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The influence of the flow rate on periodic flow unsteadiness behaviors in a sewage centrifugal pump*

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Abstract: To design a single-blade pump with a good performance in a wide operational range and to increase the pump reliability in the multi-conditional hydraulic design process, an understanding of the unsteady flow behaviors as related with the flow rate is very important. However, the traditional design often considers only a single design condition, and the unsteady flow behaviors have not been well studied for single-blade pumps under different conditions. A comparison analysis of the flow unsteadiness behaviors at different flow rates within the whole flow passage of the pump is carried out in this paper by solving the three-dimensional unsteady Reynolds-averaged Navier-Stokes equations with the Shear Stress Transport (SST) turbulence model. A definition of the unsteadiness in the pump is made and applied to analyze the unsteady intensity distributions, and the flow rate effect on the complex unsteady flow in the pump is studied quantitatively while the flow mechanism is also analyzed. The CFD results are validated by experimental data collected at the laboratory. It is shown that a significant flow rate effect on the time-averaged unsteadiness and the turbulence intensity distribution can be observed in both rotor and stator domains including the side chamber. The findings would be useful to reduce the flow unsteadiness and to increase the pump reliability under multi-conditions.

Key words: flow rate effect, flow unsteadiness, turbulence intensity, sewage centrifugal pump, multi-conditions

Introduction

Due to the Rtor-Stator Interaction (RSI), the flow around the impeller of a single-blade centrifugal pump produces a strongly asymmetrical unsteady effect at both Best Efficiency Point (BEP) and other operating points. This phenomenon, therefore, leads to a periodical hydrodynamic force acting on the impeller surface and results in strong rotor vibrations[1]. The RSI effect in centrifugal pumps was investigated numerically and experimentally. Feng et al.[2-6] investigated the RSI effect in a radial diffuser pump by a comparison among CFD calculated results, PIV and LDV measurement results, and indicated that the RSI has two kinds of effects on centrifugal pumps with diffusers. The first is the downstream effect of the impeller on the stator flow, which is characterized by unsteady effects due to the highly distorted relative impeller flow field and impeller wakes, the second is the upstream effect of the stator on the impeller flow, which causes unsteady pressures on the relative flow and velocity fluctuations.

Studies of single-blade pumps were carried out by using numerical and experimental methods. Benra et al.[7] presented an investigation of the periodic unsteady flow in a single-blade pump by using the CFD simulation and PIV measurement methods. The results of transient numerical simulations compare very well with the velocity measurements, but this is only true when all flow details are included into the numerical calculation. Pei et al.[8] investigated the flow-induced vibrations of the single-blade sewage water pump impeller under off-design conditions using numerical and experimental methods. Different strategies of the partitioned fluid-structure interaction simulation for a single-blade pump impeller were studied, and results obtained by one-way and two-way coupling strategies were compared and analyzed[9]. Pei et al.[10] evaluated the transient pressure variation in a single-blade pump

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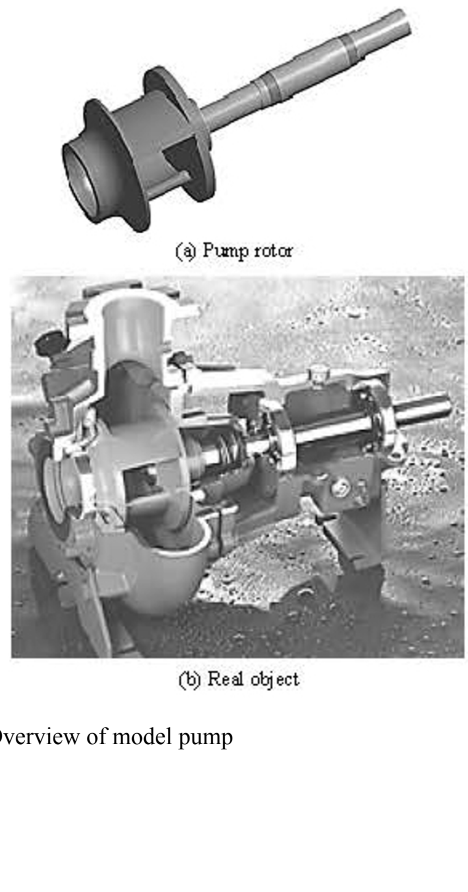
under multi-conditions by defining the standard deviation of the pressure fluctuation in a revolution period. De Souza et al.[11] focused on the optimization of single-blade impeller hydraulics from the perspective of both the performance and the solid handling ability by numerical simulations. Yasuyuka et al.[12] proposed a method of designing a single-blade centrifugal impeller for which the passed particle size is specified based on CFD analysis. De Souza et al.[13] addressed the volute design as applied to single-blade impeller pumps. Keays and Meskell[14] carried out a numerical study of a single-vanned waste-water pump using the commercial CFD software.

However, the unsteady flow field and the turbulence behavior caused by the RSI should be analyzed for single-blade pumps under different operational conditions, because the pump is not often running only at the design flow rate. The comparison analysis of flow unsteadiness behaviors under different running conditions is important to gain an insight of the complex flow in the pump and to design a single-blade pump with better performance for a wide range of reliable operations.

This paper focuses on a comparison analysis of flow unsteadiness behaviors under different flow rates for a single-blade centrifugal pump in the whole flow passage. The periodic flow unsteadiness results under different conditions are quantitatively compared by defining the unsteady intensity and the turbulence intensity in both impeller and volute, which can improve the understanding of the impeller-volute interaction in single-blade pumps as related with the flow rate.



(a) Pump rotor

(b) Real object

Fig.1 Overview of model pump

1. Computational model and method

A commercial single-stage single-suction horizontal centrifugal pump with a single-blade impeller is selected as the calculation model. An overview of the pump rotor and the test pump is shown in Fig.1. The design parameters of the pump are listed in Table 1.

Three-dimensional, unsteady Reynolds-averaged Navier-Stokes equations are solved using the Shear Stress Transport (SST) turbulence model. The structured grids for computational domains are generated using the grid generation tool ICEM-CFD 12.1 and the grid details are shown in Fig.2 with a total number of grid nodes of 2 182 132 for both rotating and stationary domains. The independence of the solutions from the number of grid nodes is checked by simulating the flow field with different numbers of grid nodes. The maximum non-dimensional wall distance $y^+ < 80$ is obtained in the complete flow field. Both the hub and shroud side chambers between the impeller and the pump casing are also included in the grid to take the leakage flow effect into account, as shown in Fig.3.

The discretization in space is of second-order accuracy, and the second-order backward Euler scheme is chosen for the time discretization. The interface between the impeller and the casing is set to the “transient rotor-stator” to capture the transient rotor-stator interaction in the flow, because the relative position between the impeller and the casing changes in each time step with this kind of interface. Two different coordinate systems are utilized for the rotatory and stationary domains, respectively. The inlet boundary condition is set to the total pressure in the stationary frame while the outlet condition is set to the mass flow rate, and all specific values are obtained from laboratory tests. The smooth wall condition is used for the near wall function. The chosen time step Δt for the transient simulation is 3.47225×10^{-4} s for the nominal rotating speed, corresponding to a changed angle of 3°, therefore, 120 transient results are included for one impeller revolution calculation. Within each time step, 10 iterations may be performed and the iteration stops when the maximum residual is less than 10^{-3}. The convergence criterion for the transient problem is that the result reaches its stable periodicity state, 9 revolutions of the impeller for each operational condition in this case are included. To obtain the stable numerical results, an initial value distribution of the flow parameters as exact as possible is required. To provide this starting solution, a steady calculation with the frozen rotor strategy is made.

2. Flow unsteadiness definition

The unsteady intensity and the turbulence intensity, as the indices of the flow unsteadiness, in both