Optimization analysis for blades of artificial heart pump based on CFD

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Abstract. In this paper, computational fluid dynamics is used to simulate and analyse the flow field of a centrifugal artificial heart pump. First, the structural parameters of the centrifugal blood pump are initially determined, and the three-dimensional model of the flow field is established. The blood supply head of the pump is calculated based on the simulation results. The head of the centrifugal blood pump is 124.31mmHg under the design conditions (rotating speed is 2400rpm, flow rate is 6L/min), which meets the blood supply requirement of the heart pump. Then, by changing the blade profile length and blade shape, the performance of the centrifugal blood pump can be improved. The standard hemolysis index of the improved centrifugal blood pump dropped from 0.0508 to 0.0417, and its head is 119.65mmHg. It indicates that while reducing the destruction of blood cells by the heart pump, the requirement of blood supply head can still be met. The simulation results of this study can provide references for the design of centrifugal blood pump blades.

1. Introduction

With the development of economy and society, profound changes have taken place in the national lifestyle. Especially with the acceleration of population aging and urbanization, the number of cardiovascular diseases continues to increase. The number of patients suffering from cardiovascular disease will continue to grow rapidly in the next ten years. Cardiovascular disease has the highest mortality rate among all diseases. Therefore, it is of great significance to the prevention and treatment of cardiovascular diseases [1].

Extracorporeal Membrane Oxygenation (ECMO), as a medical device that can effectively treat cardiovascular diseases, is mainly used to provide continuous extracorporeal breathing and circulation for patients with severe cardiopulmonary failure to maintain patients' lives. The artificial heart pump is an important component of ECMO, and its main function is to temporarily supply blood to the human body instead of the heart.

The development of artificial heart pump has gone through three generations. The first generation is a bionic pulsating artificial heart pump, which is developed according to the physiological characteristics of the human heart. It mainly uses the periodic change of the volume of the pneumatic pump to supply blood. The second generation is a non-bionic vane artificial heart pump. It relies on an external motor
to drive the blood flow in the pump through the rotation of the blades to achieve blood supply. The third generation is a magnetic levitation artificial heart pump. It uses magnetic bearings without mechanical contact, so that the rotor does not directly contact the pump casing. In this way, mechanical friction can be avoided and the damage to blood cells can be reduced [2]. Now the third-generation artificial heart pumps with more mature technology include ChinaHeart VAD [3] and HeartMate III [4].

The development of computational fluid dynamics has brought new methods to the design and research of artificial heart pumps, and has also promoted the development of artificial heart pumps. Research by Yamane et al. showed that the mechanical structure of the centrifugal blood pump has a great influence on hemolysis [5]. Chen Songsong designed artificial heart pumps with different numbers of blades, and concluded that the hemolysis characteristics of the blood pump are the best when there are 6 blades [6]. Li Weidong designed 3 different diversion cone structures and set diversion cones with different heights of 0-7mm for simulation comparison [7]. Hu Wanqian designed a series of simulation experiments to study the influence of flow rate and blade outlet width on hemolysis performance of centrifugal blood pump [8].

In the artificial heart pump, the red blood cells will experience greater shear stress. This leads to the destruction of the cell membrane, leading to the outflow of hemoglobin and other substances in the cell, and losing the function of supplying oxygen to the human body. This phenomenon is called hemolysis. Hemolysis is a problem when we design a centrifugal blood pump. In this paper, comsol is used to model and simulate the flow field of an artificial heart pump. The purpose of this paper is to explore the influence of the blade form of the centrifugal artificial heart pump on hemolysis, so as to change the structure of the artificial heart pump and improve the performance of the artificial heart pump.

2. Model and forecasting method

2.1. Establish flow field model of centrifugal blood pump

The blood supply head of a normal adult heart is 80~120mmHg, and the blood supply flow is at least 5L/min. First, determine the basic performance parameters of the heart pump. The head is 120mmHg, the flow is 6L/min, and the rotating speed is 2400rpm.

Based on the head, flow and speed determined above, the basic structural parameters of the centrifugal blood pump can be calculated preliminarily. These parameters are shown in Table 1. When designing an impeller, the overall size and shape of the impeller are usually determined first, and then the blade profile is determined. For centrifugal blood pumps, the blade profile should be designed to minimize the damage of the blades to the blood cells, while meeting the requirements of head and flow. With the traditional impeller design method, the design is only carried out in the inlet and outlet parts, and the blade profile is not involved. In fact, the blade profile has a great influence on the performance of the impeller [9]. Common blade profiles include arc, parabola, straight blade, airfoil and so on. In this paper, the quadratic Bezier curve is used, and its length is initially determined to be 22mm. The impeller model is shown in Figure 1.

| Parameter | Value |
|-----------|-------|
| Impeller inlet diameter | 16.5mm |
| Impeller outlet diameter | 44mm |
| Impeller inlet width | 4mm |
| Impeller outlet width | 2.3mm |
| Volute base circle diameter | 44.5mm |
| Volute inlet width | 4.1mm |
| Blade inlet angle | 22° |
| Blade outlet angle | 29° |

Table 1. Basic structure parameters.
After determining the main structural parameters of the centrifugal blood pump, the flow field model of the centrifugal blood pump can be initially established. The model is mainly composed of three parts—the inlet part, the impeller part and the volute part, as shown in Figure 2.

2.2. Artificial heart pump blood supply performance
After establishing the flow field model of the centrifugal blood pump, it is necessary to determine whether the design can meet the head requirement of the centrifugal blood pump. When the inlet flow is 6L/min and the rotating speed changes, the result is obtained through simulation calculation. The trend of head is shown in Figure 3. When the speed is 2400rpm, the pump head is 124.31mmHg, which is greater than the design head index of 120mmHg. It indicates that the design can meet the requirements of centrifugal blood pump.

At the same time, as the rotation speed increases, the pump head increases linearly. When the speed is between 2000 and 2800 rpm, the pump head can be predicted.

2.3. Hemolysis prediction method
Giersiepen et al. proposed a widely used hemolysis prediction method [10]. The hemolysis prediction method can be written as

\[ D = \frac{\Delta Hb}{Hb} = 3.62 \times 10^{-7} t^{2.416} r^{0.785} \]  

Where Hb is the total amount of hemoglobin, \( \Delta Hb \) is the free hemoglobin content caused by hemolysis, t is the exposure time of red blood cells, \( \tau \) is the shear stress of red blood cells.

Based on the hemolysis prediction model proposed by Giersiepen et al., Garon et al. proposed a fast hemolysis prediction method for three-dimensional numerical simulation based on the hyperbolic transport equation [11].

The hyperbolic transport equation can be written as
Where $D_l$ is the linear hemolysis index, $\sigma$ is the hemolysis destruction rate per unit time, and $V$ is the velocity vector.

\[ D_l = D^{0.785} \]  \hspace{1cm}  (3)

\[ \sigma = (3.62 \times 10^{-7})^{0.785} \tau^{2.416/0.785} \]  \hspace{1cm}  (4)

After obtaining a stable flow field through simulation calculation, considering the overall average hemolysis characteristics of the flow field, the average linear hemolysis index can be written as

\[ \bar{D}_l = \frac{1}{Q} \int \sigma dV \]  \hspace{1cm}  (5)

Where $Q$ is the flow rate of the centrifugal blood pump.

By index conversion, the hemolysis value of artificial heart can be written as

\[ D = \bar{D}_l^{0.785} \]  \hspace{1cm}  (6)

Finally, standard hemolysis index (NIH) can be written as

\[ \text{NIH} = \text{Hb} \times D \times 100 \]  \hspace{1cm}  (7)

The maximum value of NIH is 0.1g/100L.

2.4. Shear stress calculation model

The shear stress in the flow field includes the molecular shear stress caused by fluid viscosity and the Reynolds shear stress caused by turbulence. The total shear stress can be written as

\[ \tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \rho u_i u_j \]  \hspace{1cm}  (8)

\[ -\rho u_i u_j \] is the Reynolds shear stress, which can be written as

\[ -\rho u_i u_j = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \rho \kappa \delta_{ij} \]  \hspace{1cm}  (9)

Where $\mu_t$ is the turbulent viscosity, $\kappa$ is the turbulent kinetic energy, $\delta_{ij}$ is the kronecker operator.

The tensor form of the total shear stress needs to be converted into a scalar form for hemolysis prediction. The scalar form of shear stress can be calculated by the method proposed by Bludsuweit [12]. The scalar form of shear stress can be written as

\[ \tau = \left( \frac{1}{6} \sum (\tau_{ii} - \tau_{ij})^2 + \sum \tau_{ij}^2 \right)^{1/2} \]  \hspace{1cm}  (10)

3. Results and optimization

By simulation calculation under design conditions, shear stress distribution is shown in Figure 4.
As shown in Figure 5, in the flow field at the impeller, large shear stress is distributed at the inlet and outlet of the blade. It can be inferred that the structural parameters of the blade have a large influence on the shear stress. Therefore, in this paper, research the influence of blade profile length and blade shape on the flow field. The performance of the centrifugal blood pump under different structural parameters is judged by comparing the standard hemolysis index in the flow field.

![Shear stress distribution at the impeller.](image_url)

**Figure 5.** Shear stress distribution at the impeller.

### 3.1. The length of the blade profile

In the process of designing the impeller, many problems related to the blade profile were ignored. However, the blade profile has a great influence on the performance of the impeller. First of all, we consider the influence of different blade profile lengths on standard hemolysis index.

We first change the length of the impeller profile, but do not change other structural parameters. The flow field model with blade profiles of different lengths is shown in Figure 6.

![Flow field model with different blade profile length.](image_url)

**Figure 6.** Flow field model with different blade profile length.

The Standard hemolysis index of the centrifugal blood pump under different blade profile lengths is obtained by simulation calculation. The variation trend of standard hemolysis index with blade profile length is shown in Figure 7.
As shown in Figure 7, when the blade profile length is 25mm, the standard hemolysis index of the pump is the lowest. It indicates that the destruction of blood cells by centrifugal blood pump is small when the blade profile length is 25mm.

Next, we analyse the influence of the blade profile length on the average velocity of the flow field at the impeller. Fig. 8 shows the flow velocity distribution at the same height of the impeller under different profile lengths.

As shown in Figure 8, it can be found that the longer the impeller profile is, the smaller the area of the red area near the edge of the blade (high flow velocity area). The trend of the percentage of flow velocity at the impeller greater than 5m/s is shown in Figure 9, and the trend of the average velocity is shown in Figure 10. It shows that as the length of the blade profile increases, the average speed gradually decreases. The low speed can reduce the impact damage of the impeller blades to the red blood cells [13]. When the blade profile length is greater than 25mm, the percentage of the larger flow velocity
decreases slowly. This may be the reason why the standard hemolysis index of the centrifugal blood pump has not changed much. As shown in Figure 7, when the length of the impeller blade profile is greater than 25mm, the standard hemolysis index will fluctuate.

![Figure 7](image1.png)

**Figure 7.** The trend of the percentage of speed at the impeller greater than 5m/s.

As shown in Figure 10, the average flow velocity of the flow field at the impeller decreases linearly with the increase of the blade profile length. It indicates that the blade profile has a great influence on the flow field at the impeller. This can be used as a reference for the design of the impeller profile.

![Figure 10](image2.png)

**Figure 10.** The trend of the average velocity of the flow field at the impeller.

As shown in Figure 10, the average flow velocity of the flow field at the impeller decreases linearly with the increase of the blade profile length. It indicates that the blade profile has a great influence on the flow field at the impeller. This can be used as a reference for the design of the impeller profile.

### 3.2. Blade shape

When the length of the blade profile gradually increases, the volume of the flow field at the impeller gradually decreases, as shown in Figure 11. It is expected that the smaller the flow field volume at the impeller, the smaller the average velocity. Based on this idea, the volume of the flow field at the impeller is further reduced to further reduce the area of larger flow velocity in the flow field. Therefore, choose a blade form whose thickness gradually increases from the inlet to the outlet, called a thick blade, as shown in Figure 12. In this way, the volume of the liquid flowing through the impeller will be reduced.
to 3640.2mm³, and when the blade profile length is 25mm, the volume is 4545mm³. The flow field model is shown in Figure 13.

![Flow field model](image)

**Figure 11.** The trend of the flow field volume at the impeller.

![Thick blade](image)

**Figure 12.** Thick blade.

![Flow field model with thick impeller blade](image)

**Figure 13.** Flow field model with thick impeller blade.

### 3.3. Comparison

After changing the blades to thick blades, through simulation calculation, the standard hemolysis index is 0.0417, and the average speed is 2.39m/s. These parameters are all reduced compared with the blade profile length of 25mm. It indicates that with thick blades, the standard hemolysis index will be further reduced, and the centrifugal blood pump has better performance. The comparison of the centrifugal blood pump before and after the improvement is shown in Table 2.

| Numble | Blade profile | Standard hemolysis index | Head       |
|--------|---------------|--------------------------|------------|
| 1      | 22mm          | 0.0508                   | 124.86mmHg |
| 2      | 25mm          | 0.0464                   | 120.08mmHg |
| 3      | Thick blade   | 0.0417                   | 119.65mmHg |

When changing the impeller blade profile, first change the length of the blade profile. It is found that when the length of the blade profile is 25mm, the standard hemolysis index is relatively small. However, when the length of the impeller blade profile is continued to increase, the standard hemolysis index does not change significantly, and even tends to increase. Then, when the blades were changed to thick blades,
the standard hemolysis index dropped from 0.0508 to 0.0417 compared to the original design. It indicates that thick blades have better performance.

4. Conclusion
In common impeller design methods, the head of the impeller is only related to the inlet and outlet parameters. When using common methods to design impellers, we generally only design the impeller inlet and outlet diameter, blade height, and blade inlet and outlet placement angles, without considering the blade profile. However, the blade profile has a great influence on the flow field at the impeller, and the application of the centrifugal blood pump is relatively special, so it is necessary to consider the influence of the blade profile on the flow field.

In this paper, computational fluid dynamics methods are used to simulate the flow field of blood pumps with different blade profile lengths and shapes. Simulation results illustrate:
(a) As the length of the impeller profile increases, the average velocity of the flow field at the impeller decreases linearly.
(b) When the blade profile length is 25 mm, the standard hemolysis index of the centrifugal blood pump is as low as 0.0464, which is 8.66% lower than the initial design. When the blade is changed to a thick blade, its standard hemolysis index is 0.0417, which is 17.9% lower than the original design. The results show that thick blades are more suitable for centrifugal blood pumps.

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