV) is a modern display technology which combines laser technology, modern optical, electronic technology and information processing technology, it can operate quantitative measurement as well as qualitative display. PIV can obtain the entire flow information about observation domain within a certain time, and then the flow field velocity vectors distribution can be known. As a result, PIV has been widely used in real-time display and inside flow state in centrifugal pumps. PIV measurement under design flow condition was performed by Wu et al. [17], and the results show that using fluorescent particles can get a clearer picture of flow field. Besides, they also use DES numerical method to verify the correctness of the measurement results. Shi et al. [18] conducted numerical simulation and PIV experiment to investigate the flow field under high load inside the guide vanes. Yang et al. [19] measured the flow field in rotating impeller which near volute tongue of centrifugal pump using a two-dimensional PIV, the results show that the volute tongue has the greatest impact on the internal relative velocity field of centrifugal impeller under part loading condition. Chen [20] focused on numerical calculations of low specific speed submersible sewage pumps and the internal flow field was measured by means of a 2D-PIV under different operating conditions. The experimental results show that the relative velocity on the blade suction surface near the blade inlet is larger than that on the blade pressure surface while this velocity profile is reversed near the blade outlet due to the Coriolis effects. Xi [21] manufactured a mixed-flow pump with unshrouded impeller and measured the flow in the impeller at design and off-design flow rates by particle image velocimetry (PIV). Back-flow was found near casing and mid-span sections at partial flow rate. The velocity distribution in different impeller passages was similar. Shao [22] used Particle image velocimetry (PIV) technology to study steady and unsteady internal flow fields in a molten salt pump under both internal and external synchronization modes. They concluded that the relative velocity near the impeller suction surface is higher than that near the pressure surface.

The previous studies provide significant contribution to the understanding of the complicated internal flow of pumps as well as the effect of the flow rate conditions on the pump performance. However, these PIV studies mainly focus on the flow inside the impeller and the guide vane of the pumps. The flow characteristic in the rotor-stator interaction region is still not clear, since the numerical simulation has its own limitations to give convincing predictions for flow fields in such intensively turbulent conditions. Besides, the study about the effect of the rotor-stator interaction on the pump performance is still not enough, especially under the part-loading conditions.

In this study, the unsteady flow field caused by rotor-stator interaction in mixed-flow pumps is investigated based on Particle Image Velocimetry. In addition, the relative velocity distributed along monitoring lines was obtained in post-processing to analyze the spatial distributions of such flow field in different phases of mixed-flow pump impeller under part loading conditions.

2. Model

2.1. Physical model

Fig. 1 shows the geometry structure of the pump under investigation, which consists of an impeller with 4 blades, a vaned