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NUMERIC ANALYSIS ON INTERNAL FLOW OF HIGH-SPEED PUMP OF DIFFERENT STRUCTURAL STYLE

Shi Hai-xia
Chemical Machinery Research Institute, Hefei University of Technology, Hefei, China,23009
+0086-0551-2901709, +0086-0551-2901708
jdshx@263.net

He Yu-jie
Chemical Machinery Research Institute, Hefei University of Technology, Hefei, China, 23009
+0086-0551-2901709, +0086-0551-2901708
Heyujie301@163.com

Wu Jian-bo
Chemical Machinery Research Institute, Hefei University of Technology, Hefei, China, 23009
+0086-0551-2901709, +0086-0551-2901708
gmriwjb2000@msn.com

Li Qiang
Chemical Machinery Research Institute, Hefei University of Technology, Hefei, China, 23009
+0086-0551-2901709, +0086-0551-2901708
hfliqiang@163.com

ABSTRACT

In order to study the effect of the structural style of high-speed pump on internal flow, 4 types high-speed pump of different structural style are selected for comprehensive analysis，S-A turbulence model and SIMPLIEC algorithm are adopted for numerical simulation of internal flow. By comprehensively comparing the static pressure, total pressure, sectional velocity vector and flow path line, two types of high-speed pumps with cylindrical-blade impeller matching nozzle type pump casing have relatively ideal pressure field and flow condition, can reduce hydraulic loss. The comprehensive performance of 4 types of high-speed pump is predicted through computational simulation, the high-speed pump with open cylindrical-blade impeller matching nozzle type pump casing has most excellent performance, indicating the structural style of high-speed pump has effect on its internal flow and performance.

Keywords: high-speed pump, structural style, numerical simulation, flow analysis, performance.

NOMENCLATURE

D_2 Impeller diameter，m
b_2 Impeller width at outlet ，m
Z Number of long/short blades
D_3 Basic circle of volute casing，m
d_t Throat diameter of diffuser，m
L_2 Length of diffusion section of diffuser，m
θ Diffusion angle，^{0}C;
P_0 Total pressure
P_S Static pressure
c Absolute speed

P_{Oin} Total pressure at impeller inlet

P_{Oout} Total pressure at outlet of pump casing

M' Sum of moments about Z-axis

INTRODUCTION

High-speed partial emission pump is the one with special construction and low or ultra-low specific speed (<50[1]), it has the features of small flow, high head, high speed, simple construction, high reliability, convenient manufacture and repair, etc.[2], it is widely applied in the field of aviation, spray irrigation, fire fighting, petrochemical engineering etc. The medium enters the suction chamber of the pump and is discharged after passing through open impeller, annular volute casing and nozzle type diffuser, the internal flow of the pump is very complex and belongs to unsteady flow[3]. Internal flow differs for different structural style of high-speed pump and the hydraulic performance differs somewhat; in literature [4~6] only single-item numerical simulation is carried out on impeller, internal flow passage and volute, thus cannot truly reflects the overall flow condition of high-speed pump, whereas literature [7] conducted fully 3D unsteady computational simulation on the entire constant-speed centrifugal pump, in this paper focus is placed on analysis and comparison of internal flow characteristics of 4 different structures of high-speed pump, and internal flow analysis and numeric simulation study are carried out on different structures of high-speed pump for the common 4 combinations of impeller and nozzle style casing with the turbulence models of Navier-Stokes and Realizable equations for 3D turbulent flow using Fluent software, wall-function method and mesh technique for sliding between impeller and pump casing and S-A turbulence model and implicit correction SIMPLIEC algorithm of second-order central difference scheme.

STRUCTURAL STYLE OF IMPELLER AND NOZZLE STYLE PUMP CASING

4 different structural styles are formed by matching 4 types of impeller with nozzle style pump casing, among them the assembly of straight-blade impeller and nozzle style pump casing has more application in practice.

Structural style of impeller

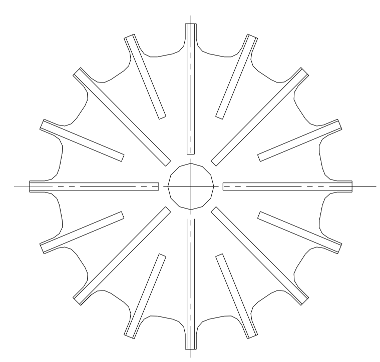
The common structural styles of impeller [8-9] at home and abroad are shown as in Fig. 1, these four types of impeller have the same geometric dimensions, see Table 1 and 2.

Table 1: Performance parameters of high-speed pump

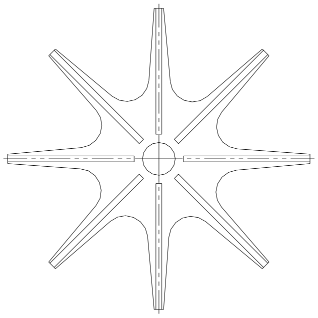
Description	Value
Flow(m3/h)	15
Head(m)	400
NPSH(m)	3.5
Speed(r/min)	8500
Power(kW)	75

Table 2: hydraulic dimensions of high-speed pump

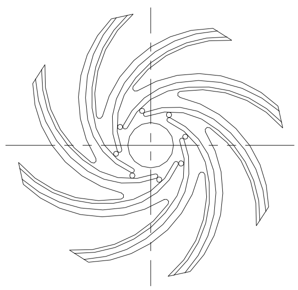
Description	Value
Impeller diameter (m)	0.17
Impeller width at outlet (m)	0.012
Number of long/short blades	8/8
Basic circle of volute casing(m)	0.186
Throat diameter of diffuser(m)	0.0095
Length of diffusion section of diffuser(m)	0.067
Diffusion angle(^{0}C)	8



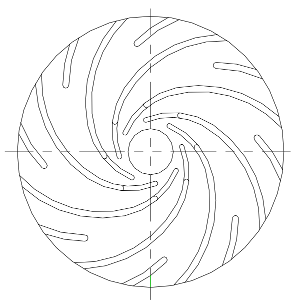
(a) Semi-open straight-blade composite impeller



(b) Open straight-blade impeller



(c) Open cylindrical-blade impeller



(d) Semi-open cylindrical-blade composite impeller

Figure 1. Structural diagram of impeller

Structural style of pump casing

The pump casing is composed of annular volute and nozzle style diffuser, as shown in Fig. 2.

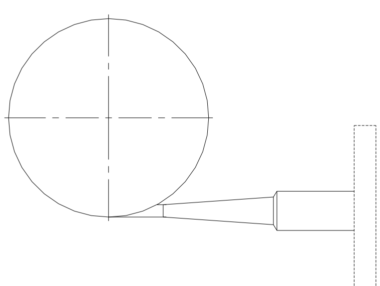


Figure 2. Structural diagram of pump casing

NUMERIC COMPUTATION

Grid division

Pro/E is applied to build 3D hydraulic model diagram of pump, and in order to obtain better computational results, a length of leading pipe whose length is 3 times of pipe diameter is added at impeller inlet and outlet of volute casing. The hydraulic dimensions of high-speed pump are generally relatively small, and the gap between impeller and pump chamber is very small, in order to obtain better computational results, the locations of small dimensions are locally encrypted in grid division, the size of grid division should not be too big. ANSYS-Fluent pre-processing software Gambit is used for grid division, and non-structured hybrid grid TGird is adopted to divide the entire model, this grid is mainly composed of tetrahedrons, and hexahedrons, cones and wedges at local locations, it can well process grid division of complex model; the max. division size of impeller and annular volute is 1, the number of division elements of impeller is 1307994 and that of annular volute is 380929.

Selection of turbulence model

Dr. Basque pointed out that the flow pattern varies significantly on the wall area of high-speed partial emission pump, the flow in the flow passage of impeller can almost be deemed to be a state of rigid motion with impeller, the rotating flow in annular volute also does not have motion relative to impeller, therefore, the stress of turbulent flow acts hardly; model of low Reynolds number is selected in the analysis of high-speed pump.

In ANSYS-Fluent, the Spalart-Allmaras model is proven to be very effective for building low Re-number model, especially it has shown very effect for wall restraining flow, and has more extensive application in rotary machinery; by reference to selection of turbulence model for numeric analysis of partial emission pump with specific speed in the range of 50~130, this model is selected as the turbulence model for numeric simulation of high-speed pump with low specific speed.

Setting of boundary conditions

The inlet boundary condition is set to be an inlet of uniform and continuous velocity without rotation, and the outlet is set to be the one of free outflow; the front and rear cover, wall of annular volute, wall of water piloting section at inlet and outlet and water body are set to be stationary; the impeller wall and water body of impeller are set to be rotary with the rotary speed of 8500 rpm, MRF model is selected and impeller wall, front and rear shroud and wall of volute housing are all set to be slipless adiabatic wall [6].

ANALYSIS OF SIMULATION RESULTS

Analysis of pressure field

Take the axial middle section of annular volute to calculate the static pressure inside the annular volute and impeller and use ANSYS-CFD-Post program to analyze the computational results.

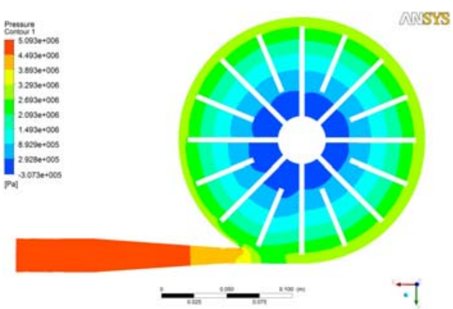
Nomenclature

Type a high-speed pump of combined construction of semi-open straight-blade composite impeller and nozzle style pump casing.

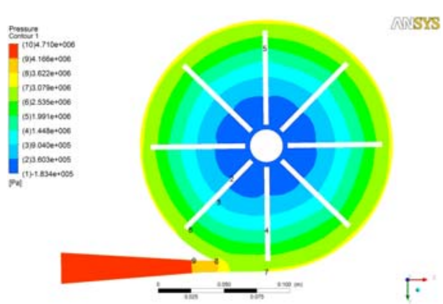
Type b high-speed pump of combined construction of open straight-blade composite impeller and nozzle style pump casing.

Type c high-speed pump of combined construction of open cylindrical-blade composite impeller and nozzle style pump casing.

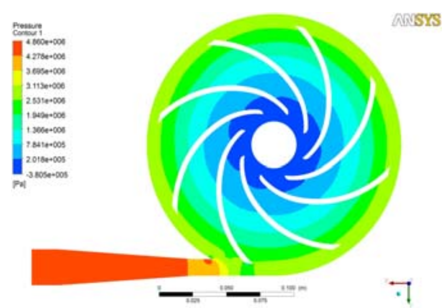
Type d high-speed pump of combined construction of semi-open cylindrical-blade composite impeller and nozzle style pump casing.



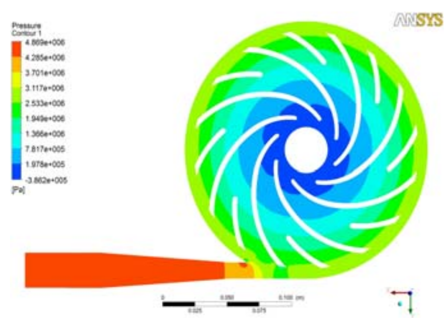
(a) High-speed pump of type a



(b) High-speed pump of type b



(c) High-speed pump of type c



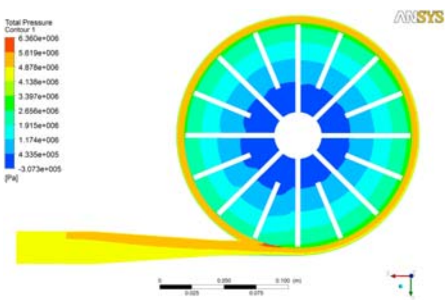
(d) High-speed pump of type d

Figure 3. Static pressure diagrams of the four types of high-speed pump

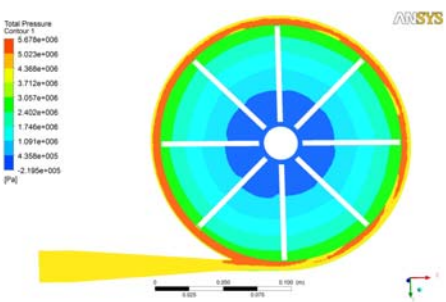
Cavitation tends to take place at the inlets of the four types of high-speed pump, the pressure presents a tendency of annular outward increment, yet the pressure gradually increases from inlet to outlet and from hub to rim, indicating the work done by blade profile increases radially. Take the tangential position of nozzle to excircle of annular volute as 0° position, in the area which is swept across the nozzle to volute shroud by the impeller from 0° position in the direction of impeller rotation, the pressure in impeller and annular flow passage has somewhat drop compared to other areas and the pressure gradient increases slowly; in the area from 0° to 90°, larger negative pressure area appears at impeller inlet and blade inlet, which extremely tends to cause cavitation.

In the annular flow passage of annular volute, the static pressure distribution is rather uniform in the range from 90° to 360° in the rotational direction of impeller; in the area from 0° to 90°, especially in front of inlet of straight pipe section, the static pressure drops significantly; in the area from straight pipe section to diffusion section, the static pressure gradually rises up, and kinetic energy is converted into pressure energy; in the triangle area at the nozzle inlet, there is a local high pressure area, indicating that the flow condition in this area is rather complex. As shown in Fig. 3, the static pressure cloud charts are basically similar, the difference between the pressure on the blade task and that on blade back of the same impeller is not great, indicating that the static pressures of the models of the four constructions are similar.

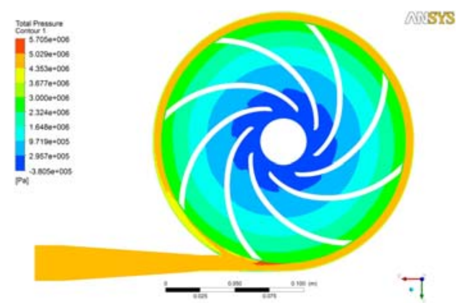
Because the performance parameters and major hydraulic dimensions of the four types of high-speed pump are the same, just the structural styles of impeller are different, the resulting effect of operation at high speeding is not substantial.



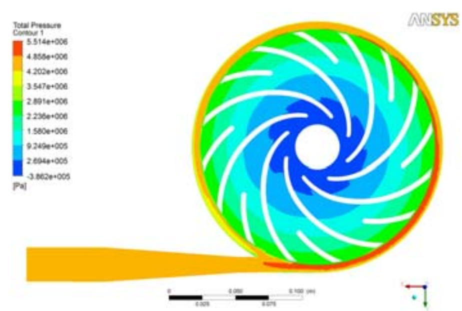
(a) High-speed pump of type a



(b) High-speed pump of type b



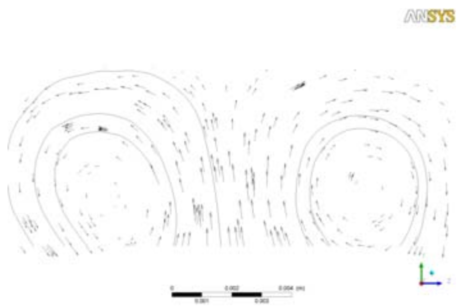
(c) High-speed pump of type c



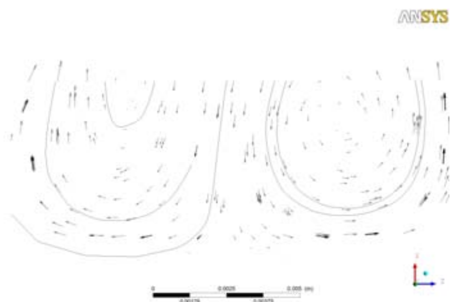
(d) High-speed pump of type d

Figure 4. Total pressure diagrams of the four types of high-speed pump

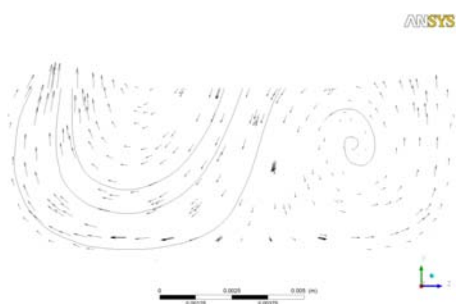
It can be seen from the total pressure cloud charts as shown in Fig. 4, that the total pressure is distributed uniformly in gradient along the radius, the pressure from hub to rim shows a ascending tendency of annular outward increment; arriving the nozzle, there is no energy loss for the equivalent tangent velocity from this position to annular volute because the medium is sprayed out tangentially along the impeller, this is also the advantage of high-speed pump for which nozzle style pump casing is selected. The total pressure on middle cross section of type d high-speed pump is biggest, second is type c and the smallest is type b, indicating the high-speed pump of the combined construction of cylindrical-blade impeller and nozzle style pump casing is better than that of straight-blade impeller and nozzle style pump casing; for the total pressure cloud charts of the pump added with short blades and those of the pump without short blades added, the distribution of their total pressures is similar, the discharge pressure of the pump added with short blades is relatively larger, indicating short blades helps increasing pump head. Whether on the blade task or back blade of the impeller, their pressures do not differ much, this indicates that the one-element theory commonly used in impeller design is reliable.



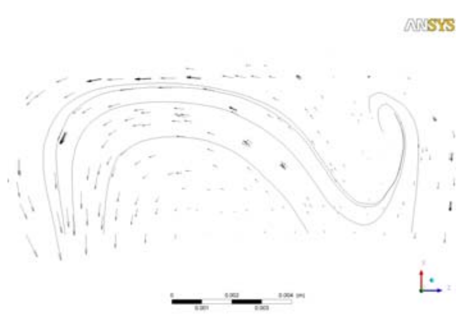
(a) 90º cross section



(b) 180º cross section



(c) 270º cross section

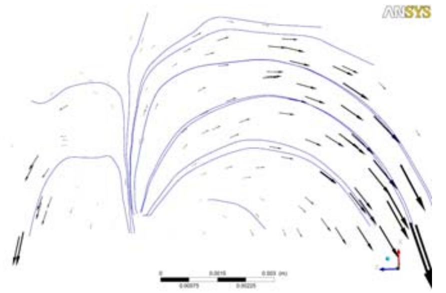


(d) 360º cross section

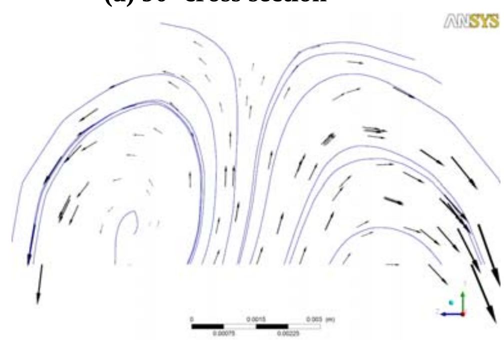
Figure 5． Cross-sectional velocity cloud charts of type a high-speed pump

Flow analysis

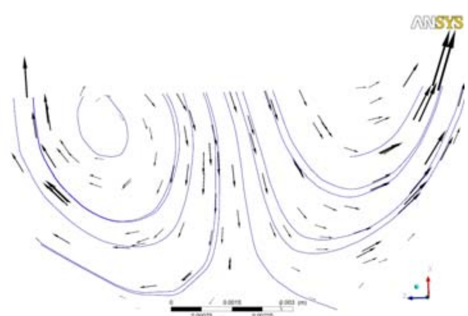
·Velocity analysis on cross section of annular volute



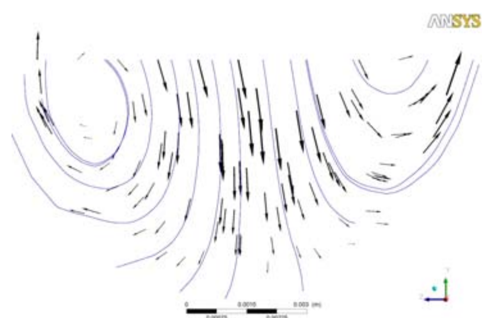
(a) 90º cross section



(b) 180º cross section

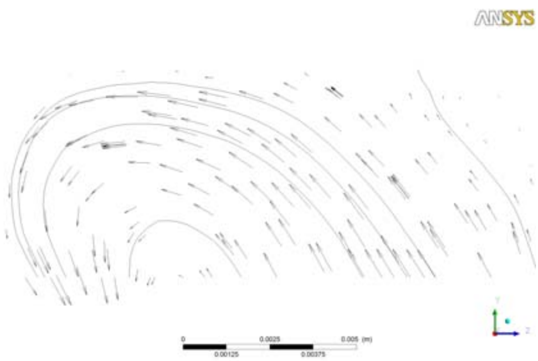


(c) 270º cross section

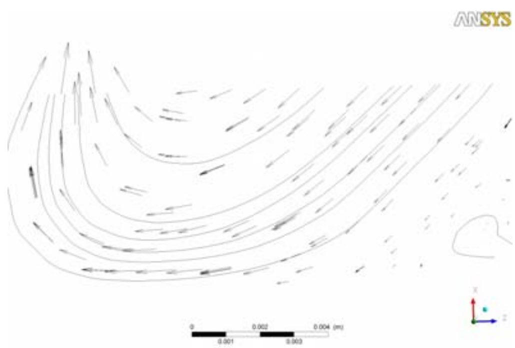


(d) 360º cross section

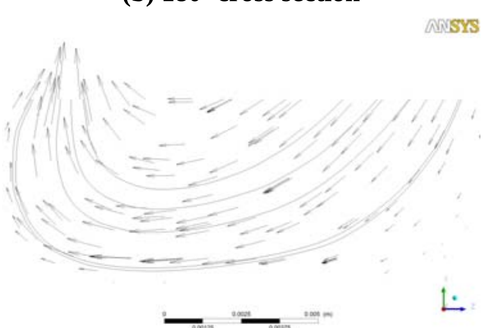
Figure 6． Cross-sectional velocity cloud charts of type b high-speed pump



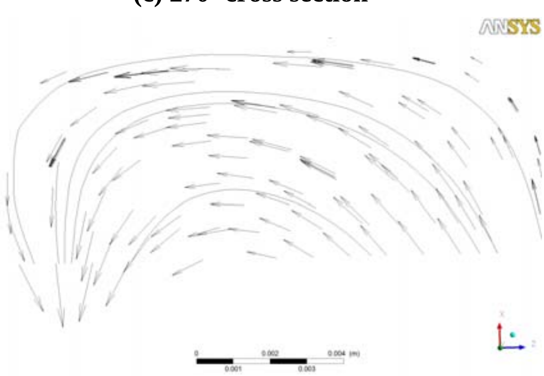
(a) 90º cross section



(b) 180º cross section

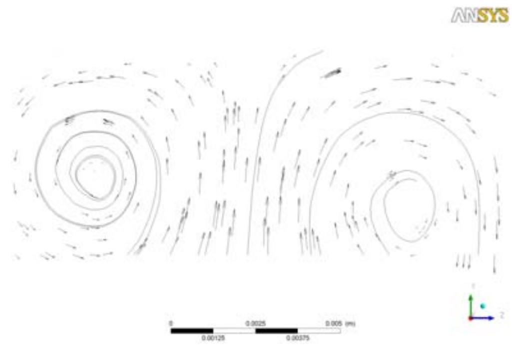


(c) 270º cross section

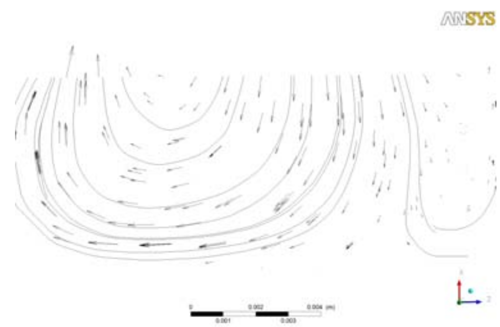


(d) 360º cross section

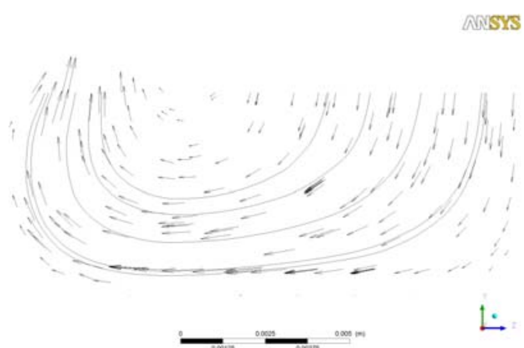
Fig. 7: Cross-sectional velocity cloud charts of type c high-speed pump



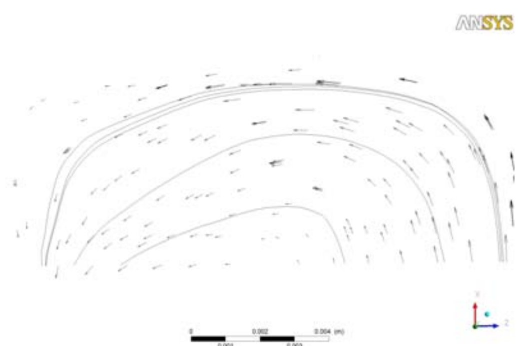
(a) 90º cross section



(b) 180º cross section



(c) 270º cross section

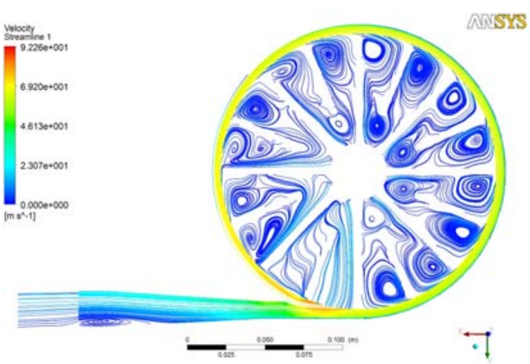


(d) 360º cross section

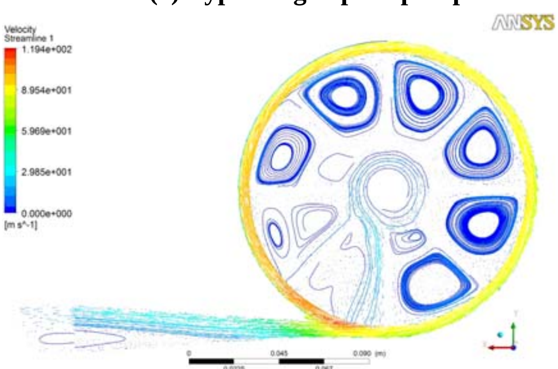
Figure 8． Cross-sectional velocity cloud charts of type d high-speed pump

The flow on the cross section at position of 90°, 180°, 270° and 360° is analyzed, as shown in Fig. 5~8. At 90° position, apparent recirculation has begun to appear in type a high-speed pump and type d, and forms counter vortex; whereas the flow of type b is toward front and rear cover, but has not yet formed vortex; At 180° position, the vortex of type a and type b is enhanced, but the vortex of type d slows down somewhat; at 270° and 360° position, the vortex of type b obtains full development and there are two vortexes opposite to each other; The vortex of type a high-speed pump slows down slightly, but is still very serious, the flow of type d high-speed pump is very good, but vortex has not yet appeared, type c has not yet formed vortex from 90° to 360°, but the flow is very good, indicating that the matching of impeller type and annular volute is relatively good. By comparing and analyzing the velocity cloud charts on four cross sections of the four types of structural style: the flow of type c high-speed pump at 90°, 180°, 270° and 360° is most uniform, there does not appear turbulent flow and recirculation etc., the internal streamline distribution is relatively smooth, though vortex appears at 90° and 180° in type d high-speed pump, the vortex decreases after flow across 180° position, and the flow after 270° is better without appearance of vortex, whereas in the flow in type a and b high-speed pump respectively, vortex always appears from 90° to 360°, therefore, the flow condition is not too optimistic.

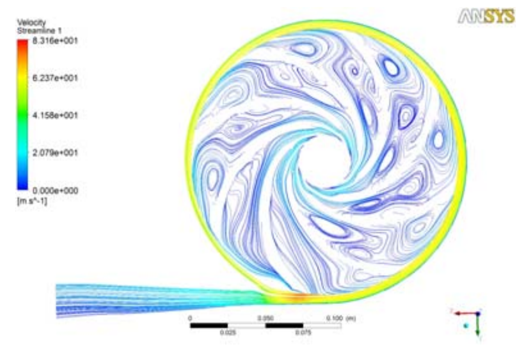
·Analysis of flow path line



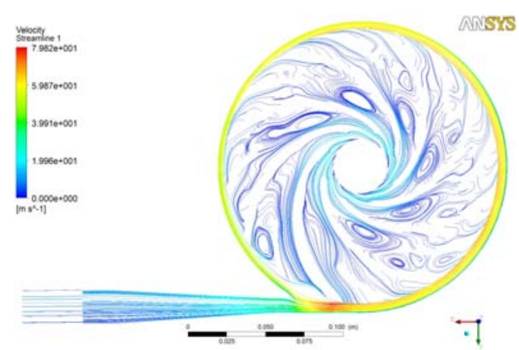
(a) Type a high-speed pump



(b) Type b high-speed pump



(c) Type c high-speed pump



(d)Type d high-speed pump

Figure 9． Flow path line diagrams of the four types of high-speed pump

Shown in Fig. 9 are the flow path lines of the four types of high-speed pump with low specific speed. The flow velocity distribution of the fluid in the four types of impeller of high-speed pump is basically consistent, especially in the annular volute, when the fluid reaches the nozzle position, the flow velocity is biggest; in the area from 0° to 90°, the flow condition in the flow passage of impeller is very good without generation of vortex and secondary flow, but with the continuous rotation of impeller, the degree of vortex development is related to shape of impeller; for the impeller with curved blades, both the amount and degree of vortex generation are on low side compared to the impeller with straight blades. The impeller of type c high-speed pump has generated relatively chaotic small vortex, full of the entire flow passage of impeller; in the entire interval of blades, type a generated sufficiently developed vortex with the rotation of impeller, but large vortex area has disappeared due to the action of short blades, and its flow condition is improved significantly relative to the flow condition of type b; type d generated smaller vortex at its inlet end, it can be obviously found that the number of vortexes is reduced greatly compared to type c in the flow passage area of short blades, the improvement of flow condition is also relatively significant, and both its flow state and vortex are best. Under the small- flow and high head operating conditions, use of type d can well improve the vortex condition of impeller and obtain better internal flow, and type c is second. When the impeller rotates again within the range of 0°~90°, as new fluid enters, the secondary flow and vortex attenuate until disappear. Because the head coefficient of open and semi-open impeller is relatively low, in the small-flow and high-head area, the performance of high-speed pump with curved blades is not as good as the pump with straight-blade impeller, and there is difficulty in machining.

The cross sections of flow passage of annular volute are equal everywhere, most of fluid flows out through the straight section of the diffuser, causing abrupt enlargement of internal space of flow passage in the area of straight section, the fluid inside the impeller rapidly flows out in order to fill the empty cavity, making most of fluid flow out of the impeller area from 0° to 90° and enters the annular flow passage, whereas the fluid in the area from 90° to 360° in the rotating direction of impeller seldom flows out of the impeller, yet the fluid in the area between two blades is relatively little, the blades lose control on this part of fluid, thus vortex is formed. This is because in the area from 0° to 90°, there is some empty space in the annular flow passage, the coefficient of mutual squeeze between fluid is relatively small; with the rotary flow of impeller, the fluid in the annular flow passage increases and the squeeze coefficient increases; the surface of annular flow passage cannot guarantee very high roughness, the rougher the surface, the bigger the energy loss of fluid on the wall, when velocity difference appears between fluid and impeller, relative slip takes place between blade end face and the fluid, the roughness of blade end face has also exerted very big influence on the fluid flow and caused energy loss, and the tangential velocity of the fluid drops accordingly. Through above analysis, the reason for reduction of tangential velocity of fluid in the annular flow passage is explained, this is also the reason that the static pressure in the area from 90° to 360° along the rotating direction of impeller is not increased, as observed in Fig. 3.

Whereas the internal flow of high-speed pump with low specific speed is relatively complex, studying the internal characteristics of high-speed partial emission pump with low specific speed plays a very good guiding role in the research of its [10].

PERFORMANCE PREDICTION ON ENTIRE FLOW FIELD OF HIGH-SPEED PUMP

Prediction of head and efficiency of high-speed pump

Using the surface integral function provided by Fluent, according to the total pressure $p_0 = p_s + \frac{1}{2}\rho c^2$ of flow field at a point [11], we can get according to the definition of head of high-speed pump:

$$H = \frac{p_{0out}}{\rho g} - \frac{p_{0in}}{\rho g} + \Delta z \qquad (1)$$

Read out moment value by Fluent through $M\omega = \rho g Q_t H_t$, calculate the sum M of moments of blades task and blades back and moment of stiffening rib surface of back cover of impeller about Z-axis, then we get an efficiency of high-speed pump:

$$\eta = \frac{\rho g Q H}{M'\omega} \qquad (2)$$

The computational model contains all flow passage components of the high-speed pump, mainly taking into account the hydraulic loss; in the computation, the surface roughness of impeller and pump chamber is taken into account, but the loss resulting from gearbox, mechanical seal etc. is neglected, this value is very small, therefore, it can represent the hydraulic efficiency, which approaches the actual efficiency value.

Total performance prediction of the four types of high-speed pump

These four types of high-speed pump are the same except for different shapes of the impellers, thus making the simulation results have comparability.

When CFD technique is used to predict the comprehensive performance of the four types of high-speed pump, the predictions are relatively accurate in the range of (0.4~1.4) Q, therefore, CFD technique is combined with the simulation results for prediction of comprehensive performance with a view to further studying their advantages and differences, as shown in Fig. 10.

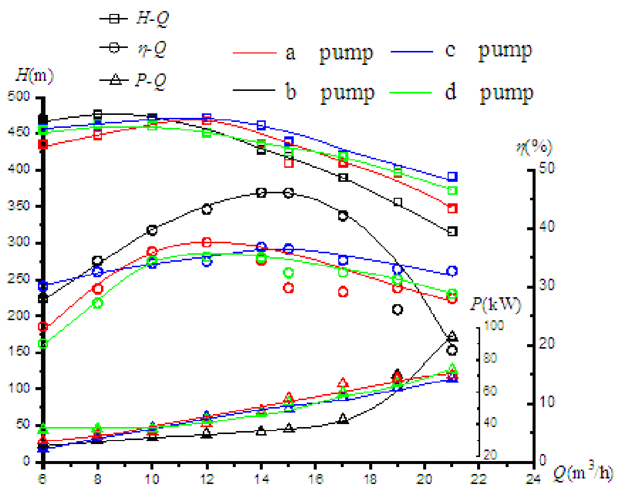


Figure10. Prediction for performance curves of the four types of high-speed pump

It can be seen from Fig. 10 that the heads of the four types of high-speed pump are basically consistent, all can reach the design operating conditions, yet, the cut-off flow of type a and b high-speed pump with straight blades exhibits more significant, all the four types of high-speed pump have distinct humps, in the range of (0.4~1.4)Q, type c performs better; viewing from efficiency characteristic curves, the efficiency of type b and c with fully open impeller has higher efficiency, the efficiency of type a and d with semi-open impeller is relatively low, and the efficiency of type b near the design operating point dominates obviously. The prediction of cut-off flow using CFD technique is not very accurate, the cut-off flow predicted by CFD is relatively big, even it cannot be calculated, therefore, further investigation is needed for this.

CONCLUSIONS

(1) Numeric simulation on internal flow of high-speed pump of different structural styles and comparison and analytical study of performance prediction are carried out.

(2) By comprehensive analysis of total pressure, static pressure, path lines and velocity cloud charts through numeric simulation, cavitation tends to take place at the inlet of all the four types of high-speed pump models, this is the reason why inducer must be added at impeller inlet, the pressure at outlet of high-speed pump with short blades is somewhat bigger, indicating that short blades are favorable to increasing pump head; the interaction between the fluid in the annular volute and wall generates vortex, causing energy loss of fluid and reduction of tangential flow velocity, even appearance of strong secondary flow; in the outlet area of the diffuser and in the outlet leading pipe there also appear relatively large recirculation and flow separation, resulting in increase of hydraulic loss, the flow state of type c and d is better; the numeric simulation results of type c high-speed pump is relatively ideal.

(3) The results of comprehensive performance prediction show that the performance of type c high-speed pump is better, and the efficiency of type b near the design operating point is significantly dominant.

(4) The simulation and prediction results obtained provide reference and basis for optimization design of high-speed pump with ultralow specific speed.

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