Analysis of the Bioprosthetic Heart Valve by using Arbitrary Lagrange–Euler Method and SIMPLE Algorithm

Bingshen Shen, Quan Yuan*, Jun Zhang, Xia Zhang, Xiao Zhang, Hua Cong

School of Mechanical Engineering, Shandong University, and Key Laboratory of High-Efficiency and Clean Mechanical Manufacture (Shandong University) Ministry of Education, Jinan 250061, P. R. China

Abstract **— In this paper, we propose a new method to analyze the fluid-structure interaction of Bioprosthetic heart valve. Arbitrary Lagrange –Euler method and SIMPLE algorithm will be combined to obtain equations coupling between the blood and the leaflets. After that, a leaflet model have been established according to the natural valve, and the model analyzed by the new method. It can be concluded that the leaflets in the abdomen and free edges have more obvious deformation that other regions. The same results can be get by the experiment which have the similar boundary conditions to the simulation. This method is proved correctness which can be used in the study of the coupling process of the leaflets and blood, and it could provide a reference and help to the manufacture of valve.**

Keywords - Finite element method (FEM); Bioprosthetic heart valve (BHV); Fluid structure interaction; Dynamic simulation; SIMPLE algorithm; Arbitrary Lagrange –Euler method(ALE)

I. INTRODUCTION

Valvular heart disease for the patient can be said to be fatal, we must take timely treatment measures, and currently the main treatment for valvular heart disease is heart valve replacement [1]. In the United States alone, there are over 80,000 people receiving valve replacement surgery each year, and every year more than 300,000 people underwent similar surgery around the world [2,3]. As people increasingly profound understanding of this disease, there will be more and more people accept valve replacement surgery.

Research on artificial heart valve has been for many years, the mechanical valve was the first artificial heart valve began to use in the surgery, and then bioprosthetric heart valve and the tissue engineering valve were put forward to substitute natural heart valve[4,5,].

The research of bioprosthetic heart valves has been rapid developed, but there are many issues that we need to optimize, especially the durability of the valve[6]. From the application field, mechanical valves and bioprosthetic heart valves were the most often used artificial heart valves. Bioprosthesis has better hydrodynamic performance, but the problem is not completely solved. Current research mainly focuses on the blood fluid dynamics, and trying to find the coupling Mechanism of the blood and leaflets [7,8]. In the support of these theories, the bioprosthetic heart valve could be designed to meet hydrodynamic conditions and could improve the durability of the valve.

Blood impact valve problems can be seen as the blood (liquid) and valve (solid) is coupled, and can be seen as fluid-structure interaction essentially. At the same time due to the special nature of blood and leaflets, we need to take targeted approaches to analysis the problem. For fluid-structure interaction, researchers have proposed many solutions, such as the classic finite element method, which is currently the most widely used to solve numerical solution of partial differential equations. On the basis of the finite element method, and researchers developed the boundary element method and boundary element and finite element mixing method. These methods are generally used to solve linear coupling, and the current nonlinear fluid-structure coupling methods are mainly arbitrary Lagrange–Euler method (ALE) and smoothed particle hydrodynamics method[9].

When the leaflet coupled with the blood, the deformation of the leaflet is relatively large, and it belongs to large deformation problem. In addition, the deformation occurs within one cardiac cycle, the time is short, so it is suitable for analysis using ALE method. ALE method is a method which can described the coordinates. In this work, ALE method combine the SIMPLE algorithm to solve the coupled equations of the leaflets and blood. This method is a base of meshing and numerical calculation, and it could get the stress distribution and deformation of the leaflets. Meanwhile, the paper also design some experiments ti compare with the simulation results. The simulation results proved correct and the method which combine the ALE method and SIMPLE algorithm is also proved can be used in the coupling problem between the leaflet and blood.

II. METHODS

A. *Basic Principle of the Arbitrary Lagrange –Euler method*

We describe the particle motion in time, there are usually two ways ---- Euler and Lagrange method. When coupled biological valves and blood, we need to define coordinates to describe the solid and fluid grid. When using the Euler method to describe the fluid mesh, it is a space left for the foundation, in the calculation process, the division of the grid structure and substance analysis is independent. So although you can describe the whole movement of the fluid inside, but is difficult to accurately position the shape of the free surface of the fluid represented. Lagrange method described solid grid when grid computing easy it is distorted, deformed, leading to the calculation difficult. Both methods have their advantages, but when dealing with the problem of coupling also flawed.

Fluid-structure coupling ask is defined by coupling equations, the domain contains both fluid and solid condition, the unknown variable that contains fluid and solid variables. In order to solve the above limitations of both methods, Hughes et al. built the kinematics equations of ALE law, and based on the finite element thought to solve the problem of viscous incompressible fluid and free-floating surface [10,11]. This approach combined with the SIMPLE algorithm can be used to deal with the problem of the bioprosthetic heart valve coupled with blood.

In the ALE method, the more fluid border region construct a suitable grid, then grid computing each step and iterative, so to avoid distortion generated grid finite element calculation. In general, meshing distortion needs to continue to divide grid. In the ALE method, each step contains an Euler calculation time step, and then through the mapping relation, strain and stress calculations obtained from fluid to solid grid maps, cycle calculations. The benefits of this calculation is the valve and the coupling of blood are synchronized, there is no time delay on the results of the calculation, so the results will be more accurate. Of course, this method requires continuous mapping as well as constantly mesh. As a result, the calculation time is relatively long if we use ALE method, in order to allow more efficient computing, sometimes using relatively coarse grid instead of a fine grid computing.

Generally ALE divided into the following three steps:

(1) The Lagrange calculation is carried out by using the method of display format, that is, the influence of the pressure gradient distribution on the speed and the energy change is considered, and the value of the pressure in the momentum equation is calculated;

(2) The velocity component is obtained by using the implicit scheme of the momentum equation (1) as the initial value of the iterative solution;

(3) The calculation of the transmission between the grid and the grid.

Blood and leaflets coupling calculation process is shown in Fig. 1.

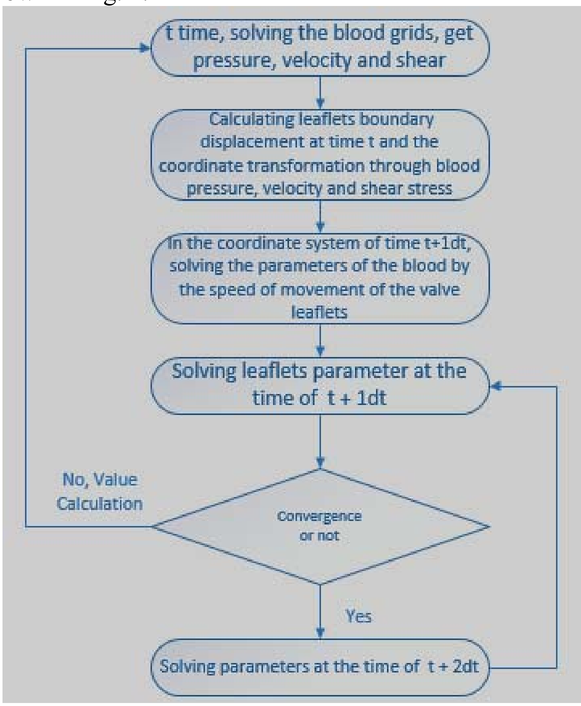


Fig.1 Blood and Leaflets Coupling Calculation Process

B. *Coupled of the ALE and SIMPLE*

Non-stationary incompressible fluid (herein refers to the blood) Navier-Stokes equation of continuity as follows [12]:

$$\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \vec{\nabla} \vec{V} + \frac{\vec{\nabla} p}{\rho} - 2\frac{\eta}{\rho} \vec{\nabla} \cdot D = \vec{0} \tag{1}$$

V represents blood velocity, P represents the fluid pressure, the mass density of the blood is ρ , the dynamic viscosity of the fluid is η, the gradient of the fluid pressure is $\vec{V}$, Blood deformation tension is D.

The momentum and equation of the solid (herein refers to the valves) are as follows:

$$\rho a_i - \sigma_{ij,j} - \rho f_i = 0 \quad \text{in } {}^s\Omega(t) \tag{2}$$

$$\sigma_{ij} n_j - t_i = 0 \quad \text{in } {}^s\Gamma(t) \tag{3}$$

${}^s\Omega(t)$ is the leaflets region at the time t, t_i is a traction surface of the leaflets, and σ_{ij} is the stress of the leaflets. a_i represents the acceleration in the direction of i of the nodes.

ALE method is a very effective method to solve the fluid structure coupling. By introducing the velocity parameter of the moving mesh, we can get the ALE modified Navier-Stokes equation of the viscous incompressible fluid:

$$\rho\left(\frac{\partial u_i}{\partial t}+\left(u_i-\overrightarrow{u_j}\right)\frac{\partial u_i}{\partial x_j}\right)-\frac{\partial}{\partial x_j}\left(u\left(\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i}\right)\right)+\frac{\partial p}{\partial x_i}=0 \quad (4)$$

$$\frac{\partial u_j}{\partial x_j}=0,\ i,\ j=1,2,3 \quad (5)$$

$u_j, j=1,2,3$ represents the velocity of the blood in the different moments. $\overrightarrow{u_j}, j=1,2,3$ is the zone velocity in different moments. μ represents the fluid dynamic viscosity. The calculation process can be divided into three steps:

a. Calculation speed in small regions

$$\hat{u}_j^n=\frac{x_j^{n+1}-x_j^n}{t_j^{n+1}-t_j^n},\ j=1,2,3 \quad (6)$$

b. Complete the calculation, and according to the ALE-based Navier-Stokes equations, get the $\overline{u}_j^{n+1}$, in the regions of $G(t^n)$.

c. Get the velocity of $u_j^{n+1},\ j=1,2,3$ by using the First-order optimization

$$u_j^{n+1}(x^{n+1})=\overline{u}_j^{n+1}(x^n),\ j=1,2,3 \quad (7)$$

$$p^{n+1}(X^{n+1})=\overline{p}^{n+1}(X^n),\ j=1,2,3 \quad (8)$$

The key to the valve coupled with the blood is the data transfer between blood and leaflets. This requires blood and leaflets in the fluid-structure coupling corresponds to the boundary displacement compatibility condition and meet force equilibrium between pointing.

$$\underline{d}_f=\underline{d}_s,\ n\cdot\underline{\tau}_f=n\cdot\underline{\tau}_s \quad (9)$$

In order to establish the mapping between the coupling surfaces, we use SIMPLE algorithm fluid and solid nodes corresponding to the nodes [13]. SIMPLE algorithm is a pressure correction algorithm method, and can be used to calculate the flow field. In this paper, the role of the blood to the leaflets have been seen as steady-state problem, discrete the equation by the SIMPLE algorithm and the fix the speed equation and pressure equation, thereby solving the pressure and speed. Coupled systems of equations can be written as the following formula:

$$F[X]\equiv\begin{bmatrix}F_f\left[X_f,\underline{d}_s(X_s)\right]\\ F_s\left[X_s,\underline{d}_f(X_f)\right]\end{bmatrix}=0 \quad (10)$$

C. Mathematical Modeling

Leaflets are attached to a supporting stent, the shape of the supporting stent determines the shape of the valve. So we consider the shape of the supporting stent when the valve model has been built, and combined with digital modeling approach, the structure of the valve can be simplified. The valve is a thin-film structure, made of a biological material, mainly porcine and bovine pericardium. We simplify the leaflets into a surface, the surface can get upset our model valve.

After calculation, we found that the spherical surface and the round table Boolean operations can be carried out to obtain a monolithic surface leaflets. Then arraying the model of leaflets, we can get three-piece bioprosthesis leaflets model [14].

We have established the spherical surface and the round table by t Equation (11):

$$\begin{cases}x^2+y^2+z^2=13.4^2\\ (x-13)^2+y^2=\left[R_b+(z+13.4)\tan\alpha\right]^2\end{cases} \quad (11)$$

Modeling process is shown in Fig. 2.

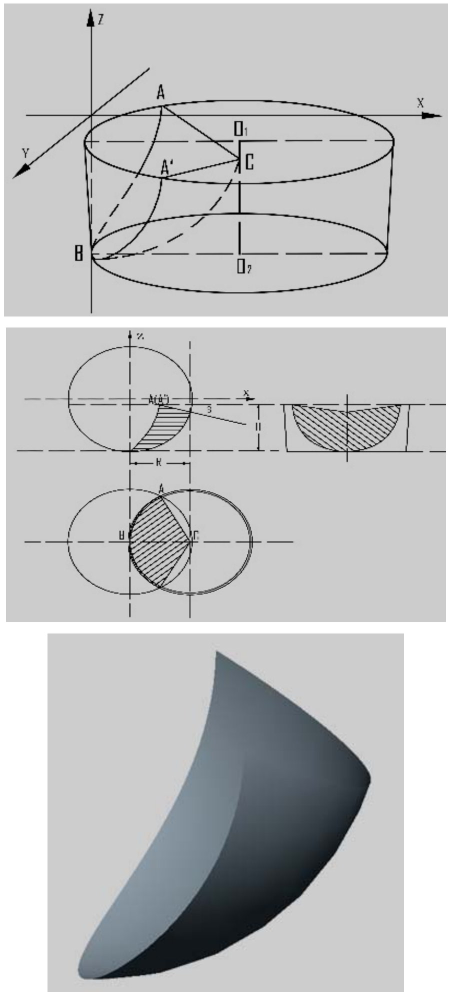


Fig.2 Modeling Process

Leaflets and blood are coupling in the carotid sinus, so we have established a model of carotid sinus, the valve on the carotid sinus to obtain a similar Coupling Model with the actual situation, as shown in Fig. 3.

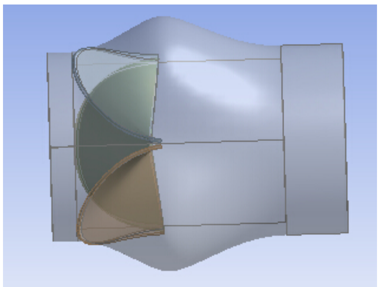


Fig.3 Coupling Model of leaflets and blood

D. Boundary Condition

Within a cardiac cycle, the leaflets being opened and closed again. The key point of the leaflets and coupled analysis of blood in the opening and closing time, this time is very short. Aortic pressure is greater than the pressure of the ventricles, when the valve is opened, the pressure of the ventricles fish aorta valve when the pressure is off. We need a physical parameter to describe the open and close condition. We input speed to the coupling equation, and then the pressure which leaflets suffered can be get. In order to simulate real blood flow, we have established the following inlet velocity curve, which is shown in Fig. 4.

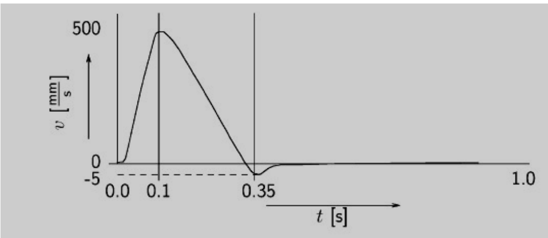


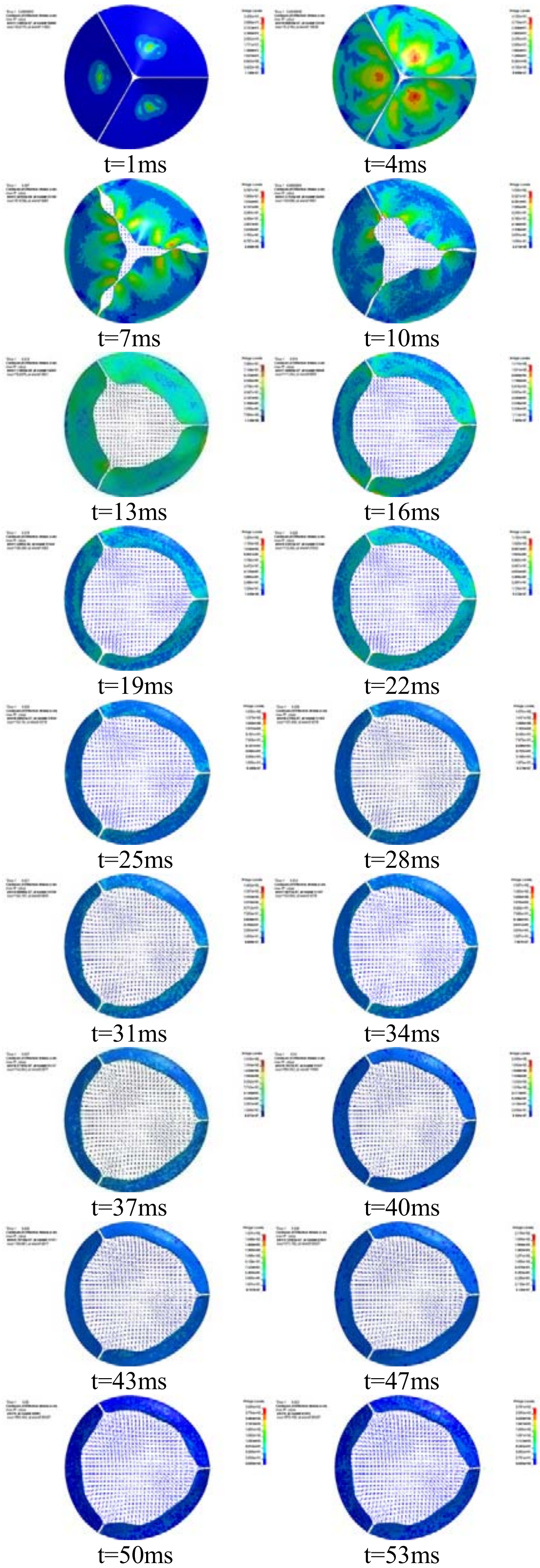
Fig.4 Inlet Velocity Curve

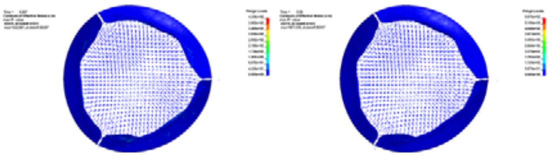
In addition inlet velocities, we also need to define the parameters of the blood itself. Blood is incompressible viscous fluid, we define the density of blood is 1.105g / cm^3, a viscosity of 0.00466Pa • s, the modulus of elasticity of volume of 3×10^8N / m^2, the temperature of the blood is normal human body temperature of 36 ℃[15].

III. SIMULATION AND EXPERIMENT

A. Stress Distribution and Deformation

In the analysis software, we observed the deformation and stress distribution of the bioprosthetic heart valve through a period of continuous screenshots, as shown in Fig. 5. In the spherical model, the valve can be smoothly opened and presented as a circle shape.





t=57ms t=60ms

Fig.5 Stress Distribution of the Spherical Leaflets

B. Analysis of simulation results

Through leaflets coupling process simulation, we got the leaflets distributed by the force as well as the opening and closing the valve leaflets in the process of deformation. From the screenshot got from analysis, it can be observed that the stress in the abdomen and free edge concentrated obviously at the open process of the leaflet. In addition, the stress concentration area migrate to the area between leaflets. When fully open when the valve leaflets, the leaflets distributed by force than to open the process to small, the force is mainly distributed in the free edge. From the deformation, the valve leaflets open from the middle of three pieces of leaflets began, gradually spread until the leaflets fully open. Since leaflets is biological material, the edge is very thin, so we can see the edge of the leaflets will fluctuate with the blood, eventually leaflets fully open and have a large effective opening area.

C. Experiment results and discussion

In order to verify the accuracy of using ALE method and SIMPLE algorithm, we use similar biological model valve to do pulsatile flow experiments, and observe the valve in the open process. Schematic diagram of the biological valve is shown in Fig. 6.

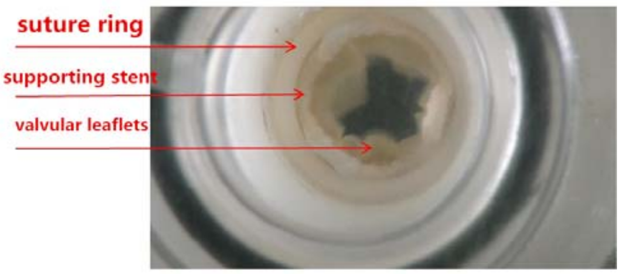
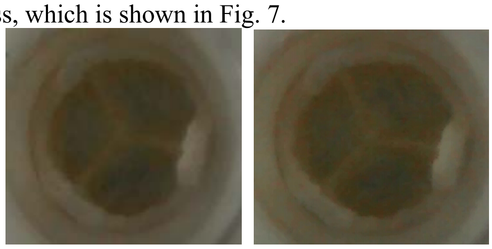
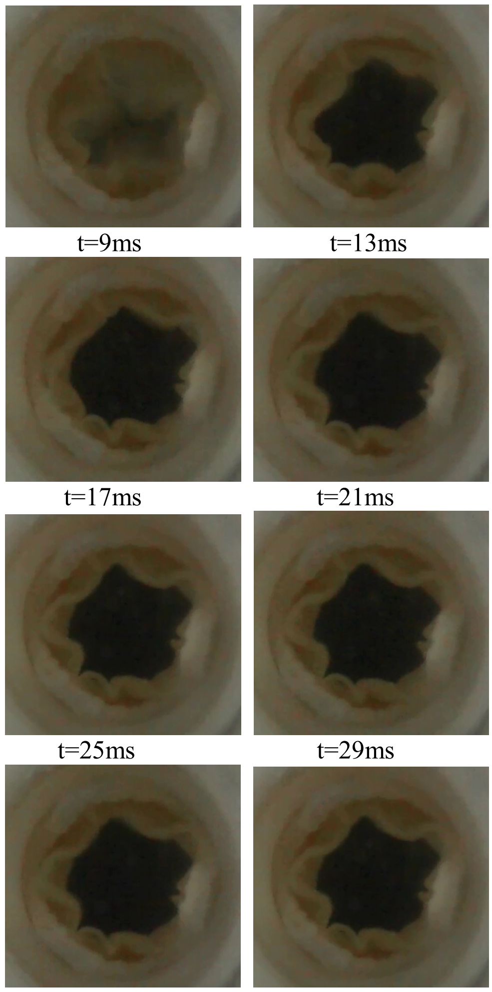


Fig.6 Schematic Diagram of the Bioprosthetic Heart Valve

We selected ten pictures to represent the valve opening process, which is shown in Fig. 7.



t=1ms t=5ms



t=9ms t=13ms

t=17ms t=21ms

t=25ms t=29ms

t=33ms t=37ms

Fig.7 Opening Process of the Valve

In order to observe the leaflet open process, we set up a similar experimental condition to simulation. We tested a total of 20 times of cardiac cycle to see the valve open state. The results from the screenshot we can see, the leaflets also open from the middle part at the beginning, and the process of opening is very fast. After some time, the leaflets were fully open, and achieve the predicted state. Comparison with the valve leaf deformation simulation, we found that the leaflet opening process is very similar to the simulation process of the valve. Fig. 8.is the change of effective orifice area (EOA) in the opening process.

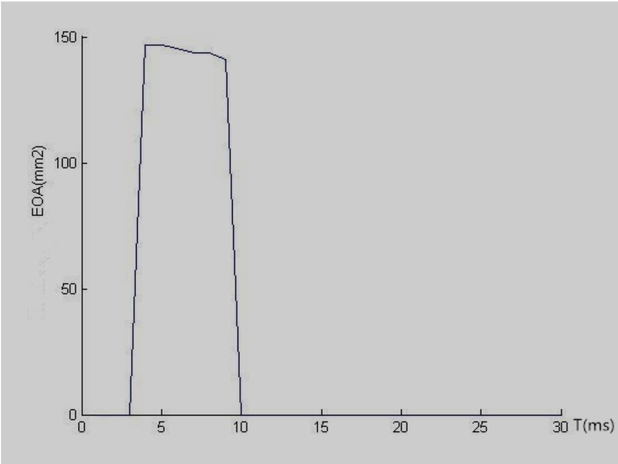


Fig.8 Effective Orifice Area Changes by the Time

Experiments simultaneously calculates the effective opening area of the leaflets, in the figure above, we can see the rise of the curve is the flap leaves open the process. At the top of curve in the graph, the leaflets were fully open, which is similar to the simulation.

IV.CONCLUSION

In this article, ALE method and the SIMPLE algorithm have been combined to solve the coupling of leaflets and blood problems. We have established solid (leaflets) and fluid (blood) mappings based on ALE method and SIMPLE algorithm, and deduces coupled equations between them. In order to confirm the accuracy of this method, we have established a model leaflet and blood, and the boundary conditions similar to actual situation were applied into model. Subsequently, the model was analyzed through the method we put forward. In the simulation results, the stress distribution occurs in the abdomen and the free edge in the open process. Finally, simulation results were confirm by experiment. The simulation and the experiment can proved that it is feasible to combine the ALE method and SIMPLE algorithm to solve the coupling of leaflets and blood problems, and it could provide a reference to the manufacture of valve.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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DISCLOSURE

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