Analysis of backflow effect in a centrifugal pump

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Abstract. Backflow might appear near the impeller inlet under low discharge conditions due to excessive pressure difference near the blade leading edge. The shear layer between the swirling backflow and the main flow rolls up and forms a backflow vortex at the impeller’s inlet. Backflow vortex cavitation occurs at the vortex core if the pressure there drops lower than vapor pressure. In order to investigate the effect of backflow on pressure, flow rate and cavity volume, the backflow phenomena for a centrifugal pump was calculated using SST k-omega turbulence model and Rayleigh-Plesset cavitation model. Results show that the general flow characteristics are correctly predicted. Furthermore, the development of cavities and backflow have been illustrated in this paper. It is also shown that the backflow occurring at the inlet of impeller significantly affects the general performance of the centrifugal pump. The generation and collapse of the cavities caused by the backflow lead to the oscillation of cavity volume, which is the main reason for large-cycle fluctuation of inlet flow rate.

1. Introduction

Centrifugal pumps are usually required to operate in a wide range of flow rate. Under low flow rate conditions, a backflow occurs near the impeller inlet due to the excessive pressure difference across the blades near leading edge. The backflow has an opposite velocity with the axial main flow and a high tangential velocity due to the rotation of the impeller. Therefore, the shear layer between the swirling backflow and the main flow rolls up and forms a backflow vortex at the impeller’s inlet. The increase of the main flow velocity owing to the displacement effect of backflow causes a pressure drop at the vortex core. Backflow vortex cavitation occurs if the pressure there drops lower than vapor pressure. In such a case, flow rate and pressure fluctuations will occur, which have negative effects on the stability of the pump system.

Most of the detailed investigations about backflow have focused on axial pumps and inducers. Yamanishi et al. [1] investigated the fundamental characteristics of the backflow vortex at the inlet of an inducer based on the LES code. Qiao et al. [2] studied the response of backflow to the flow rate fluctuation for an inducer to discuss its effect on cavitation instabilities. Yokota et al. [3] devised an experimental apparatus to observe the vortex structure caused by the main flow and swirling backflow by small air bubbles. Yamamoto [4] has observed and investigated cavitation surge occurring in cavitating centrifugal pumps. He also noticed the important role of the backflow in the dynamics of cavitation surge. Blaire et al. [5] studied the backflow near the inlet of a centrifugal pump at partial
flow rates by static pressure measurements and visualizations. Yamamoto et al. [6] discussed the energy transfer under cavitation surge in a centrifugal pump and explained the large phase lag observed in the experiments from the dynamics of backflow.

This paper presents a numerical investigation of the backflow phenomena near impeller inlet for a centrifugal pump using a commercial code CFX. The effect of backflow on pressure, inlet flow rate and cavity volume has been analyzed based on the unsteady numerical simulation of cavitating flow.

2. Simulation setup

2.1. Computational domain and grids
The calculation model is a single stage centrifugal pump with specific speed $n_s=179$, rotating speed $n=1500\text{rpm}$, design flow rate $Q_d=384\text{m}^3/$h and impeller inlet diameter $D_s=188\text{mm}$. The computational domain is divided into four regions: inlet pipe, impeller, volute and outlet pipe. Each region is discretized independently: structured grids are used for inlet and outlet pipes and unstructured grids for impeller and volute regions. The surface mesh of the pump model is shown in Figure 1.

![Figure 1](image)

Figure 1. Calculation mesh: (a) General view with inlet and outlet pipes; (b) Impeller (shroud removed); (c) Detail of the tongue region.

2.2. Physical model
In the present study, water and vapor have been used as working fluids in ambient condition. A homogeneous multiphase model has been applied for the cavitation model [7]. The Rayleigh-Plesset model has been employed to describe the growth of a gas bubble with the saturated vapor pressure of 3540Pa. Turbulence effects have been modeled with SST k-omega model and standard wall functions for the near wall flow [8]. A high resolution scheme has been used for the advection term. The second order scheme has been used for the temporal term.

2.3. Boundary conditions
Constant total pressure and mass flow rate boundary conditions have been used for the inlet and outlet, respectively. The blades and impeller walls are rotating while other walls are stationary. Interfaces between the rotational and stationary regions have been defined. The non-slip boundary condition has been imposed on solid walls.

3. Calculation Results

3.1. General cavitating characteristics
Cavitating flow has been simulated under the condition with flow rate $0.5Q_d$ and $NPSH$ (Net Positive Suction Head) 2.31m. Figure 2 shows that there are obvious fluctuations for the head, inlet flow rate
and cavity volume in the pump. All the fluctuations have a low-frequency component of about 0.3$f_n$ ($f_n$ is the impeller rotating frequency).

Figure 2. Head and inlet flow rate fluctuations.

Figure 3 and Figure 4 illustrate the general distribution of cavities inside the pump at different instants, viewing in X-Y and Y-Z plan. The parameter $z/D_s$ is the dimensionless axial distance from impeller inlet. The vapor areas in blue correspond to 5% vapor volume fraction. These images show the cavities are not only attached on blade suction side near leading edge but also appear in the inlet pipe periodically. As has been observed in previous research, the cavities inside the inlet pipe are not attached to the wall but appear as a hollow cylinder located in the shearing layer between the main flow and the reversed flow. Figure 5 shows the fluctuations of cavity volume in different parts. It is observed that the cavity volume in inlet pipe and impeller fluctuate synchronously with the total cavity volume in the pump domain.

![Figure 2. Head and inlet flow rate fluctuations.](image-url)
3.2. Backflow and pressure distribution in inlet pipe

Previous researches have been concluded that the reversed flow inside the inlet pipe plays an important role on the cavitation in inlet pipe [4,6]. Results have been also shown that the reversed flow...
length in the inlet pipe also fluctuates with the development of cavities. Figure 6 and Figure 7 show the general development of backflow. The dotted line marks the section \( \frac{z}{D_s} = 3 \). The reversed flow is located near the pipe wall and has an obvious tangential velocity component because of the rotation of the impeller.

![Figure 6](image)

Figure 6. Development of backflow streamlines during one cycle.

![Figure 7](image)

Figure 7. Backflow volume fluctuation in inlet pipe.

### 3.3. Pressure fluctuations and distribution in inlet pipe

At first, the pressure fluctuations at different locations in inlet pipe have been monitored during calculation and are plotted in Figure 8. Five points on the axial line (Figure 8a), five points on section \( \frac{z}{D_s} = 1 \) in the middle region of inlet pipe (Figure 8b) and five points on section \( \frac{z}{D_s} = 0.135 \) near the impeller (Figure 8c) have been selected, where \( r/R \) is the dimensionless radial distance and \( R \) is the radius the of inlet pipe.

![Figure 8](image)

Figure 8. Pressure fluctuations: (a) Points on the axial line; (b) Points in the middle region of inlet pipe; (c) Points near the impeller.
In the center of the pipe, the pressure reduces gradually from the inlet pipe to the impeller inlet and this characteristic dominates the main flow in the inlet pipe. In radial direction, the pressure close to pipe wall is higher than that in main flow region in both sections, due to the centrifugal force. For the radial points of $r/R=0.96$, the pressure at section $z/Ds=0.135$ is much higher than that at section $z/Ds=1$. This means there is a reversed pressure gradient in axial direction in this region which causes the backflow in inlet pipe. At the point of $r/R=0.4$, the pressure keeps constant (3540 Pa) from 0.03s to 0.09s, which means cavity occurs at this point during this period. It is meaningful to notice that the pressure at different positions fluctuates synchronously.

The pressure distribution in Figure 9 also indicate that the reversed pressure gradient in axial direction near pipe wall is the reason for the reversed flow. Furthermore, the low pressure area inside the pipe locates in the shearing area, which causes the cavitation in inlet pipe.

3.4. Axial velocity fluctuations in inlet pipe

Figure 10 shows the axial velocity fluctuations on different positions on the axial line of inlet pipe. Due to the blocking effect of backflow, the axial velocity near the impeller (at the points $z/Ds=0.4$) is larger than others. Comparing these characteristics with Figure 2, it is observed that the velocity of $z/Ds=1.47$ changes consistently with inlet flow rate, but the waveforms of the velocity at points $z/Ds=0.83$ and $z/Ds=0.4$ present certain phase difference with inlet flow rate waveform. This may be caused by the rotational momentum of impeller.

4. Discussion

During the calculation, the total pressure at inlet and the outlet flow rate $Q_2$ (the dotted line in Figure 2) is set constant, which means that the pipe acoustic response was not included in the calculation. In the
same calculating condition, if cavitation model is not included, the results show no such low frequency fluctuations and only some frequencies related to the rotation and blade passing frequency appear. It implies that such fluctuations might be related to the cavitation phenomenon in the pump. Thus a detailed analysis focused on the reason for such cavitation instability has been performed.

Figure 11 shows the relation between cavity volume changing rate $\frac{dV_c}{dt}$ and the difference between inlet and outlet flow rate $Q_2 - Q_1$. As they are roughly equivalent, it means that the law of conservation of mass is satisfied during the calculation.

**Figure 11.** Cavity volume changing rate and flow rate difference between inlet and outlet.

For this reason, there is a phase difference between cavity volume and inlet flow rate fluctuations. During the growth stage of the cavity, the inlet flow rate is less than the outlet discharge. With the collapse of cavities, the inlet flow rate is greater than outlet discharge.

Meanwhile, the intensity of backflow is greatly related to the flow rate. The decrease of flow rate will increase the region of reversed flow and vice versa. This is also clearly shown in Figure 12. The phase of backflow volume fluctuation is opposite with that of inlet flow rate. At 0.024s, the backflow streamline near the dotted line is intensive and extend to the section about $z/D_s=3.1$, as shown in Figure 6a. At this moment, the backflow volume reaches a peak and the inlet flow rate become minimum. Then the backflow volume decreases while the inlet flow rate increase. During this period, the backflow streamlines near the dotted line become few and scattered. At 0.104s, the backflow streamlines shrink backward to the section $z/D_s=2.85$, and the backflow volume falls down to a minimum while inlet flow rate reaches its maximum.

So it can be concluded that the periodic growth and condensation of cavities in the pump cause the fluctuations of flow rate and backflow.

**Figure 12.** The fluctuations of flow rate, backflow volume, inlet pressure and cavity volume.
On the other hand, the cavity growth and condensation are controlled by the pressure as can be seen in Figure 12. The cavity volume increases with the decrease of inlet pressure and vice versa. So, the relation among pressure, inlet flow rate and backflow intensity is very important to understand the periodic evolution of the cavities in the pump.

Figure 12 shows that after \( t=0 \)s (or \( t=0.124 \)s in the second cycle), with the decrease of pressure, the cavity volume begins to increase, which cause the decrease of flow rate and consequently the increase of backflow intensity. With further decrease of pressure, cavities begin to appear in the shearing layer in inlet pipe. From 0.026s, several dispersed cavities appear in inlet pipe near the main flow. Then the cavities grow and aggregate progressively and extend forward to the position \( z/D_s=0.55 \) at 0.064s when they reach the maximum volume. During this stage, the pressure in inlet pipe decreases slowly. Furthermore, the growth of cavities in the center of the inlet pipe near impeller leading edge reduces the reversed pressure gradient in this region and thus the reversed flow volume begins to decrease and the inlet flow rate starts to increase.

When the cavity volume becomes maximum, the cavities in inlet pipe reach the high pressure region. After that, cavities begin to collapse. The collapse of cavities leads to the sudden increase of local pressure. The local high pressure spreads to the low-pressure region and leads to the collapse of cavities near the impeller. The pressure oscillates intensely with high frequency during this stage of cavity evolution (from 0.026s to 0.104 s). This is due to the random growth and collapse of the cavities in shearing layer. With the decrease of cavity volume, the inlet flow rate increases and become larger than outlet discharge, which causes the decrease of backflow volume.

After the cavities in inlet pipe totally disappear, the pressure near impeller increases rapidly, which further decreases the cavity volume and lead to the increase of reversed pressure gradient. This causes the increase of backflow volume. Further increase of backflow will decrease the pressure in inlet pipe and lead to the growth of cavities. Then a new cycle will start.

5. Conclusions
In this paper, the backflow phenomena near impeller inlet for a centrifugal pump was calculated using SST k-omega turbulence model and Rayleigh-Plesset cavitation model. Large-cycle fluctuations of head, inlet flow rate and cavity volume in the pump have been predicted under the condition of \( 0.5 Q_d \) and \( NPSH=2.31 \)m. The general development of cavities and backflow region in inlet pipe is illustrated. Analysis have been made for the fluctuations of pressure, inlet flow rate and cavity volume. The results show that the backflow occurred at the inlet of impeller significantly affects the general performance of the centrifugal pump. The generation and collapse of cavities caused by the backflow lead to the oscillation of cavity volume. The oscillation of cavity volume is the main reason for the large-cycle fluctuation of inlet flow rate.

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Nomenclature

\[ NPSH = \frac{P_{in}-P_{v}}{\rho g} + \frac{v_{in}^2}{2g} \]

\( NPSH \)  
net pressure suction head (m) \( NPSH = \frac{P_{in}-P_{v}}{\rho g} + \frac{v_{in}^2}{2g} \)

\( n_s \)  
specific speed

\( n \)  
rotating speed

\( P_{inpipe} \)  
static pressure in inlet pipe (Pa)

\( P_v \)  
saturated vapor pressure (Pa)

\( H \)  
pump head (m)

\( Q_1 \)  
flow rate of pump inlet (m³/s)

\( Q_2 \)  
flow rate of pump outlet (m³/s)
\( Q_d \) design flow rate (m\(^3\)/s)

\( V_c \) cavity volume (m\(^3\))

\( V_{\text{backflow}} \) backflow volume in inlet pipe (m\(^3\))

\( D_s \) diameter of impeller inlet (m)

\( R \) radius of inlet pipe (m)

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