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Analysis of blood cell particles in axial blood pump by using computational fluid dynamics/discrete element method model

Cheng Lizhi[1,2], Tan Jianping[1], Yun ZHong[1], Xu Yan[2]

[1] School of Mechanical and Electrical Engineering, Central South University Changsha 410083, China
[2] Department of Mechanical and Electrical Engineering, Changsha University Changsha 410022, China
E-mail: jptan@163.com

Abstract. Computational fluid dynamics/discrete element method (CFD-DEM) model was used to investigate the microscopic motion law of blood cells in a blood pump. The macro-hydrostatic performance indexes of the blood pump, as well as the characteristics of motion, collision. Result showed that collision among the blood cells mainly occurred at the front guide and the back guide, and the collision rate between the blood cells and the wall surface was 2.3 times the collision rate among the blood cells at the front guide vane area of the vane rotor.

1. Introduction

Blood pump as an important supplementary device for life saving has become the focus of research for scholars worldwide [1,2]. CFD technology can be used to conduct more detailed analyses of flow field to obtain the specific area where the solid-phase blood cell particles are broken and damaged. However, no technical breakthrough exists in CFD technology to study the dynamic characteristics of the motion and collision of blood cell particles at different time points and positions. Alobaid[3] built the extended CFD/discrete element method (CFD-DEM) evaluation model, which can accurately predict the motion and pressure gradient of particles. Fries[4] simulated the dynamic CFD-DEM coupling of particles on the fluid bed and studied the dynamic properties of particles. Ren[5] investigated the CFD-DEM coupling of conical gas–solid flow characteristics, the gas–solid flow structure, particle velocity, and the distribution of particle concentration. With CFD-DEM liquid–solid–gas multiphase flow coupling technology, particle distinct element method can be used to analyze the motion, collision, and breakage of molecular-scale blood cell particles, taking into consideration the true blood rheology characteristics of blood cells to lay the foundation for building the hemolytic index model for blood cell mechanical properties and blood rheology coupling.

2. Calculation model

2.1 Geometric model

This work studies the axial blood pump model (Fig. 1). The model consists of three parts, namely, the front guide, the vane wheel, and the back guide. In addition to supporting the rotor of the vane wheel, the front and back guides divert the flow of blood at the inlet and outlet. The inner diameter of the blood pump is 16 mm and the total length is 81 mm. The rotor vane is formed by two long blades and two short blades, and the clearance between the blade tip of the rotor and the inner wall of the body is 0.1 mm. To simplify the calculations, the blood cell model used was a single sphere with a radius of

0.01 mm, as blood is mainly composed of red blood cells.

Fig. 1 Axial blood pump model

2.2 Division of meshes

As the vane wheel rotates at a high speed, the inner flow field is divided into three parts, namely, blood pump front guide fluid, vane wheel fluid, and back guide fluid, to increase the calculation accuracy. All three parts used non-structural tetrahedral meshes. The clearance fluid on the blade tip is encrypted by the mesh on the border. The space between the meshes of the front and back guide fluids is set at 0.4, and the space of some meshes of the vane wheel fluid is set at 0.1. The total number of meshes is 2 586 162. Fluent was used to import the mesh file, and the unit is converted to mm. Surface finish, exchange, and considerable refinement were conducted on the meshes, and the quality was checked.

3. Border conditions

Through multiple numerical calculations, the multiple reference frame parameter was used in Fluent to calculate the standard $k-\varepsilon$ used by the model, and pressure inlet and outlet were used to obtain stable calculation results. The other Fluent and EDEM (Engineering Discrete Element Method) coupling calculation parameters are listed in Tables 1 and 2.

Table 1. CFD calculation parameters

Parameters	**Values**
Inlet pressure p_i / Pa	1 333
Outlet pressure p_e / Pa	13 333
Viscosity μ_b / (Pa·s)	0.004 7
Simulation time t / s	0.2

Table 2. EDEM calculation parameters

Parameters	**Values**
Particle diameter d_p / μm	10
Particle density ρ_p / (kg·m^{-3})	1 050
Particle shear modulus G_p / Pa	100 000
Border shear modulus G_w / Pa	100 000
Particle Poisson ratio v_p	0.3
Border Poisson ratio v_w	0.3
Static friction coefficient μ_p	0.3

4. CFD-DEM analysis of the flow field and blood cell particles in the blood pump

4.1 Analysis of blood cell particle collision

From the number of collision times and rates of blood cell particles among themselves and between the blood cell particles and wall surface (including vane wheel surface, flow guide surface, and the inner wall surface of the pump body), the collision laws under different velocities are essentially the same, and the collision rate is quite stable (Fig. 2). When blood cell particles flow to the vane wheel area, they do not flow completely and collide with the vane wheel that rotates at high speed at a velocity of 1.2 m/s. As the linear speed of the vane wheel, particularly the blade top, is quite high, the blood cell particles are instantly driven to collide with the wall surface and with each other. With the creation of the passageway, particularly at the back guide area, the flow becomes stable and the diversion effect is quite significant.

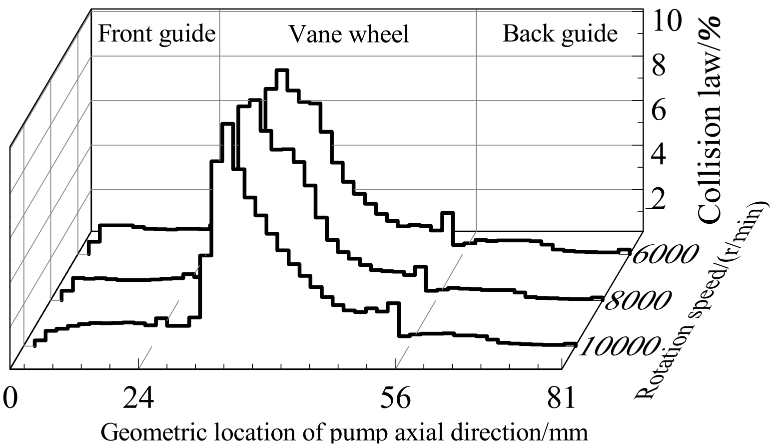

Fig. 2 Total collision rate of the blood pump at different velocities

The collision law of blood cell particles against the wall surface was thoroughly analyzed. As shown in Fig. 3, the rates of collision among the blood cell particles and between blood cell particles and the wall surface are similar, but the two types of collision rates are not the same when the fluid passes various parts of the pump body. The blood pump model shown in Fig. 1 consists mainly of the collision among blood cell particles because it only has four guide blades, and the flow is mainly streamlined. Based on the field velocity of blood fluid in Fig. 5, when the blood cell particles entered the vane wheel area with the blood fluid, the velocity of blood cell particles is significantly different from the linear velocity of the vane wheel. At this point, a large amount of blood cell particles are driven toward the wall surface, and the rate of collision between the blood cell particles and the wall surface is 2.3 times the rate of collision among the blood cell particles. With the flow diversion effect of the vane wheel blades and the back guide blades, the two types of collision rates are similar and are lower than the inlet.

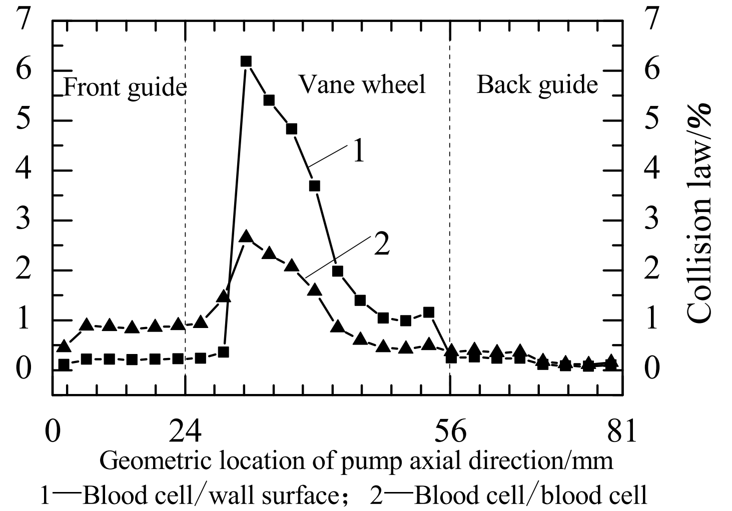

Fig. 3 Collision rate between blood cells and wall surface in the blood pump at 8 000 rpm

5. Conclusions

The liquid–solid multiphase coupling technology based on CFD-DEM used particle distinct element method to analyze the motion law of molecular-scale blood cell particles in the axial blood pump, taking into consideration the macro flow of blood cells. The convergence characteristics of blood cell particles were also studied. This axial blood pump has similar collision law at 10 000 rpm. The collision mainly occurred among the blood cell particles at the front and back guides. The collision rate between the blood cell particles and the wall surface at the front guide blade area of the vane wheel is 2.3 times the collision rate between blood cell particles. The collisions have created evident blood cell particle convergence phenomena at the clearance between the vane wheel and the back guide as well as the outlet of the back guide.

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