Research on cavitation characteristic of inducer

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Abstract: The inducer has significant effect on improving the cavitation characteristic of a centrifugal pump. The fact which can not be neglected is that the inducer itself is a kind of axial pump. Research on inducer's cavitation characteristic is very important. Several inducers were designed and modeled by Pro/E software. The mesh of flow field was done by ICEM and imported to ANSYS CFX to analyze the inducer’s cavitation characteristic. The relationship between cavity length and head breakdown was discussed. With the decrease of NPSH, there is a slight increase in the head just prior to the decrease associated with head breakdown. This conclusion coincides with experimental results. The influence of backflow eddy on the inducer's cavitation characteristic was analyzed, and the change of backflow eddy in the process of cavitation was illustrated. It can be concluded that the correlation between the inducer head breakdown and the relative cavity length is very close which agrees well with the theoretical and experimental results. As the inlet pressure is decreased, inception almost always occurs in the tip vortex generated by the corner where the leading edge meets the tip. And backflow vortex gradually disappears in the process of cavitation.

1. Introduction
Cavitation is a complex process of two phase flow, which can arouse a big interference in the flow field, and change the distribution of pressure field and flow field, and consequently change the energy characteristic of hydraulic machinery [1].

Numerical simulation of the flow field of inducer was completed by Guo Xiaomei etc. [2], they found that the clearance cavitation is the most serious, just as the axial flow pump.

When the cavitation number $\sigma$ is reduced to a value at which the head is beginning to be affected by the cavitation, the flow and pressure of the whole system will oscillate intensely. Another characteristic of auto-oscillation is that it appears to occur more readily when the inducer is more
heavily loaded; in other words at lower flow coefficients. These are also the circumstances under which backflow will occur. Indeed, Badowski (1969) puts forward the hypothesis that the dynamics of the backflow are responsible for cavitating inducer instability [3].

Yamamoto (1991) has observed and investigated auto-oscillation occurring in cavitating centrifugal pumps [4]. He also noted the important role played by the backflow in the dynamics of the auto-oscillation. The data of the cavitation surge got by Yamamoto showed that, the correlation between the auto-oscillation frequency and the relative cavity length is very close.

The relationship between the hydrofoil lift coefficient and the relative cavity length was got by Acosta in 1955 [5] by using the theory of free streamline. His experiment data in 1966 [6] showed that when the ratio of the cavity length to the hydrofoil chord length increased to a certain value, the lift coefficient broke down.

In this study, cavitation characteristics of several different types of inducers were analyzed by using CFX software. The relationship between the inducer cavity length and head breakdown was investigated, and the influence of the tip backflow eddy on the inducer cavitation characteristic was analyzed.

2. Design and modeling of inducers

Under the same flow rate and rotating speed, according to the design method of variable-pitch inducer [7], two inducers with the same tip diameter and different cascade solidities were designed, and the structural parameters were shown in table 1. On the basis of inducer 1 (of 3 blades and an leading edge wrap angle of 90°, labeled as inducer (c)), by changing the blade number and the leading edge wrap angel, inducer (a) of 3 blades and an leading edge wrap angle of 140°, inducer (b) of 2 blades and an leading edge wrap angle of 140°, and inducer (d) of 2 blades and an leading edge wrap angle of 90° were got. On the basis of inducer 2, by decreasing the inlet and outlet hub-to-tip ratio, inducer (e) was got , and inducer 2 was labeled as inducer (f). The modeling of the inducers were done by using Pro/E software, the results were shown in figure 1.

| Table 1. Structural parameters of inducers. |
|---------------------------------------------|
| 1       | 2       | 1       | 2       |
| Flow Rate $Q/m^3/h$ | 120 | 120 | Inlet Pitch $S_i/mm$ | 107 | 86 |
| Rotating Speed $n/r/min$ | 1450 | 1450 | Outlet Pitch $S_i/mm$ | 177 | 139 |
| $NPSHR/m$ | 0.5 | 0.5 | Blade Number $z$ | 3 | 3 |
| Inlet Hub-to-tip Ratio $\xi_i$ | 0.25 | 0.32 | Cascade Solidity $\tau$ | 2 | 2.5 |
| Outlet Hub-to-tip Ratio $\xi_i$ | 0.4 | 0.5 | Leading Edge Wrap Angle $\theta^/$ | 90 | 90 |
| Inlet Flow Coefficient $\varphi$ | 0.206 | 0.148 | Blade Spacing $t/mm$ | 182 | 182 |
| Cavitation Specific Speed $C$ | 1698 | 2393 | Chord length of Tip Section $l_1/mm$ | 365 | 454 |
| Tip Diameter $D/t/mm$ | 174 | 174 | Chord length of Hub Section $l_2/mm$ | 204 | 267 |
| Tip Inlet Settle Angle $\beta_{i1}/^\circ$ | 11 | 9 | Wrap Angel of Tip Section $\theta_{i}/^\circ$ | 232 | 294 |
| Hub Inlet Settle Angle $\beta_{i1}/^\circ$ | 38 | 26 | Wrap Angel of Hub Section $\theta_{i}/^\circ$ | 322 | 384 |
| Tip Outlet Settle Angle $\beta_{i2}/^\circ$ | 18 | 14 | Axial Length of Hub Section $L_2/mm$ | 127 | 120 |
| Hub Outlet Settle Angle $\beta_{i2}/^\circ$ | 39 | 27 | Axial Length of Tip Section $L_1/mm$ | 91 | 92 |
3. Calculation method of cavitation flow

3.1. Meshing
The leakage of the tip clearance and the aroused backflow should be analyzed, so when the water model was created, a tip clearance of 1 mm was considered.

Water model was meshed after imported to ANSYS-ICEM software. Due to the structure of inducer is relatively complex, adaptive unstructured grid method was used. Because the tip clearance was tiny, grids near the tip were refined. Cavitation mainly happens near the blade surface, so in order to accurately simulate the cavitation development, grids near the blade surface were also refined, and the quality of grids were above 0.3.

3.2. Calculation method
For most of cavitation flow simulation, the typical homogeneous flow model in ANSYS CFX was used. The mass transfer process between the liquid phase and vapor phase was calculated by Rayleigh-Plesset equation [8].

Continuity equation and the Reynolds averaged Navier-Stokes equations were used to simulate the flow field in the inducer, and the RNG k-ε turbulence model was used to close the equations.

The total pressure of inlet and the mass flow of outlet were selected as the boundary condition. By adjusting the inlet total pressure, the development of inducer’s cavitation was controlled. The initial conditions of the cavitation calculation were depended on the results of non-cavitation results. The 25°C water was chosen as the medium, and the vapor pressure was set to be 3169 Pa. The average diameter of bubbles was set to be 2.0×10^{-6} m. The frozen-rotor interface was selected as the interface between inducer and the inlet or outlet. The convergence precision was set to be 1.0×10^{-5}.

4. The relationship between head breakdown and cavity length

4.1. Hydrofoil lift coefficient and cavity length
If the cavity flow can be approximated by single, fully developed or attached cavities on each blade, then this allows recourse to the methods of free streamline theory. The results of approximate linear theories for a partially cavitating solution (Acosta 1955) of a hydrofoil yields a lift coefficient [5]:

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Figure 1. Three-dimensional model of inducers.
where $l$ is the ratio of the cavity length to the chord length of the foil, and $\alpha$ is the incidence angle.

The relationship between $l$ and $\sigma$ (cavitation number) is:

$$\sigma = \frac{2 - l + 2(1-l)^{\frac{1}{2}}}{l^{\frac{1}{2}}(1-l)^{\frac{1}{2}}}$$

(2)

Therefore, if the incidence angle $\alpha$ is given, the theoretical solutions of the relation curve of $C_L - \sigma$ and relation curve of $l - \sigma$ can be got.

The lift coefficients, $C_L$ (solid lines), and the ratios of cavity length to chord, $l$ (dashed lines) at an incidence angle of 4°, are from the partial cavitation theory of Acosta (1955) [5], as shown in figure 2. Also shown are the experimental results of Wade and Acosta (1966) [6] for $l$ (triangles) and for $C_L$ (circles) where the open symbols represent points of stable operation and the solid symbols denote points of unstable cavity operation.

Figure 2. Theoretical and experimental results of hydrofoil cavitation characteristic.

As shown in figure 2, with the decreasing of the cavitation number, the ratio of the cavity length to the chord length increased gradually. With the decreasing of cavitation number, there was a rising process of the lift coefficient before it broke down quite rapidly. The small increase in the lift coefficient which occurs as the cavitation number is decreased toward the critical value of $\sigma$ is, in fact, observed experimentally with many single hydrofoils (for example, Wade and Acosta 1966) as well as in some pumps. The critical value of $\sigma$ corresponds to a certain value of $l$. In other words, when the ratio of the cavity length to the chord length increased to a certain value, the lift coefficient broke down.

4.2. Inducer head breakdown and cavity length
The cavitation characteristics of three different kinds of inducers, respectively of 3 blades and an leading edge wrap angle of 140°, 2 blades and an leading edge wrap angle of 140°, 2blades and leading edge wrap angle of 90°, were compared using CFX software. They had the same tip diameter and rotating speed, and worked under the same rated flow.
With the NPSH of the three inducers gradually decreasing, the heads broke down respectively at point 1, 2 and 3, as shown in figure 4. The corresponding distribution of cavity were shown in figure 3.

As shown in figure 3, the same conclusion can be drawn through the different inducers that the head breakdown is more related to the cavity length along the flow direction on the suction surface of blade rather than to the cavity coverage area.

In order to verify the conclusion above, another three kinds of inducers were compared. They had the same tip diameter and rotating speed, and worked under the same rated flow.

With the NPSH of the three inducers gradually decreasing, the heads broke down respectively at point 1, 2 and 3, as shown in figure 6. The corresponding distribution of cavity were shown in figure 5.

As shown in figure 6, the moment when the inducer head begun to drop is depended on the relative cavity length along the flow direction on the suction surface of blade, but not on the cavity coverage area.

In addition, it’s important to note that, as shown in figure 2, no matter the theoretical calculation curves or the test results, they all suggested that, there would be a slight increase before hydrofoil lift coefficient dropped sharply. In fact, this was found in a lot of tests of hydrofoils and pumps, such as
the data obtained by Kawaguchi and Oshima [9] in 1963. This phenomenon occurred when the pump worked under small flow rate, which was tested by Guinard etc. [10]. The cavitation characteristic curve of inducer got by Kamijo etc. [11] in 1977, also showed that, there was a rising process before the inducer lift coefficient dropped sharply.

In this study, the numerical simulation result, that is the obtained cavitation characteristic curves of inducers also showed that the head increased to a certain value before broke down. The reason perhaps lay in that the cavity covered part of the flow passage formed by suitable cavitation may on the contrary improve the flow characteristics.

Backflow vortex appears more often in the inducer and centrifugal pump under small flow rate. Badowski (1969) puts forward the hypothesis that the dynamics of the backflow are responsible for cavitating inducer instability [3]. The relationship between inducer cavitation and backflow vortex was analyzed.

5. Relationship between inducer cavitation and backflow vortex

Pressure difference between suction surface and pressure surface of inducer may cause the leakage flow between the tip of the blades and the pump casing. Below a certain critical flow coefficient, the pressure difference driving the leakage flow becomes sufficiently large that the tip leakage jet penetrates upstream of the inlet plane of the impeller, and thus forms an annular region of “backflow” in the inlet duct. As a result of the existence of shear layer between backflow and main inlet flow, a series of vortex structures formed. As the inlet pressure decreases, cavitation inception almost always occurs in the blade tip area, controlling the tip vortex of inducer is the key to restrain cavitation instability.

When an instable situation develops to a certain extent, there will appear some variable to break this imbalance. The formation and development of cavitation, to some extent, is to break this imbalance. With the development of cavitation, backflow area in the inlet gradually decreases. Inducer (b), of two blades and an leading edge wrap angle of 140°, was numerical simulated. Backflow vortex and corresponding cavitation development were shown in figure 7.

![Figure 7. Backflow eddy disappears in cavitation process.](image)

Cavitation development of inducer under rated flow, and the NPSH is 3.87 m, 2.7 m, 1.7 m, 1.5 m, 1.1 m and 0.7 m respectively.
As shown in figure 7, there is a general tendency that the cavitation area develops towards the center of vortex. With the development of cavitation, the backflow vortex, near the leading edge gradually disappears and the distribution of streamline gradually became more uniform. Along with the disappearance of backflow vortex, the flow characteristic was improved.

**Conclusions**

(1) Although of different patterns, the inducers have the same characteristic that the head break down is related to the chord length along the flow direction on the suction surface of blade, which is consistent with existing theories and experimental results.

(2) With the NPSH gradually decreasing, the head increased to a certain value before broke down. The reason perhaps is that the cavity’s covering part of the flow passage formed by suitable cavitation may to some extent improve the flow characteristics. The reason also related to the backflow vortex.

(3) Cavitation and backflow vortex are closely related. Cavitation inception always occurs in the blade tip area where backflow vortex exists. There is a general tendency that the cavitation area develops towards the center of vortex. With the development of cavitation, the backflow vortex near the leading edge gradually disappears.

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