Numerical simulation of the cavitation characteristics of a mixed-flow pump

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Abstract. As a kind of general equipment for fluid transportation, pumps were widely used in industry which includes many applications of high pressure, temperature and toxic fluids transportations. Performances of pumps affect the safety and reliability of the whole special equipment system. Cavitation in pumps cause the loss of performance and erosion of the blade, which could affect the running stability and reliability of the pump system. In this paper, a kind of numerical method for cavitation performance prediction was presented. In order to investigate the accuracy of the method, CFD flow analysis and cavitation performance predictions of a mixed-flow pump were carried out. The numerical results were compared with the test results.

1. Introduction

As a kind of general equipment for fluid transportation, pumps were widely used in industry which includes many applications of high pressure, temperature and toxic fluids transportations. Performances of pumps affect the safety and reliability of the whole special equipment system. Cavitation in pumps always causes the loss of performance and erosion of the blade, which could affect the running stability and reliability of the pump system.

Recently, studies on hydraulic model design and performance improvement of large flow rate mixed-flow pumps has been carried out widely1-6. Cavitation performance improvement of large hydraulic machinery such as pump and turbine has been a hot topic for decades. Wu and Zhang7-8 has been studied the cavitation characteristic of high speed mixed-flow pump during rapid starting-up process by using experimental methods. Van Os M J9 analysed the blade parameters which may affect the cavitation performance. Wu10 discussed the cavitation characteristics of mixed-flow pump during starting period and the relations between cavitation performance and flow rate, rotational speed.

In this paper, a kind of numerical method for cavitation performance prediction was presented. In order to investigate the accuracy of the method, CFD flow analysis and cavitation performance predictions of a mixed-flow pump were carried out. The numerical results were compared with the test results.

2. Physical model and numerical method

2.1. Pump and test rig
The hydraulic performance and cavitation characteristics of a mixed-flow pump were predicted by using the CFD method. The specific speed of the pump \( n_s \) was equal to 387. The parameters of the pump were showed in table.1. The structure and computational grid were shown in figure.1. In order to evaluate the accuracy of the numerical results, the steady state hydraulic and cavitation performance tests were carried out. The structure of the performance test rig was showed in figure.2. The test rig was an open type recycles system which consists of gate valves, pipes, cistern, pump, flow meter, torque and speed sensor, pressure transducers and data collection system.

**Table 1. Specifications of mixed-flow pump.**

| Geometric Specifications | Hydraulic Specifications |
|--------------------------|--------------------------|
| Suction diameter 300 (mm) | Rotate Speed 980rpm |
| Outlet diameter 300 (mm) | Flow rate 0.21 (m³/s) |
| Impeller diameter 341 (mm) | Total head 7 (m) |
| Specific speed 387 | Efficiency 83% |
| Number of vanes 4 | NPSH 3.5(m) |

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

1. inlet 2. inlet valve 3. inlet pressure transducer 4. outlet pressure transducer 5. mixed-flow pump 6. torque and speed transducer 7. motor 8. flow meter 9. outlet valve 10. outlet 11. water tank

**Figure 2. Installation diagram of the test rig system.**

2.2. Numerical method
In the present study, the multi-reference frame (MRF) and Standard k-\( \varepsilon \) turbulent model were used to describe the rotational turbulent flow while No-slip boundary condition was used at walls. The pressure-velocity coupling is calculated through the SIMPLE algorithm. Second order upwind scheme with numerical under-relaxation is applied for the discretization of convection term and central
difference schemes for diffusion terms. Velocity inlet and pressure outlet boundary conditions were adopted to simulate the inlet and outlet of the computational domain of the axial-flow submersible pump system. Mixture multi-phase flow model were adopted to simulate the cavitation in the pump.

3. Results and discussions

3.1. Hydraulic performance

The steady state performance under five different rotate speeds was tested and the test data were compared with the numerical results, as shown in figure 3. It can be seen from figure 2 that the numerical results meets well with the test results and the numerical method could predict the hydraulic characteristics accurately.

![Figure 3. Steady state Q-H performance under different rotational speeds of the mixed-flow pump.](image)

![Figure 4. Cavitation characteristic curve of the mixed-flow pump \(Q_o=0.21 \text{ m}^3/\text{s}\).](image)

3.2. Cavitation performance

The NPSH\(_c\) of the pump under design flow point \(Q_o=0.21 \text{ m}^3/\text{s}\) was predicted and the cavitation characteristic curve was shown in figure 4. It can be seen from the figure that, with the decreasing of NPSH\(_a\), the total height dropped slowly first and then dropped sharply. The NPSH\(_c\) of 3% height drop was predicted as 3.6 meters which was close with the test result of 3.5 meters.

![Figure 5. Shows the pressure distribution of the blade surfaces under different NPSH\(_a\).](image)

Figure 5 shows the pressure distribution of the blade surfaces under different NPSH\(_a\). From the graphs show, low pressure areas obviously exist on the suction side of the blade surface. With the decreasing of NPSH\(_a\), the pressure of low pressure region dropped gradually until close to the saturated vapor pressure of water. Cavitation occurred and the cavitation region grew obviously.

\[ NPSH_a=5.6\text{m} \quad NPSH_a=5.0\text{m} \quad NPSH_a=4.7\text{m} \]
Figure 5. Static pressure distribution on the blades of mixed-flow pump under different NPSH.<n>NPSH_a = 3.5m  \hspace{1cm} NPSH_a = 3.2m  \hspace{1cm} NPSH_a = 2.9m  
(a) Pressure surface  

NPSH_a = 5.6m  \hspace{1cm} NPSH_a = 5.0m  \hspace{1cm} NPSH_a = 4.7m  
(b) Suction surface

Figure 5. Static pressure distribution on the blades of mixed-flow pump under different NPSH_a.

The distribution of the surface of cavitation clouds in the pump were showed in figure 6. The red surface stands for the isosurface of vapor phase volume fraction equal to 80 percent. Figure 5 shows that the cavitation clouds were located at the suction surface of the blade which near the leading edge. With the decreasing of NPSH_a, the cavitation clouds grew and blocked the passage of the pump impeller and inlet. When the cavitation developed badly, the pump performance decreased sharply and even cannot working properly.
Figure 6. Cavitation region in the mixed-flow pump under different NPSH_a

4. Conclusions
In this paper, a kind of numerical method for cavitation performance prediction was presented. In order to investigate the accuracy of the method, CFD flow analysis and cavitation performance predictions of a mixed-flow pump were carried out. The numerical results were compared with the test results. Based on the analysis of the results, we can know that the cavitation characteristics of the mixed-flow pump were properly predicted by using the numerical method adopted in this paper.

With the numerical method adopted in this paper, the cavitation characteristic curve and cavitation clouds can be predicted accurately. The numerical results of NPSH_c meet well with the test value.

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