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INTERNAL FLOW CHARACTERISTICS OF CENTRIFUGAL PUMP DURING CLOSING VALVE STARTUP

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ABSTRACT

To prevent power overload, centrifugal pumps are usually started with the valve closed. In view of the little research on the transient characteristics of centrifugal pumps during closed-valve start-up, this paper presents a numerical simulation of the internal flow field of a low specific speed centrifugal pump during rapid closed-valve start-up with the non-constant flow by numerical simulation techniques. The study shows that the overall internal pressure tends to increase gradually with the increase of rotating speed.

KEYWORDS: The centrifugal pump, start-up, numerical simulation, the transient characteristics.

1. INTRODUCTION

The start-up process of a centrifugal pump is an Inevitable transient process. With the expansion of the application field of cutting-edge technology, such as the launch of underwater weapons, the study of such transient performance becomes more and more necessary. Studies have shown that centrifugal pumps exhibit significant transient effects during transient operation, clearly distinguishing them from steady-state processes. Tsukamoto conducted a theoretical and experimental study of the start-up process and shutdown process of a centrifugal pump and concluded that the impulse pressure and the delay of the circulation around the vane are the main causes of the difference between transient and quasi-steady-state.[1,2] Tsukamoto et al. studied the problem of fluctuating transients when the speed of a centrifugal pump varies in a sinusoidal law. It was found that the higher the frequency of rotating speed fluctuation, the more obvious the difference between transient and quasi-steady states.[3] Lefebvre and Barker conducted an experimental study of the acceleration and deceleration transient processes of a mixed flow pump and showed that the quasi-steady-state assumption is not reliable in predicting the transient performance of the pump.[4] Thanapandi and Prasad conducted an experimental study of the transient characteristics of a worm-cylinder pump at different valve openings under normal start-up and shutdown situations and found that the ordinary transient operating process satisfies the quasi-steady-state assumption, while they analyzed the transient effects for the first time using the characteristic method.[5] Antoine Dazin et al. proposed a method that adopted angular momentum equation and energy equation to predict the internal torque, power, and head of the impeller under transient operating conditions, and showed that transient effects are related to the evolution of the flow field in addition to the acceleration magnitude and flow magnitude.[6] Tanaka and Tsukamoto conducted an experimental study on the cavitation performance of centrifugal pumps during the processes of valve closing, valve opening, start-up, and shutdown. It is found that during valve closing and valve adjustment the non-constant pressure and flow rate are related to cavitation, and the fluctuation of pressure and flow rate is related to cavitation fluctuation or water flow separation. Transient behavior is classified according to the increase or decrease of the flow. The transient behavior during valve opening and start-up processes is very different from the transient behavior during valve closing and shutdown processes.[7-9] In China, a few scholars have also started numerical simulations and experimental studies on the start-up process of centrifugal and mixed-flow pumps, and also found that the process exhibits obvious transient effects. However, the above study was basically carried out with the outlet valve at a certain opening. But for some high-power pumps, in order to prevent power overload at startup, often need to close the valve to start, and there are not many papers on the pump in the closed valve startup research. This paper proposes to present a numerical simulation with the non-constant flow of the internal flow field of a low specific speed centrifugal pump during rapid closed-valve start-up by numerical simulation techniques and expects that the basic characteristics of changes in this transient process will be initially grasped to provide guidance for the study of starting characteristics of various rotating machines.

2. NUMERICAL SIMULATION METHODS

2.1 Computational model

The pump used in the numerical simulation is a low specific speed centrifugal pump with a specific speed of 45. The design parameters and main dimensions of the centrifugal pump are shown in Table 1, blade molded lines adopt double arc cylindrical form, and the volute size change rule adopted Archimedes spiral form, $R = 0.0825 + 0.015\theta / 360$ (m), θ is the spiral angle starting from the baffle tongue.

Table 1: Description of centrifugal pump parameters.

D_i / mm	50	β_2	25°
D_o / mm	40	β_1	25°
d_2 / mm	160	Z	5
b_2 / mm	10	n / rpm	1450
d_1 / mm	48	$Q / m^3 \cdot h^{-1}$	6
b_1 / mm	20	H / m	8

2.2 Grid division

GAMBIT software was used for grid division, except for the pump inlet where a hexahedral mesh was used, all other areas were unstructured tetrahedral mesh. After checking, the equal angle slope and equal size slope of the grid are both less than 0.85, and the quality of the grid is good. The number of model meshes was checked for correlation and it was found that the mesh irrelevance requirement was considered to be met when the variation of the calculated external characteristics was less than 2%, and the total number of meshes in the final calculation domain was 508792. This grid number is not sufficient for simulating the flow in the boundary layer, but it is sufficient for the prediction of the external characteristics and the distribution of macroscopic physical quantities in the internal flow field. Figure 1 shows the mesh division of the computational domain, for better display of the blade surface mesh, the front cover mesh is not shown on the right impeller.

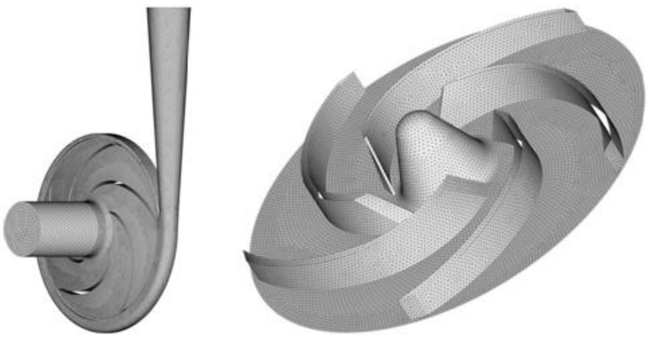

Figure 1: Computational grid.

2.3 Solution Controls

Numerical computation of three-dimensional, incompressible, non-constant, viscous fluids using FLUENT 6.3, a commercial computational software based on the finite volume method. During the start-up process, the Reynolds number changes rapidly from zero to millions, the flow changes rapidly from laminar flow in the initial stage to turbulent flow, and the flow modal changes are very large. This paper uses the RNG turbulence model of the Vortex sticky model, which was proposed by Yakhot and Orzag in 1986 and has been proven to be very effectively suitable for the internal flow of the pump, and it can better handle flows with high strain rates and a larger degree of streamline curvature. The impeller rotating speed variation is loaded using a user-defined function. According to some information, the motor rotating speed changes during the start-up process is approximately rising exponentially

$$n = n_{\max}(1 - e^{-t/t_0}) \qquad (1)$$

Where $n_{\max}$ is the maximum rotating speed, which is 1450rpm in this article, $t_0 = 0.15\,\mathrm{s}$.

The volume conservation equation, continuity equation, and momentum equation for a non-constant non-compressible viscous flow in integral form within an arbitrary control volume V surrounded by a moving boundary S are

$$\frac{d}{dt}\int_V \boldsymbol{Q}\mathrm{d}V + \int_S \boldsymbol{F}\cdot\mathrm{d}S = \int_S \boldsymbol{D}\cdot\mathrm{d}S + \int_V \boldsymbol{S_u}\mathrm{d}V \quad (2)$$

Where $\boldsymbol{Q}$ is the conserved quantity, $\boldsymbol{F}$ is the convective flux, $\boldsymbol{D}$ is the diffusive flux, and $\boldsymbol{S_u}$ is the source term, which is denoted as follows

$$\boldsymbol{Q} = \begin{bmatrix} 1 \\ \rho \\ \rho\boldsymbol{u} \end{bmatrix}, \quad \boldsymbol{F} = \begin{bmatrix} -\boldsymbol{u}_\mathrm{b} \\ \rho(\boldsymbol{u} - \boldsymbol{u}_\mathrm{b}) \\ \rho\boldsymbol{u}(\boldsymbol{u} - \boldsymbol{u}_\mathrm{b}) \end{bmatrix} \qquad (3)$$

$$\boldsymbol{D} = \begin{bmatrix} 0 \\ 0 \\ \mu\nabla^2\boldsymbol{u} \end{bmatrix}, \quad \boldsymbol{S_u} = \begin{bmatrix} 0 \\ 0 \\ -grad\ p \end{bmatrix} \qquad (4)$$

Where ρ is the density of the fluid, $\boldsymbol{u}$ is the motion velocity of the fluid, $\boldsymbol{u}_\mathrm{b}$ is the motion velocity of the boundary in the dynamic grid, μ is the dynamic viscosity of the fluid, and p is the pressure of the fluid. In this paper, the spring approximation model and mesh reconstruction are used to achieve the dynamic mesh update, and the best solution effect can be achieved by adjusting several control factors in it.

Zero through-flow due to valve closure. In this paper, we still use velocity inlet condition and free outflow boundary condition. Considering the stickiness reason, the no-slip boundary condition is used at the wall, and the standard wall function method is used in the low Reynolds number region near the wall to deal with the problems caused by the high Reynolds number turbulence model. The time discretization of the transient term is in first-order implicit format, the spatial discretization of the convection term is in first-order windward format, the spatial discretization of the diffusion term is in central difference format with second-order accuracy, and the spatial discretization of the source term is in a linearized standard format. The coupling of velocity and pressure is realized by the SIMPLE algorithm. All variables in the iterative calculation use the default under-relaxation factor. The time step is 0.001s, and the start-up time is 1s. The maximum number of iterations in each time step is set to 40 (Actual calculations show that this setting ensures computational convergence in each time step), and the residual convergence accuracy is 0.001.

3. ANALYSIS OF RESULTS

3.1 External characteristic prediction

In the radial centrifugal pump, the direction of fluid movement will change significantly, and the resulting dynamic reaction force will become an important part of the axial force, Figure 2 gives the rise of the dynamic reaction force during the start-up process. At the start-up time t <0.2s, the overall trend of dynamic reaction force rise, probably due to the initial start-up the numerical calculation error, and weaker dynamic and static interference effects; At 0.2s< t <0.5s, the dynamic reaction force volatility rises more smoothly; At 0.5s < t < 1.0s, the dynamic reaction force shows a more periodic fluctuation characteristic.

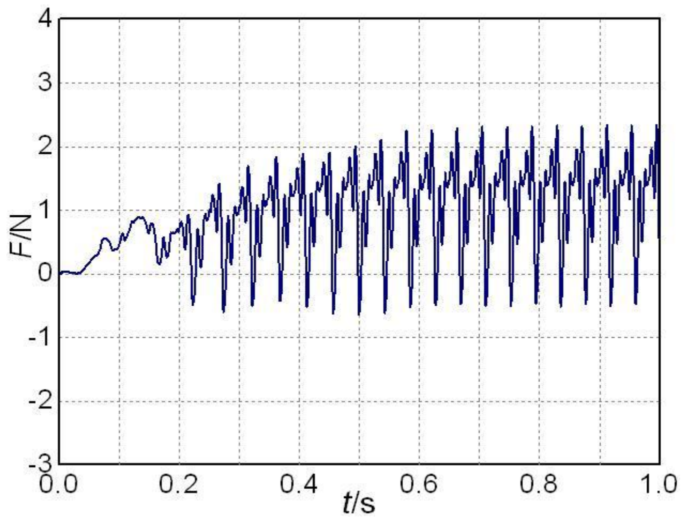

Figure 2: The time history of the impeller dynamic reaction force rising.

3.2 Flow field analysis

During start-up, the rotating speed is accelerated sharply, resulting in a rapid increase in the internal pressure as well. Figure 3 shows the evolutionary results of total pressure at the mid-section location at different moments of the start-up process. As the rotating speed increases, the overall internal pressure also shows a gradual increase trend, which is similar to the real situation. At arbitrary moments, the ordinary laws within the pump are present. For example, at the same radius, the lateral pressure on the pressure side is higher than the lateral pressure on the suction side; The pressure gradually increases from the inlet to the outlet; The low-pressure area at the inlet makes the pump most prone to cavitation, etc. As the rotating speed increases, the central pressure gradually decreases, and the possibility of cavitation is greater.

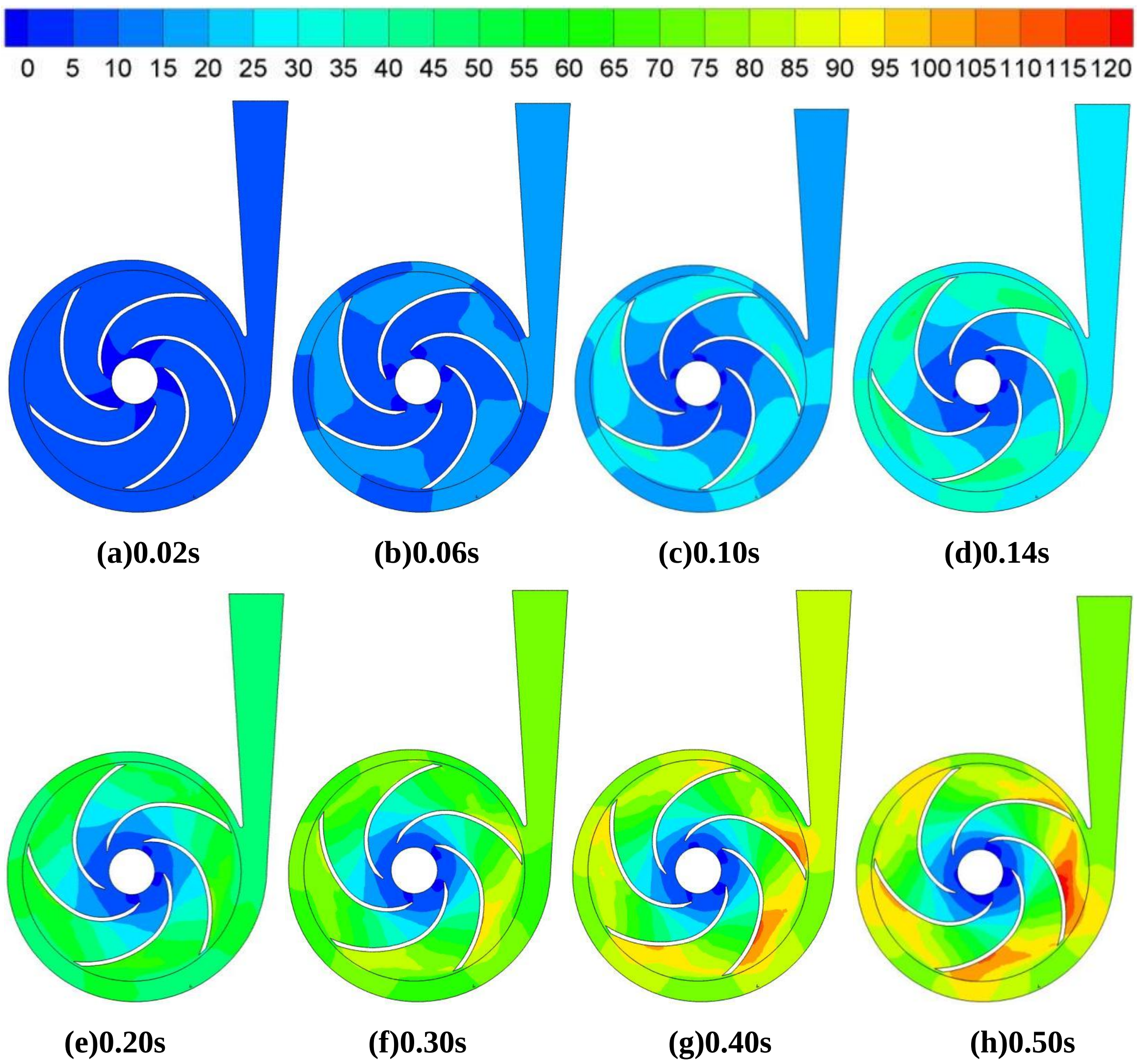

Figure 3: Time history of total pressure evolution during start-up.

4. CONCLUSION

As the rotating speed increases, the overall internal pressure also shows a gradual increase trend, which is similar to the real situation. At arbitrary moments, the ordinary laws within the pump are present. The current study is only a preliminary start-up calculation model, there are still many problems, such as the adoption of approximate speed variation law, whether the selection of turbulence model is the most appropriate, whether the solving control is the most economical, and the complete model including the front and rear cavity and clearance is considered for solving, etc.

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