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# Analysis of Cavitation Performance of Inducers

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## 1. Introduction

Low specific speed centrifugal pumps have low flow rates and high heads. They are widely applied in the petroleum, chemical, aerospace, pharmaceuticals, metallurgy, and light industries, among others. With the development of space technology and petrol chemical industry, the highly stable cavitation performance of centrifugal pumps has been put forward. Poor cavitation performance is one of the key problems in low specific speed centrifugal pumps. The most effective method for solving this problem is adding an inducer upstream of the impeller to identify the influence produced by different pre-positioned structures. This chapter focuses primarily on the analysis of the cavitation performance of inducers to identify the influence imposed by different inducers on the cavitation performance of a centrifugal pump. The chapter is organized into five sections. First, the status of research on cavitation performance is reviewed. Second, the research model is described. Third, the simulations of the different inducers are presented. Fourth, the cavitation performance experiment is carried out. The conclusion ends the chapter.

## 2. Research status

Numerical calculation techniques have developed rapidly in recent years, and many works have been carried out on inducer flow and its cavitation performance. The results of the one-phase simulation of single and serial inducers (Cui et al., 2006) show that inducers can increase impeller inlet pressure, the easy to cavitate position is located at the rim of the suction surface near the inlet, and cavitation does not take place in the second inducer. The flow in the screw inducer is numerically calculated (Wang Jian-ying & Wang Pei-dong, 2006), and the results show that the head can be efficiently increased by adding a screw inducer. Guo et al. (2010) carried out a simulation of the flow in two different inducer structures, and showed that parameters including helical pitch, axial length, and blade wrap angle pose considerable influence on cavitation. Cavitation is an important phenomenon in the design of an inducer. The understanding and prediction of the mechanisms associated with cavitation have progressed significantly the past few years. Unsteady flow in the equal pitch inducer is numerically calculated by adopting the cavitation and mixture model (Ding & Liang, 2009). The results show that the area prone to cavitation is the rim of the suction surface. Unsteady flow in the progressive pitch inducer is also calculated using the Euler multiphase model and standard k-ε turbulence model (Yuan et al., 2008; Kong et al., 2010). The findings show that rounding out the blade inlet can improve the cavitation performance

of the inducer. The rotation cavitation of one channel and four channels of the inducer is simulated by adopting the unsteady cavitation model (Langthjem & Olhoff, 2004). The complex cavitation flow of the inducer is solved using the CRUNCH program and multiple unstructured grids (Li, 2004). The inducer's cavitation performance is determined through the simulation (OkitaK et al., 2009; Li & Wang, 2009). In references (Kunz et al., 2000; Medvitz et al., 2001), a preconditioned Navier-Stokes method has been applied to calculate cavitation flows in centrifugal pumps. Some numerical works have been developed to predict cavitation inception, cavity dimensions, and/or thresholds corresponding to pump head drops (Ait-Bouziad et al., 2003, 2004; Mejri et al., 2006). Researchers (Hosangadi & Ahuja, 2001) used a hybrid unstructured mesh to simulate the cavitation flows over a hydrofoil and a cylindrical headform. Hosangadi (2006) presented a good comparison of simulated and experimental data on breaking down a helical flat-plate inducer configuration in cold water. The influence of steady cavitation behavior on pump characteristics and on the final head drops was also simulated (Benoît et al., 2008).

In spite of these relevant works, more studies are needed to improve on earlier achievements. To reveal the mechanism of two-phase flow in an inducer under cavitation conditions, four different inducers are designed, gas-liquid two-phase flows are simulated, and a corresponding external cavitation experiment is carried out. In this paper, the mixture model and standard k-ε turbulent model are adopted for the simulation. The inducer, impeller, and volute are made as an entire channel for simulation by adopting a gas-liquid two-phase model. During the simulation, the radial gap between the inducer blade tip is taken into account, and the value is 1 mm.

## 3. Research model

The research object is a high-speed centrifugal pump with an inducer (four different structures) upstream of the impeller (see in Fig.1). The flow rate is 5 $m^3/h$, head 100 m, rotation speed 6 000 r/min. Seen from the inlet, rotation direction of inducer is clockwise. The centrifugal pump's impeller is shown in Fig.2. Four different inducers are adopted. One is equal-pitch. Second is long equal-pitch (with longer pitch than the first one). Third is progressive pitch. Fourth is with short splitting blades that with two long and two short blades (we call it two-long and two-short inducer in this chapter). The first three inducers are shown in Fig.3. Their parameters are shown in table 1. The last one is shown in Fig.4. Main geometry parameters are shown in table 2.

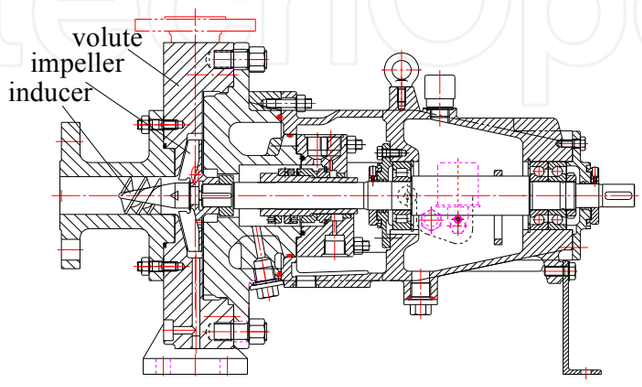



Fig. 1. The high-speed centrifugal pump with an inducer upstream of the impeller

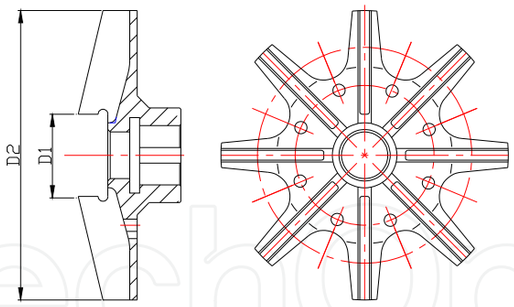



Fig. 2. Impeller

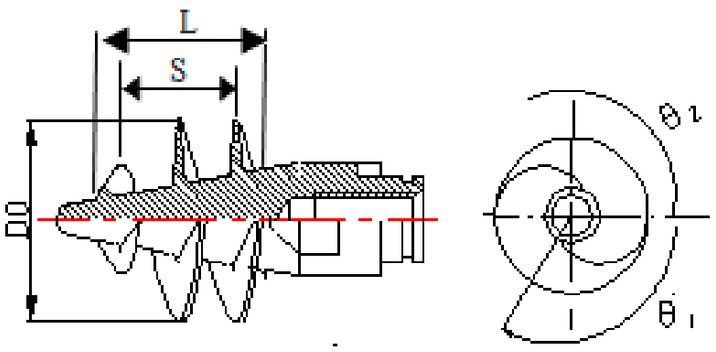



Fig. 3. Inducers with two blades

| parameters | S | L | $\theta_1$ | $\theta_2$ |
|---|---|---|---|---|
| Equal-pitch inducer | 20 | 24.3 | 120 | 317.5 |
| Long-equal-pitch inducer | 28 | 37 | 120 | 355.3 |
| Progressive pitch inducer | $155.5\tan(\beta_i)$<br>$6.6 \le \beta_i \le 12.6$ | 33 | 120 | 354.3 |

Table 1. Parameters of the inducers with two blades

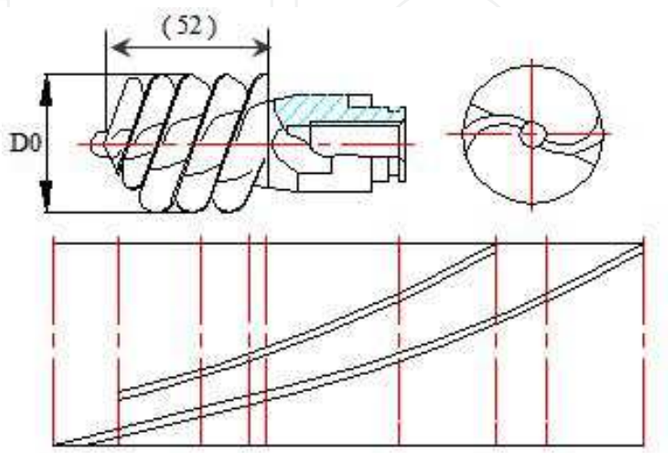



Fig. 4. Inducer with two long and two short blades

| Geometry parameter | D0 (mm) | D1 (mm) | D2 (mm) |
|---|---|---|---|
| Diameter | 38 | 28 | 136 |

Table 2. Main geometry parameters

## 4. Numerical simulations

### 4.1 Control equation

Mixture model is a simplified multiphase flow model, which is used to simulate different phases with different velocities. In many cases, the mixture model is a good alternative to Eulerian model, and it can get good results as other good multiphase model. The fluent software numerical code solves the standard k-ε turbulent model equations of a homogeneous fluid (Fortes et al., 2007, Coutier et al., 2004). Previous studies (Yuan et al., 2008, Tang et al., 2008, Benoît et al.,2008) pointed out that the Mixture model can successfully yield quantitative predictions of cavitation flow global parameters (i.e., characteristic frequencies, vapor structure size). As the gas-phase volume is relatively few when the inducer cavitates, the gas and liquid phases are supposed to be incompressible . So the mass equations are adopted as bellow:

$$\frac{\partial \rho_m}{\partial t} + \nabla \bullet (\rho_m \vec{v}_m) = \dot{m} \tag{1}$$

$$\vec{v}_m = \frac{a_1 \rho_1 \vec{v}_1 + a_2 \rho_2 \vec{v}_2}{\rho_m} \tag{2}$$

Where

$$\rho_m = a_1 \rho_1 + a_2 \rho_2 \tag{3}$$

$$\vec{v}_m = (a_1 \rho_1 \vec{v}_1 + a_2 \rho_2 \vec{v}_2) / \rho_m \tag{4}$$

Momentum Equation for the Mixture:

$$\frac{\partial (\rho_m \vec{v}_m)}{\partial t} + \nabla \bullet (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m{}^T)] + \rho_m \vec{g} + \vec{F} + \nabla \cdot (a_1 \rho_1 \vec{v}_{dr,1} \vec{v}_{dr,1} + a_2 \rho_2 \vec{v}_{dr,2} \vec{v}_{dr,2}) \tag{5}$$

Energy Equation for the Mixture

$$\frac{\partial}{\partial t}(a_1 \rho_1 E_1 + a_2 \rho_2 E_2) + \nabla \bullet (a_1 \vec{v}_1 (\rho_1 E_1 + p) + a_2 \vec{v}_2 (\rho_2 E_2 + p)) = \nabla \cdot (k_{eff} \cdot \nabla T) + S_E) \tag{6}$$

Volume Fraction Equation for the Secondary Phase

$$\frac{\partial}{\partial t}(a_p \rho_p) + \nabla \bullet (a_p \vec{v}_m \rho_p) = -\nabla \cdot (a_p \vec{v}_{dr,p} \rho_p) \tag{7}$$

### 4.2 Computational grids

As the channel of the whole pump is complex and irregularly twisted, unstructured tetrahedral grids are adopted to the channel of inducers and impellers. The GAMBIT software is adopted to draw grids. The computational domain of the high speed pump with equal-pitch inducer consists of 200,097 nodes, 666,699 unit girds, with long-equal-pitch inducer 202,673 nodes, 680,657 unit girds, with progressive pitch inducer 209,658 nodes, 721,189 unit girds, with two-long and two-short inducer 202,673 nodes, 680,657 unit girds. The quality of the grids is satisfied with the solver's demand. The grids are shown in Fig.5.

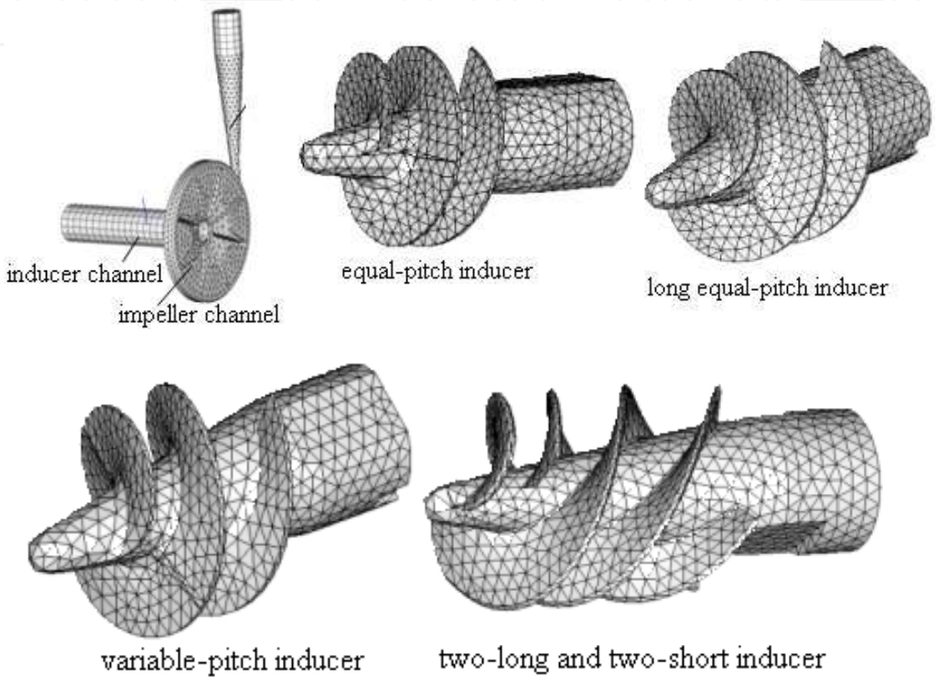



Fig. 5. Computational grids and inducers' grids

### 4.3 Boundary conditions

1. Inlet. Velocity-inlet is specified on the inlet.
2. Outlet. Static pressure is specified on the outlet. In order to get the distribution of the pressure and the gas-liquid phase volume fraction, the value of the outlet pressure should be the one which will ensure the pump to cavitate. The value is also got by the cavitation performance experiment. It can be seen in the table3.

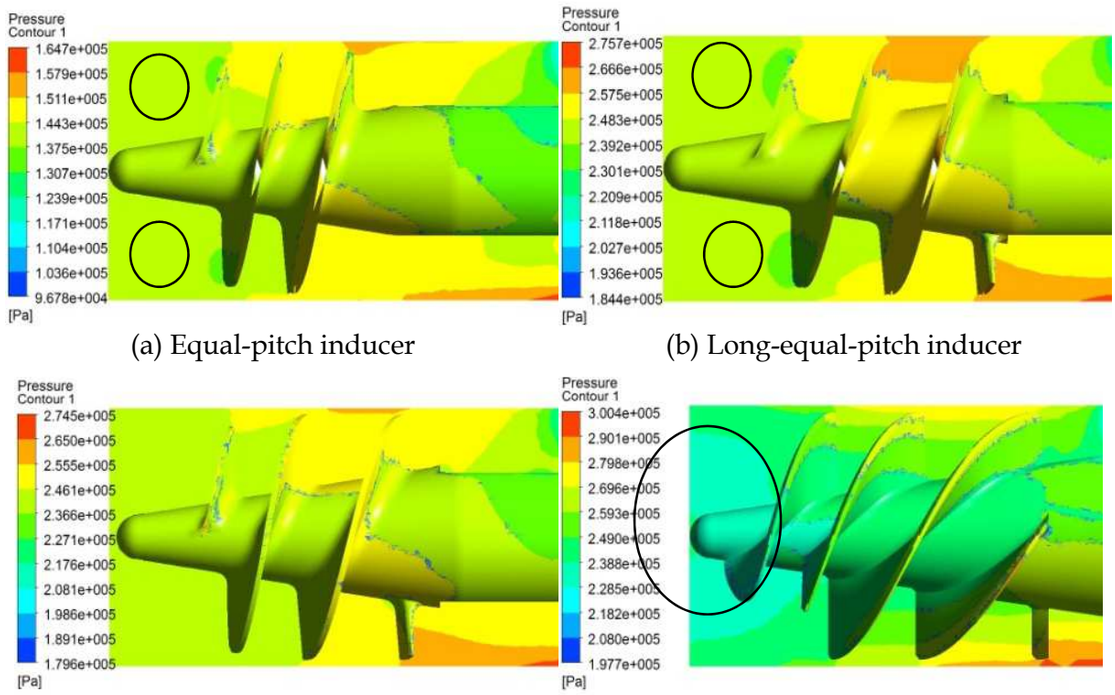
| Inducers | Absolute total pressure/Pa |
|---|---|
| Equal-pitch inducer | 920627.3233 |
| Long-equal-pitch inducer | 932401.728 |
| Progressive pitch inducer | 932376.728 |
| Two-long and two-short inducer | 946138.5334 |

Table 3. Pressure on the outlet

3. Multi-phase flow. The Mixture model is adopted, and the number of the phases is set as two. The main phase is water-liquid, and the secondary phase is water-vapor. The saturated steam pressure is 3540 Pa.
4. Wall. No slip boundary conditons is specified.
5. Coordinate system. The moving coordinate system is adopted in the channel of the inducer and the impeller, and the rotation speed is set as 6 000 r/min, while the static coordinate system is adopted in the channel of the inlet pipe and the volute.

### 4.4 Results of numerical simulation

According to above, simulations are done. The velocity distribution and the static pressure distribution are got. For the cavitation mostly depends on the static pressure, the static pressure is chosen to be mainly analyzed. In order to know the pressure distribution mechanism law, the axial profile is chosen to be analyzed, which is shown in Fig.6. The static pressure distribution on the inducer is show in Fig.7.



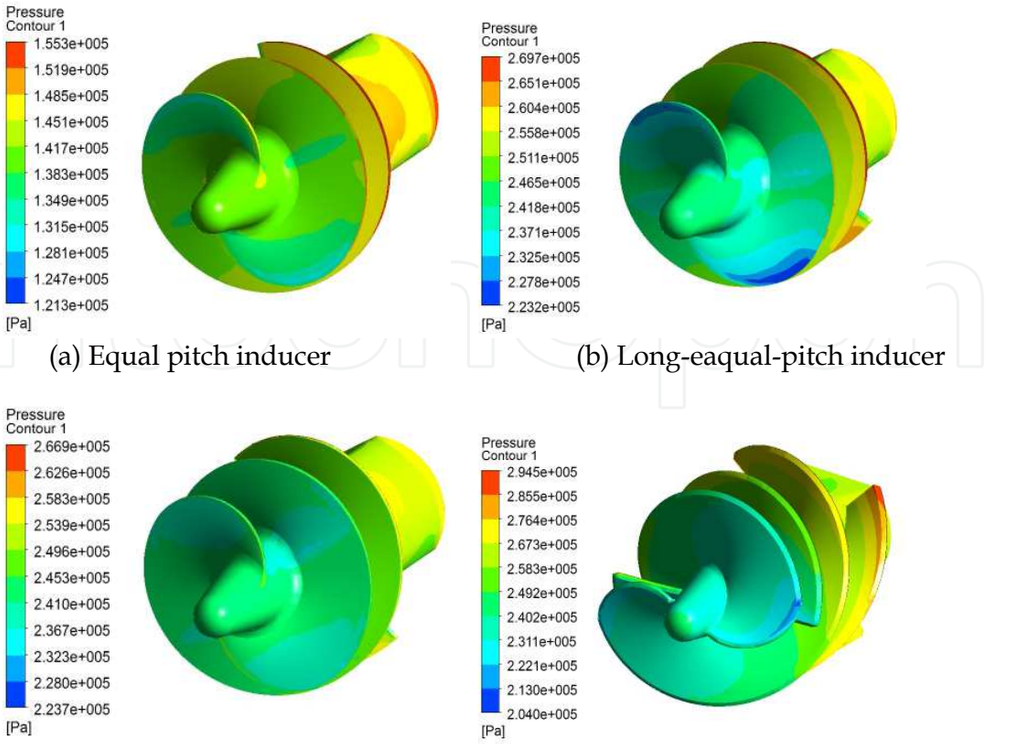

(a) Equal-pitch inducer (b) Long-equal-pitch inducer

(c) Progressive pitch inducer (d) Inducer with two long and two short blades

Fig. 6. Static pressure distribution in the axial channel

Fig.6 shows that the static pressure increases gradually from inlet to outlet. The pressure difference between the outlet and th inlet is different. Heads upstream of the impeller can be computed by the pressure difference. Fig.6 shows that near the suction side of the blade low pressure area exists in the equal-pitch inducer, long equal-pitch inducer. The pressure in the inducer's inlet is lower in the two-long and two-short inducer.

In order to know the pressure distribution on the inducers, take the inducers as the research object, which can be seen in Fig.7.




(a) Equal pitch inducer (b) Long-eaqual-pitch inducer

(c) Progressive pitch inducer (d) Inducer with two long and two short blades

Fig. 7. Static pressure distribution on the inducer

| Inducers | Absolute static pressure distribution range/Pa |
|---|---|
| Equal-pitch inducer | 121300~155300 |
| Long-equal-pitch inducer | 223200~269700 |
| Progressive pitch inducer | 223700~266900 |
| Two-long and two-short inducer | 204000~294500 |

Table 4. Static pressure distribution range

Fig. 7 shows that under the design work condition, the static pressure increases gradually from inlet to outlet.The pressure difference between the outlet and the inlet can be got by the simulation. Heads can be computed by the pressure difference, and the result is listed in the table 5.

| Inducers | Head of the high-speed centrifugal pump /m |
|---|---|
| Equal-pitch inducer | 97.01 |
| Long-equal-pitch inducer | 98.21 |
| Progressive pitch inducer | 98.12 |
| Two-long and two-short inducer | 98.90 |

Table 5. Head of the high-speed centrifugal pump

Table 5 shows that the head of the high-speed centrifugal pump is the highest with the two-long and two-short inducer. Second is with long equal-pitch inducer. Third is with progressive pitch inducer. Fourth is with equal-pitch inducer. This is mainly relevant to the helical pitch（$L$, which can be seen in Table 1）. The helical pitch of the two-long and two-short inducer is about 52 mm, long-equal-pitch 37 mm, progressive pitch 33 mm, equal-pitch 20 mm.

$NPSH_r$ can be computed by the equation 8.

$$NPSHr = \frac{{v_0}^2}{2g} + \frac{\lambda {w_0}^2}{2g} \tag{8}$$

Where

$$\lambda = 1.2tg\beta_0 + (0.07 + 0.42tg\beta_0)(\frac{s_0}{s_{\max}} - 0.615)\frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{9}$$

where，

$v_0$ – average velocity slightly before the vane inlet.
$w_0$ – average relative velocity near slightly before the vane inlet.
$\lambda$ – blade inlet pressure drop coefficien.
$\beta_0$ – relative flow angle of the front cover flow lines.
$S_0$, $S_{\max}$ – width of the vane inlet and the max width

According to the simulation results, $v_0$ and $w_0$ can be got, and combining with the equation 8 and 9, $NPSH$r can be computed. The results are show in table 6.

| Inducers | $NPSH_r$ of the high-speed centrifugal pump /m |
|---|---|
| Equal-pitch inducer | 0.5910 |
| Long-equal-pitch inducer | 0.2624 |
| Progressive pitch inducer | 0.3450 |
| Two-long and two-short inducer | 0.3691 |

Table 6. $NPSH_r$ of the high-speed centrifugal pump

Table 6 shows that the centrifugal pump has best cavitation performance when it is with the Long-equal-pitch inducer. Second is with Progressive pitch inducer. Third is with Two-long and two-short inducer. Fourth is with Equal-pitch inducer. This influence order on the cavitation is not same with the influence on the head. The pump with two-long and two-short inducer has highest head, but the cavitation is not the best. The reason is that the inducer is with four vanes, and the extruding coefficient is increased.

## 5. Cavitation performance experiment

In order to identify the cavitation performance of the pump with four different inducers, the external performance experiments are carried out. The experiment equipment is shown in

Fig. 8. And the test pump is shown in Fig.9. The test inducers are shown in Fig.10. The pump's performance curves under the design point are shown in Fig.11.

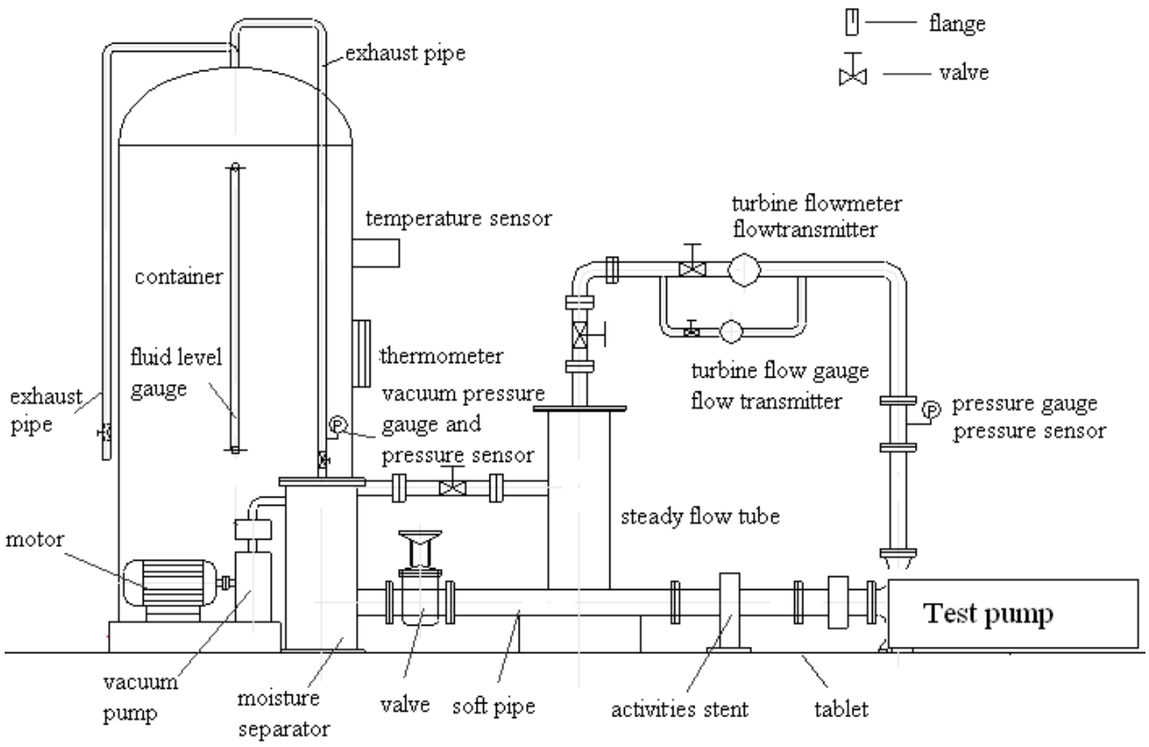



Fig. 8. The experiment equipment

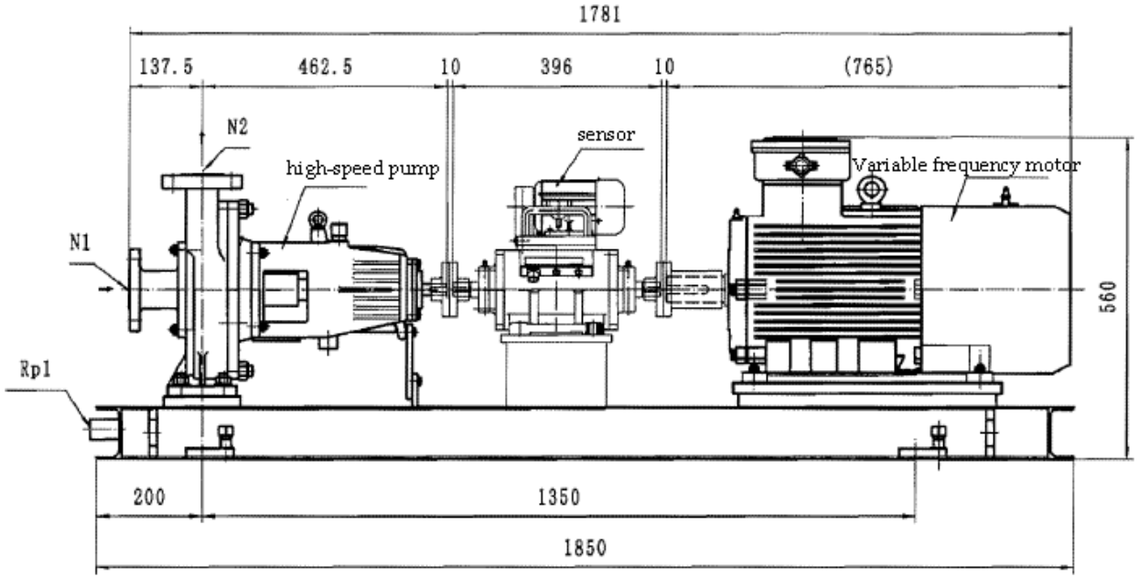



Fig. 9. The test pump

The parameters of the high-speed centrifugal pump are described as previous. The sensor's rated torque is 100N·m. The operation range of the speed of rotation is from 0 to 10000 rpm. The variable frequency motor's rotation is from 0 to 9000r/min，and its max power is 22kw. It is controlled by an inverter.



Fig. 10. Test inducers

Test inducers are made by the rapid prototyping. The inducers are respectivly equal-pitch inducer, long equal-pitch inducer, progressive pitch inducer, and the inducer with two long and two short blades.

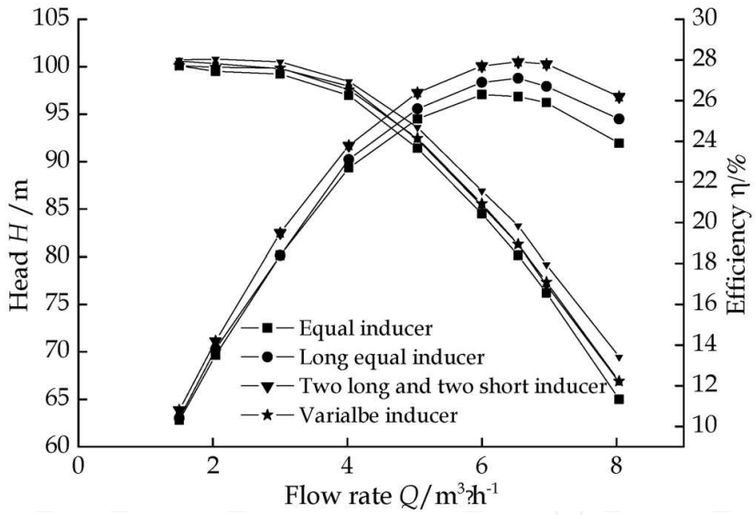



Fig. 11. External performance curves

The H-Q performance curve has no positive slope whether it is with any inducer. On the design work condition, the heads and efficiencies are listed in table 7.

By the contrast of the head in the Table 7 (got by the experiment) and Table 5 (got by the simulation) , it shows that the two values are very close, and has the same law. The pump has highest head when it is with the two-long and two-short inducer, second is with the long-equal-pitch inducer, third is with the progressive pitch inducer, and fourth is with the equal-pitch inducer.

Fig.12 shows head variation with the decrease of the inlet pressure

| Inducers | Head /m | Efficiency/% |
|---|---|---|
| Equal-pitch inducer | 96.97 | 22.7 |
| Long-equal-pitch inducer | 97.96 | 23. 8 |
| Progressive pitch inducer | 97.58 | 23. 1 |
| Two-long and two-short inducer | 98.45 | 23.8 |

Table 7. Heads and efficiencies of the high-speed centrifugal pump

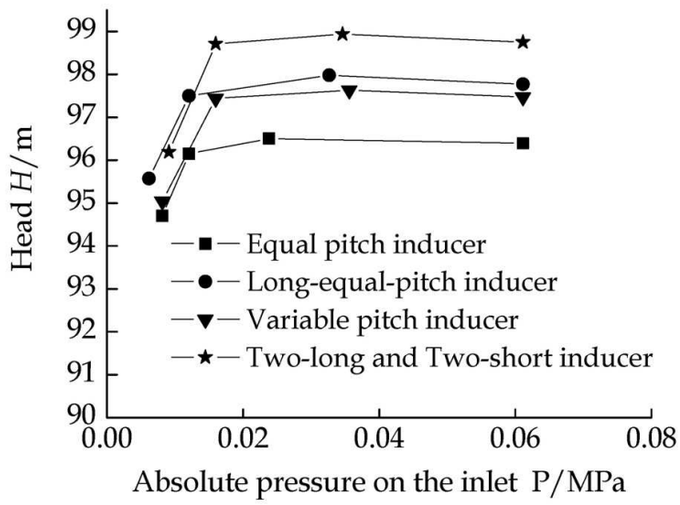



Fig. 12. Head variation with the decrease of the inlet pressure

With the decrease of the inlet pressure, the head of the pump will decline suddenly. From Fig.12, the critical point can be got, and the value is listed in table 8.

| Inducers | Absolute pressure on the inlet P/Pa |
|---|---|
| Equal-pitch inducer | 10103.07357 |
| Long-equal-pitch inducer | 8141.311713 |
| Progressive pitch inducer | 15988.35915 |
| Two-long and two-short inducer | 9067.163601 |

Table 8. Absolute pressure on the inlet

Figure 13 shows that at low flow rate, the cavitation performance of the equal-pitch inducer is not so good, while the long-equal-pitch inducer is good. At high flow rate, the two-long and two-short inducer has best cavitation performance. While the progressive pitch inducer has good cavitation performance whether at the low flow rate or high flow rate. On the design work condition, the *NPSH*r values are shown in table 9.

Compared with the values got by the simulation in Table 6, it shows that the *NPSH*r values are very close. The long equal-pitch inducer has best cavitation performance, second is progressive pitch inducer, third is two-long two-short inducer, and last is equal-pitch inducer.

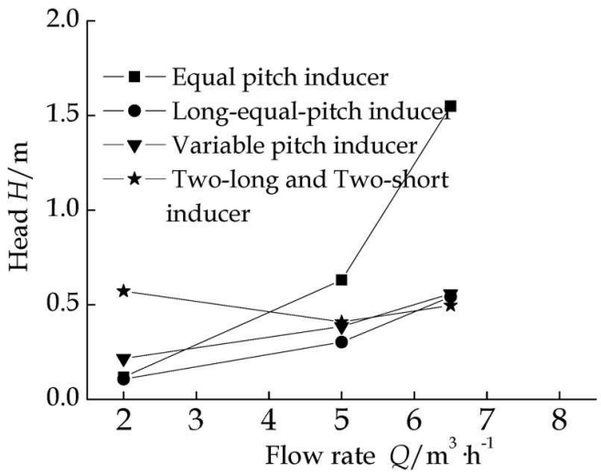



Fig. 13. *NPSH*r-*Q* curve

| Inducers | $NPSH_r$ of the high-speed centrifugal pump /m |
|---|---|
| Equal-pitch inducer | 0.6305 |
| Long equal-pitch inducer | 0.3026 |
| Progressive pitch inducer | 0.3852 |
| Two-long and two-short inducer | 0.4090 |

Table 9. $NPSH_r$ of the high-speed centrifugal pump

## 6. Conclusion

The flow of the centrifugal pump with inducers which are respectively with equal-pitch, long-equal-pitch, progressive pitch, two-long and two-short blades are numerically simulated. The corresponding external performance experiment is carried out. From the above, the conclusions can be got as follows:

1. The comparison of the simulation and experiment shows that the trend of every performance curve is similar. For design work conditions, the results obtained from the simulation and experiment are close.
2. The high-speed pump with different inducers has different heads. The head of the high-speed centrifugal pump reaches its highest with two long and two short inducers. The second highest head is achieved with a long equal-pitch inducer. The third highest is realized with the variable pitch inducer, and the fourth is achieved with an equal pitch inducer.
3. Adding an inducer can improve pump cavitation performance. The long equal pitch inducer exhibits the best cavitation performance; the second is the progressive pitch inducer; the third is the device with two long and two short inducers, and the last is the equal pitch inducer.
4. The pump with an inducer's head is mainly relevant to the helical pitch *L*. So when design inducer, the helical pitch *L* should be longer appropriately.
5. The research can supply significant guide for inducer's design.

## 7. Appendix

Notation

| | |
|---|---|
| $a_1, a_2$ | liquid-phase/gas-phase volume fraction |
| $F$ | volume force (N) |
| H | head (m) |
| $\dot{m}$ | cavitation effect of mass transfer |
| $n$ | rotation speed (r $min^{-1}$) |
| $Q$ | flux ($m^3$ $h^{-1}$) |
| $v$ | mass mean velocity (m $s^{-1}$) |
| $v_1, v_2$ | liquid-phase/gas-phase velocity (m $s^{-1}$) |
| $\rho$ | mixture density (kg $m^{-3}$) |
| $\rho_1, \rho_2$ | liquid-/gas-phase density (kg $m^{-3}$) |
| $\mu_1, \mu_2$ | liquid-/gas-phase dynamic viscosity (pa·s) |

## 8. Acknowledgment

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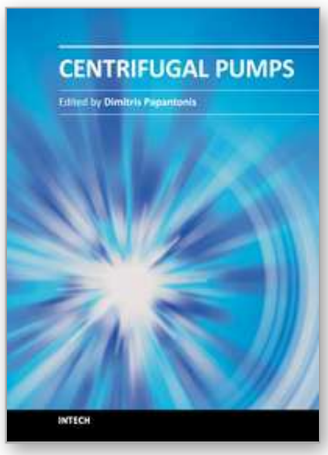
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**Centrifugal Pumps**

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The structure of a hydraulic machine, as a centrifugal pump, is evolved principally to satisfy the requirements of the fluid flow. However taking into account the strong interaction between the pump and the pumping installation, the need to control the operation, the requirement to operate at best efficiency in order to save energy, the provision to improve the operation against cavitation and other more specific but very interesting and important topics, the object of a book on centrifugal pumps must cover a large field. The present book examines a number of these more specific topics, beyond the contents of a textbook, treating not only the pump's design and operation but also strategies to increase energy efficiency, the fluid flow control, the fault diagnosis.

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