doi:10.3772/j.issn.1006-6748.2019.02.008

Theoretical and experimental research on influence of rotor taper on performance of cone-shape helical pumps①

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Abstract

The structure of a rotor has full impact on the performance of cone-shaped helical pumps. Numerical simulation and experimental tests are applied to get pressure, velocity and flow of a cone-shaped helical pump, and explores flow condition of blood in artificial blood pump. Rotors with four different tapers of artificial pump are designed. The flow condition of blood at the entrance, near the front diffuser, near the rotor, near the rear diffuser and at the exit, the pressure difference between entrance and exit and flow of artificial blood pump with different taper rotors are simulated, and then the influence rules of rotor taper on the performance of cone-shaped helical pump are revealed. In order to verify the correctness of theoretical analysis, rotors with three different tapers are manufactured, physical model of artificial blood pump are built, and then the actual lift and flow of blood pump with different rotors are measured respectively. The results show that taper of rotor increases, the circumfluence of blood near the front and rear diffuser decreases, the blood flows more smoothly, the energy consumption is less, and then the guide role of blade is greater. The blood at the exit of blood pump flows along the axial direction steadily. As taper of rotor increases, the pressure difference between the entrance and exit and the flow of blood pump increase subsequently. The flow condition of blood and performance of blood pump with No. 3 rotor are the best. The proposed research analyzes the influence of rotor taper on performance of blood pump quantitatively, and provides the theoretical reference for the design and improving of cone-shaped helical pump.

Key words: cone-shaped helical pump, rotor taper, circumfluence, flow condition, energy consumption

0 Introduction

Due to simple structure, small size and high efficiency, vane pump is one of the primary development directions of cone-shaped axial pumps[1,2].

At present, some scholars have done great investigation on the structure and performance of cone-shaped blood pumps. Koochaki et al.[3] designed a new miniature axial blood pump which could be easily implanted in the human body. Flow pattern through the pump has been predicted and overall pump performance and efficiency has been computed. Wu et al.[4] established blood flow channel models of maglev axial blood pump and compared the performance of pump with the diffusers of different parameters. The results showed that diffuser structures with thickening blade, 6 blades, 24° leading edge blade angle and 90° trailing edge blade angle, exhibited the best hydraulic performance. Su et al.[5] detached the blade from the diffuser hub to avoid irregular flow field. The results showed that the rotary diffuser hub improved the flow field significantly, especially near the diffuser hub. Gao et al.[6] analyzed numerically the hydrodynamic performance of an axial blood pump based on the stream-lined design. The results indicated the distributions of blood velocity field, pressure field and shear strain rate were all even, changing gradients were small, thus the blood destruction could be reduced effectively. Li et al.[7] designed a two-stage axial blood pump to reduce rotating speed and improve hemolytic performance of blood pump. The results indicated that the maximum stress of blood pump appeared in the inlet and outlet, besides, maximum stress of rear impeller inlet reduced signifi-

① Support by the National Natural Science Foundation of China (No. 51705445), Natural Science Foundation of Hebei Province of China (No. E2016203324) and Open Foundation of the State Key Laboratory of Fluid Power and Mechatronic Systems (No. GZKF-201714).
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Received on May 6, 2018

cantly with the effects of front impeller.

Liu et al.[8] studied the blood flow distribution in outflow cannula of an axial left ventricular pump. The results indicated that there was spiral flow and the flow became normal to the wall of cannula nearby the outlet of the blood pump. The flow in the cannula becomes smooth and steady gradually. The outflow cannula can decrease the spiral flow, which is helpful to improve the flow characteristics of the blood flowing from the axial blood pump.

Rotor is a power component of the artificial blood pump, and it has a full influence on pressure, flow and flowing condition of blood[9,10]. Hironori et al.[11] have done great investigation on the structure and performance of the blood pump. The spiral rotor has the characteristics of less shear force and higher efficiency of the blade on the blood. By studying the influence of the helical rotor taper on the blood pump performance parameter, the influence law of the rotor on the artificial blood pump can be found, which can lay a good foundation for the study of blood pump. But up to now, no effort toward the influence of taper of rotor on the flow condition of blood in artificial blood pump is found. So this study analyzes numerically and experimentally the effect of taper of rotor on performance of artificial blood pump, reveals the flow law of blood, and provides theoretical reference for the design and improving of cone-shaped helical pump.

1 Influence of taper of rotor on performance of blood pump

Artificial blood pump consists of inlet, front diffuser, rotor, rear diffuser and outlet[12], as shown in Fig. 1.

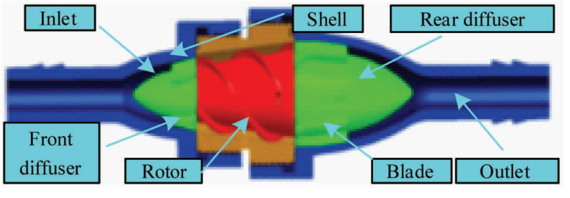


Fig. 1 Artificial blood pump

The big end and small end are inlet and outlet of blood pump respectively, and the blood flows helically along axial direction of rotor driven by blades[13], as shown in Fig. 2.

Due to the convenience of processing and the influence of existing experimental conditions in the laboratory, four different tapers of the rotor are designed, such as 5.950°, 7.125°, 8.300° and 9.460°. The pitch of the rotor is 35 mm, and blade number of rotor, front diffuser and rear diffuser are 3, 8 and 8 (Fig. 3) respectively.

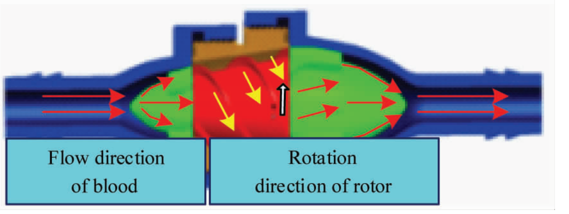
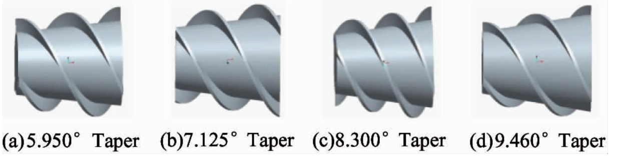


Fig. 2 Flow direction of blood in artificial blood pump



(a) 5.950° Taper (b) 7.125° Taper (c) 8.300° Taper (d) 9.460° Taper

Fig. 3 Rotor with different tapers

The models of blood pump and flow channel of artificial blood pump are established using Solidworks. The boundary condition of artificial blood pump is pressure inlet and outlet, and the contact face between rotor and diffuser is interface. The rotor is set for moving reference frame, and its rotate speed is 8000 r/min.

1.1 Velocity vector at entrance

The velocity vector of blood at entrance of blood pump is shown as Fig. 4.

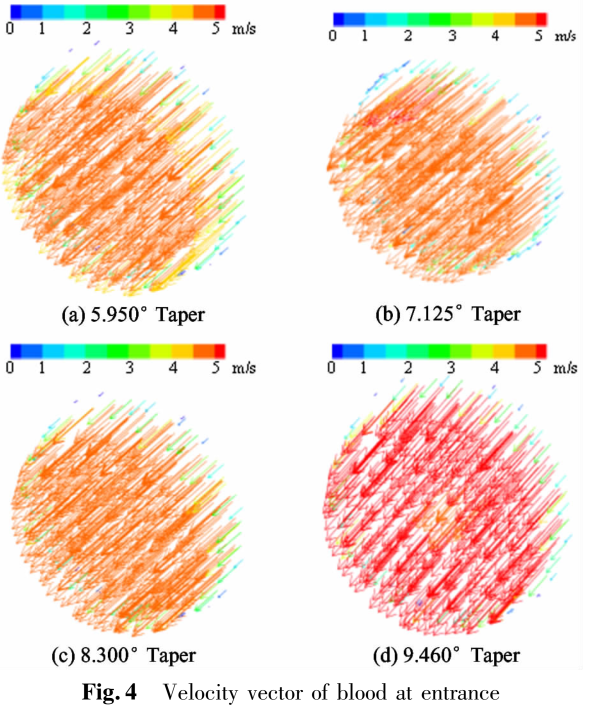


Fig. 4 Velocity vector of blood at entrance

The blood at entrance is not yet affected by the structure of blood pump, so it flows smoothly along axial direction of blood pump. The axial velocity amplitude of blood at entrance changes with the taper of rotor

(Fig. 4). The average velocity at entrance of blood pump with different rotor is shown as Table 1.

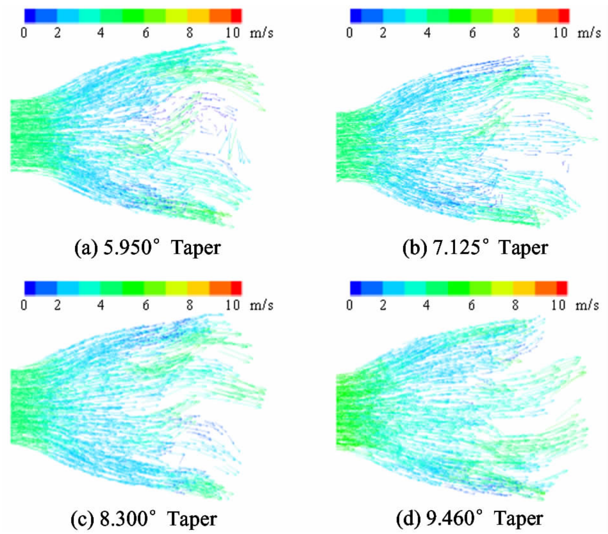
Table 1 Average velocity at entrance of blood pump with different taper of rotor

Taper of rotor(°)	5.950	7.125	8.300	9.460
Average velocity (m/s)	4.33	4.61	4.60	4.79

According to Bernoulli equation, when the velocity of blood at entrance of blood pump is relatively high, the pressure of blood decreases and even the partial vacuum is formed[14]. As the taper of rotor increases, the negative pressure at entrance increases gradually, the self-absorption performance of blood pump is improved, and then it results in the increases of velocity of blood at the entrance of blood pump ultimately.

1.2 Velocity vector near the front diffuser

The blood near front diffuser is subjected to thrust effect of guide vane, and the tangential velocity is generated[15]. There are obvious circumfluence and flow divert, and then swirls may occur (Fig. 5). So it can cause large energy loss, and even affects the flow stability of blood near the front diffuser.



(a) 5.950° Taper (b) 7.125° Taper (c) 8.300° Taper (d) 9.460° Taper

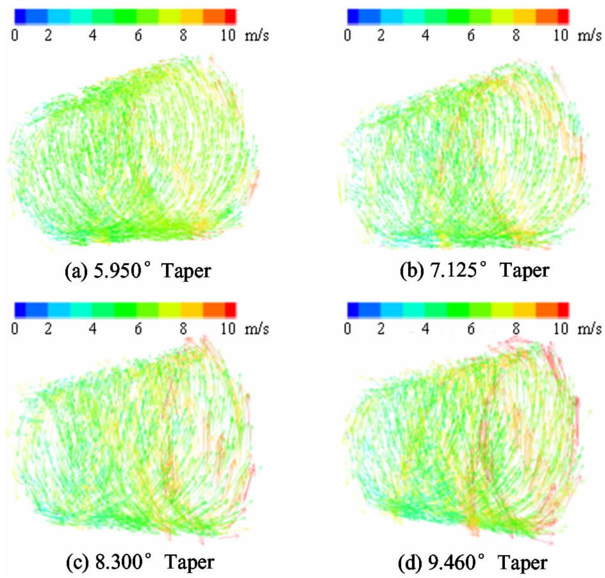
Fig. 5 Velocity vector of blood near front diffuser

As the taper of rotor increases from 5.950 ° to 9.460 °, swirls and energy loss of blood near the front diffuser decrease, blood flows more smoothly, and then the flow stability of blood near the front diffuser increases greatly.

1.3 Velocity vector near rotor

The blade of rotor is a key component of blood pump, and the velocity and pressure of blood near rotor can be improved by rotation of blade[16].

When blood flows through the front diffuser, the velocity of blood on left end of rotor is lower. Due to the thrust effect of blade, the velocity of blood on right end of rotor can be improved. Especially the blood near the blade of rotor bears the larger thrust force, and its velocity is greater than the other position, as shown in Fig. 6.



(a) 5.950° Taper (b) 7.125° Taper (c) 8.300° Taper (d) 9.460° Taper

Fig. 6 Velocity vector of blood near blade of rotor

As the taper of rotor increases from 5.950 ° to 9.460 °, thrust effect of blade of rotor and velocity of blood increase. But the partial rapid growth of blood between exit of rotor and rear diffuser would have a devastating impact on tissue of blood.

1.4 Velocity vector near the rear diffuser

Due to thrust effect of blade of rotor, blood with high pressure and velocity has a large impact on rear diffuser, and then circumfluence and turbulence of blood is generated easily. So it is necessary to correct flow direction of blood at exit of blood pump and reduce energy loss of blood[17,18].

When blood flows through blades of rear diffuser, the circumfluence and turbulence occur in the appropriate position, and then blood flows in disorder and irregularly. The flow velocity of blood near the back of blade of rear diffuser on the front end is large. When it flows into the area of rear diffuser, the flow velocity of blood can be improved by the guide role of blade, and then the tangential velocity has been modified, shown as Fig. 7.

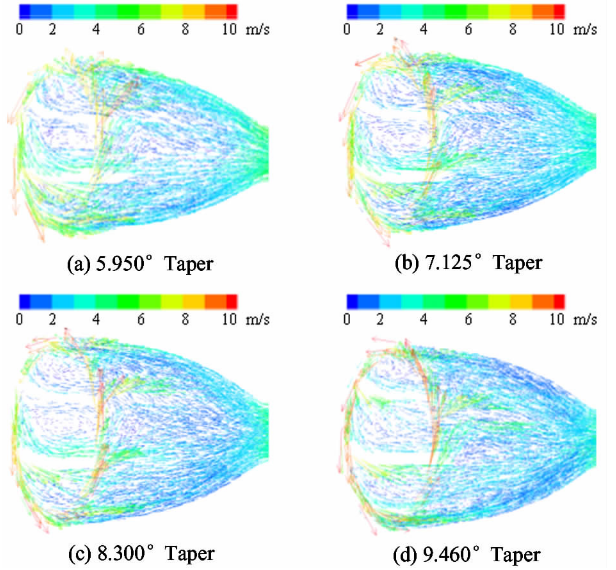


Fig. 7 Velocity vector of blood near blade of rear diffuser

As the taper of rotor increases from 5.950 ° to 9.460 °, the flow condition of blood after flowing through rear diffuser can be improved. The blood flows more smoothly, the circumfluence phenomenon of blood can be decreased, and the flow direction of blood becomes uniform.

1.5 Velocity vector at exit

The exit of blood pump links directly to blood vessels of human body, so it is important to make sure the flow condition of blood at exit of blood pump is very good[19].

As the taper of rotor increases from 5.950 ° to 9.460 °, the tangential velocity and axial velocity of blood at exit of blood pump decreases and increases gradually. The devastating impact on tissue of blood reduces and the performance of blood pump gets better (Fig. 8).

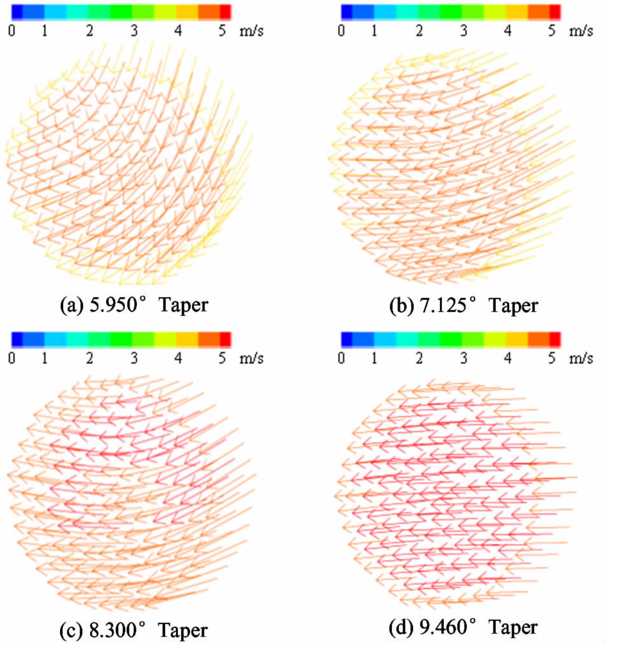


Fig. 8 Velocity vector of blood at exit

In order to analyze the influence of taper of rotor on the exit velocity, average value of exit velocity of blood pump with different rotor can be calculated (Fig. 9).

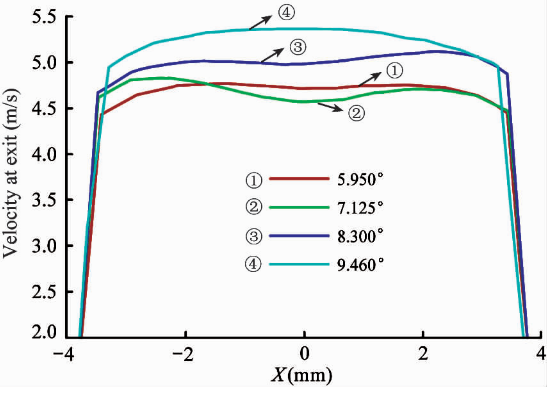


Fig. 9 Outlet velocity of blood pump with different rotor

As the taper of rotor increases from 5.950 ° to 9.460 °, the average velocity at the exit of blood pump increases, and the order is 4.37 m/s (5.950 °) < 4.50 m/s (7.125 °) < 4.75 m/s (8.30 °) < 4.97 m/s (9.460 °). The flow of blood pump can be improved with the taper of rotor.

1.6 Flow and pressure difference between inlet and outlet

The flow of blood pump can be improved with the taper of rotor (Fig. 10). As the taper of rotor increases from 5.950 ° to 7.125 °, the flow increases from 13.69 L/min (5.950 °) to 13.73 L/min (7.125 °), and the changing flow of blood pump is very small. As the taper of rotor increases from 8.300 ° to 9.460 °, the flow increases from 14.54 L/min (8.300 °) to 15.30 L/min (9.460 °), and the changing flow of blood pump is large.

As the taper of rotor increases, the pressure difference between inlet and outlet of blood pump increases gradually (Fig. 10).

Increasing the taper of rotor, pressure, flow and performance of blood pump would be improved. But blood pump is installed inside human body, the size of blood pump is limited strictly. So higher request is put forward for the structure design and performance improving of blood pump because of its install position.

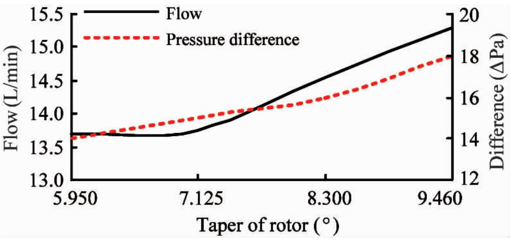


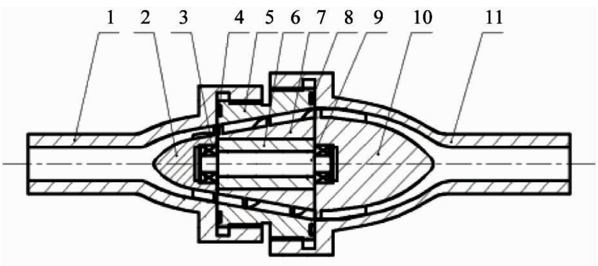
Fig. 10 Flow and pressure difference of blood pump with different rotor

2 Experimental test of taper of rotor on performance of blood pump

In order to verify the correctness of theoretical analysis, a physical model of artificial blood pump is built, which can provide the theoretical reference for the design and improving of cone-shaped helical pump.

2.1 Manufacture

The blood pump is shown in Fig. 11. The materials of shell, diffuser and rotor are plexiglass, PTFE and PTFE respectively. Rotor axis is made of stainless steel and Nd-Fe-B magnetic stripes with high magnetic energy.



1, 11—inlet and outlet; 2, 10—front and rear diffuser; 3—sliding bearing; 4, 8—O-ring; 5—shell; 6—magnet; 7—rotor; 9—axis

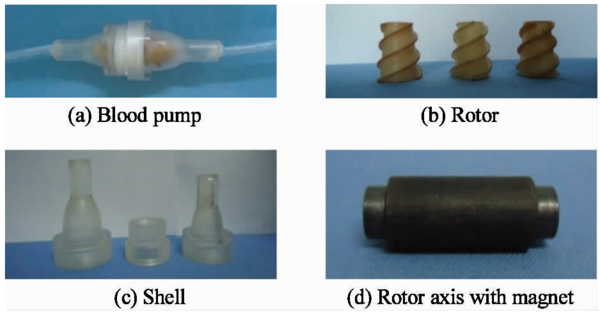
Fig. 11 Blood pump

Three rotors with different taper are manufactured with CL30 NC Machine Tools of Yanshan University. The taper of No. 1, No. 2 and No. 3 rotors are respectively 7.125 °, 8.300 °, and 9.460 °. The blades of front and rear diffusers are oval-shape. The pitch and number of blade of rotor are respectively 35 mm and 3. The physical prototype of blood pump and key components are shown in Fig. 12.

2.2 Experimental device and principle

2.2.1 Experimental device

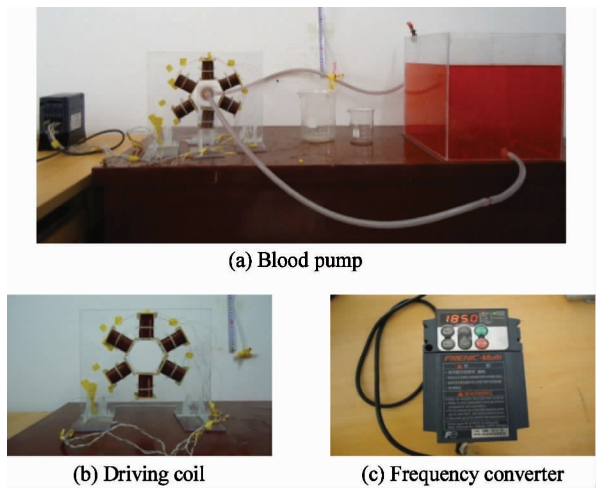
The physical prototype of blood pump is made up of body of blood pump, frequency converter and driving coil (Fig. 13). Body of blood pump consists of inlet, front diffuser, shell, rotor, outlet and rear diffuser.



(a) Blood pump (b) Rotor (c) Shell (d) Rotor axis with magnet

Fig. 12 Blood pump and key components

Permanent magnet and needle roller bearings are installed inside the rotor and the front and rear diffusers respectively. The shell is sealed by O-ring and the inlet and outlet are linked with plastic tubes. Six driving coils with cylindrical symmetry are winded by 4 000 turns of Φ 0.625 enameled wires, and diameter of the center hole is 80 mm. Model FRN0.75E1S frequency converter has an important role of adjusting rotation of rotor.



(a) Blood pump (b) Driving coil (c) Frequency converter

Fig. 13 Prototype and key components of blood pump

2.2.2 Experimental principle

Cone-shaped helical pump is derived by electromagnetism. When the power source is turned on, the alternating magnetic field generated is coupled with permanent magnet to drive rotor to revolve at high speed. The rotation speed, pressure and flow of blood pump can be adjusted by changing frequency of frequency converter. Partial vacuum is formed by rotation of rotor at entrance of blood pump, and then blood can be inhaled from inlet of pump. After guiding and diversion of blade of diffuser, blood flows into blade groove of rotor and is continually pushed to outlet. Blood flows gradually along the axial direction toward the human body after guiding the role of blade of rear diffuser.

2.3 Experimental step

(1) Build blood pump prototype experimental table, link inlet of blood pump to water tank, and link outlet to throttle.

(2) Fill blood pump with media, and check seal of blood pump. Make sure that level in water tank and axis of blood pump should be positioned in the same horizontal plane.

(3) Adjust frequency of frequency converter, and change rotation speed of blood pump. Improve rotation of rotor gradually at 150 r/min intervals, and view relationship between flow and lift of blood pump.

(4) Replace No. 2 and No. 3 rotor, and repeat above operations.

2.4 Experimental result

Flow and lift of blood pump can be measured with cup, stopwatch and tape measures. Relationship between flow and lift of blood pump with No. 1 rotor is recorded. Rotation of pump increases gradually from 5250 r/min at 150 r/min intervals, and the maximum withstand rotation speed of physical prototype of blood pump is tested. The result of experimental test is shown as Table 2.

Table 2 Flow of blood pump with different lift and rotation speed (L/min)

		Rotation speed (r/min)				
		5250	5400	5550	5700	5850
Lift (mmHg)	7.60	1.50	1.60	1.64	1.66	1.69
	15.20	1.36	1.50	1.54	1.56	1.64
	22.80	1.33	1.38	1.45	1.48	1.52
	30.40	1.28	1.29	1.30	1.36	1.36
	38.00	1.14	1.15	1.25	1.26	1.29
	45.60	0.97	1.02	1.07	1.10	1.13
	53.20	0.80	0.87	0.95	0.96	0.99
	60.80	0.61	0.71	0.77	0.79	0.83
	68.40	0.40	0.56	0.56	0.60	0.68
	76.00	0.12	0.30	0.36	0.44	0.48
	89.70	0.00	0.00	0.00	0.21	0.41
	91.20	—	—	—	0.00	0.18
	98.80	—	—	—	—	0.00

According to Table 2, as the rotation speed of blood pump increases, the flow and lift of blood pump can be increased gradually, and it is accorded with simulation result. Simulation results and experimental results of blood pump at 5700 r/min are contrasted (Fig. 14).

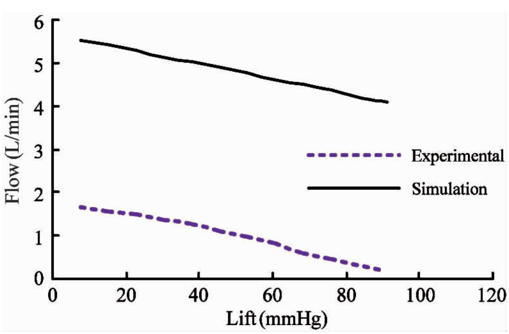


Fig. 14 Lift and flow of artificial blood pump

The error between the theoretical value and experimental value is caused by internal leakage duo to processing and assembling tolerance of blood pump, and it is within the limits permitted by project. The changing trends of lift and flow of blood pump by numerical simulation are generally consistent with that by experiment test.

Similarly, simulation results and experimental results of blood pump at 5400 r/min and 5700 r/min are contrasted (Table 3).

Table 3 Simulation and experimental data of blood pump

			Maximum flow (L/min)	Maximum lift (mmHg)
Rotation speed (r/min)	5400	Simulation	5.30	315.8
		Experiment	1.60	89.7
	5700	Simulation	5.60	360.1
		Experiment	1.66	91.2

According to Table 3, simulation values of flow and lift of blood pump are triple experimental values at 5400 r/min and 5700 r/min. Processing and assembling precision of blood pump is very low, and then the leakage of blood pump is large. Finally it results in error between simulation value and experiment value.

Replace No. 2 and No. 3 rotor, and repeat above operation. The flow and lift of blood pump with three different rotors at 5700 r/min are measured and recorded (Fig. 15).

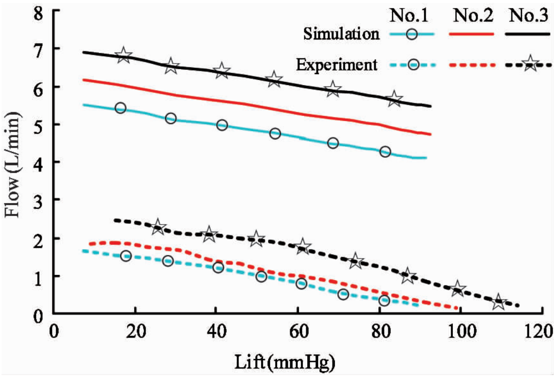


Fig. 15 Simulation and experiment value of blood pump with three rotors

According to Fig. 15, the order of flow of blood pump with three different rotors at the same lift is No. 2 rotor (8.300 ° taper) > No. 3 rotor (9.460 ° taper) > No. 1 rotor (7.125 ° taper). There is error between the theoretical value and experimental value. The degree of linearity of simulation flow and lift is obviously better than experimental value. So high request is put forward for structure design and processing and assembling precision of blood pump.

3 Conclusions

The blood at the entrance is not yet affected by structure of blood pump, so it flows smoothly along axial direction of blood pump.

The blood near the front diffuser is subjected to thrust effect of guide vane, and the tangential velocity is generated. As taper of rotor increases, the circumfluence of blood near the front diffuser decreases, the blood flows more smoothly, the energy consumption is less, and then the guide role of blade is greater.

Due to thrust effect of blade of rotor, the velocity of blood near the rear diffuser has been improved significantly. As the taper of rotor increases, the circumfluence and energy loss of blood can be decreased, and blood flows more smoothly, and then guide role of rear diffuser gets greater.

The blood at the exit of blood pump flows more smoothly along the axial direction steadily after the guide role of blade of rear diffuser.

As taper of rotor increases, pressure difference between entrance and exit and flow of blood pump subsequently increase.

By contrasting flow condition of blood of blood pump with three different rotors at entranced, front diffuser, rotor, rear diffuser and exit, the flow condition of blood and performance of blood pump with No. 3 rotor (9.460 ° taper) are best.

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