Simulation of Blood flow in Artificial Heart Valve Design through Left heart

N. Hafizah Mokhtar¹, Aizat Abas²,
¹, ² School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia

Corresponding author: aizatabas@usm.my

Abstract. In this work, an artificial heart valve is designed for use in real heart with further consideration on the effect of thrombosis, vorticity, and stress. The design of artificial heart valve model is constructed by Computer-aided design (CAD) modelling and simulated using Computational fluid dynamic (CFD) software. The effect of blood flow pattern, velocity and vorticity of the artificial heart valve design has been analysed in this research work. Based on the results, the artificial heart valve design shows that it has a Doppler velocity index that is less than the allowable standards for the left heart with values of more than 0.30 and less than 2.2. These values are safe to be used as replacement of the human heart valve.

1. Introduction

The heart is one of the most essential organs in human body. The function of human heart is to pump blood throughout the body in human circulatory system by carrying oxygen and nutrients to human tissue while removing carbon dioxide from human body [1]. The heart has four main chamber which are the upper chambers and two lower chambers. The upper chamber is called atria while the lower chamber is namely ventricles. The atria is act as receiving blood while the ventricle carry blood away from the heart [2]. As human heart has four main chambers, to prevent blood from flowing back into the heart, there one-way system present in the heart namely heart valve. The heart valve has four main valves which are tricuspid valve, bicuspid valve, mitral valve and aortic valve. Tricuspid valve and aortic valve have three flaps that functioning to allow blood pass into heart and block the blood from flowing backward into ventricle. Besides, bicuspid valve and mitral valve have two flaps which are allow blood from the body system into ventricles and block blood from flowing backward to human body. Consequently, heart valve diseases are frequently affecting human health which is disturbing the flow of blood throughout the human body. There are two critical diseases conditions that may affect flow of the blood which are called stenosis and regurgitation. A stenosis is known as valve narrowing due to valve does not open fully that will obstruct flow of blood into human body [3]. Furthermore, regurgitation knowns as valve that does not close properly and causing blood flow to backwards. These diseases might harm human body due to heart need to pump more volume of blood that required for human boy. The heart valve that commonly effected from these diseases are aortic and mitral valve.

For severe heart valve diseases, a surgery is needed to replace malfunctions heart valve with an artificial heart valve. There are several types of artificial heart valves, commonly are bio-prosthesis and mechanical heart valve. In few decades, mechanical heart valve is become favourable for the replacement of heart valve due to bio-prosthesis heart valve need as anti-coagulant therapy after surgery [4]. There are several basic types of mechanical heart valve which are caged –balled valve,
mono-leaflet valve, bi-leaflet valve and tri-leaflet valve. While for bio-prosthesis, the commonly types involved in surgery are stented bio-prosthesis, stent-less bio-prosthesis and percutaneous bio-prosthesis. Haemodynamic, durability and thrombosis are main factor that need to be consider for an artificial heart valves. Therefore, in this research work, a bi-leaflet heart valve is choose to analyse the blood flow of artificial heart valve in human heart. The 3D model of bi-leaflet is constructed using computer –aided design (CAD) software and simulated by computational fluid dynamic (CFD) software to carry out stress analysis, flow pattern and vorticity of an artificial heart valve.

2. Methodology

2.1. Artificial heart valve design

The CAD model of the artificial heart valve in this project is constructed using Computer-aided design (CAD) software. The artificial heart valve consist of housing, two leaflets, flat and straight surface as shown in Figure 1 (a) and Figure 1 (b). The diameter of the mechanical heart valve is 28mm. The length of the model mechanical heart valve is 14mm.

![Figure 1. Geometry of artificial heart valve (a) Isometric view (b) Front view](image)

2.2. Simulation Using CFD Software

2.2.1. FVM Formulation

Prior to the commencement of the CFD simulation, it is important to look at the governing equations underlying the physics taken place. Although there are additional complex conditions such as pulsatile flow and non-Newtonian fluids properties, the governing equations are the same as other fluids problem. The fundamental governing equations are the continuity equation and the Navier-Stokes equations.

(a) Continuity equation

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]  

Since blood is considered as incompressible fluid, the rate of change of density will be zero. Hence, the continuity equation will be simplified as follow:

\[
\nabla \cdot \mathbf{v} = 0
\]

(b) Navier-Stokes equations

\[
\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f}
\]

In Navier-Stokes equations, the viscosity coefficient, \( \mu \) is not a constant.
2.2.2. Stress Analysis. As the heart valve operates under the blood pressure conditions, it might be damaged or impaired. For this works, artificial heart valve is analysed using mechanical analysis. Stress and strain on mechanical mitral heart valve, during opening and closing, were determined with a finite element analysis including deformation. Support at the outer ring body is fixed with 120mmHg pressure is applied in Y-direction [5]. All the materials involved in this work is define as pyrolytic carbon which has a tensile yield strength of 120 MPa.

2.2.3. Flow Analysis. The flow of blood through the valves will be simulated for different angles of leaflets and the flow pattern will be observed. Assume the flow is laminar and steady state. The density and dynamic viscosity of the blood is 1060 kg/m-3 and 0.0035 Pa s respectively [6].

3. Result And Discussion

3.1. Stress Analysis Result.

From this paper, stress analysis for artificial heart valve is conducted when artificial heart valve is closed and open. The result of stress analysis for artificial heart valve as shown in Figure 3 and 4.

![Figure 2](image)

**Figure 2.** Stress analysis for artificial heart valve when case is closed. a) Stress (b) Strain (c) Deformation

![Figure 3](image)

**Figure 3.** Stress analysis for artificial heart valve when case is opened. a) Stress (b) Strain (c) Deformation

| Valve Type | Stress (Pa) (Min) | Stress (Pa) (Max) | Strain (Min) | Strain (Max) | Deformation (m) (Min) | Deformation (m) (Max) |
|------------|------------------|------------------|--------------|--------------|-----------------------|-----------------------|
| Closed     | 289.33           | 1.298x10^7       | 9.947x10^-6  | 0.00395      | 0                     | 1.036x10^-5           |
| Opened     | 111.48           | 5.679x10^7       | 2.732x10^-8  | 0.0118       | 0                     | 1.844x10^-5           |
From Table 1, simulation results showed that the maximum of stress, strain and deformation when the artificial heart valve is fully opened. It is shows in Figure 3 and Figure 4, the maximum of stress and strain is occurred at the hinge joint of leaflets. Deformation are observed in the middle of the leaflets as well as near the corners where two leaflets meet. This shows that, inertia of flow effect stress analysis result due pressure loads act into the leaflets [7]. This stress analysis is done to ensure the structural rigidity for an artificial heart valve during closed and opened.

3.2. Flow Analysis of Artificial Heart Valve

From Figure 5, simulation of fully opened and closed for artificial heart valve are done to analyse flow pattern analysis and vortex formation.

![Flow velocity of artificial heart valve](image)

**Figure 4.** Flow velocity of artificial heart valve

![Vortex formation from artificial heart valve](image)

**Figure 5.** Vortex formation from artificial heart valve
Based on the velocity contour in Figure 5, we can observe flow pattern of artificial heart valve during is closed, open one third, open two-third and fully opened. As shown in Figure 5, in fully open condition, there are flow separation at the middle area central of artificial heart valve. The peak velocity occurring from flow analysis is 0.2329m/s. When it is fully close, there are some leakage at the hinge area of both leaflets. Besides, the vortex formation at middle section of artificial heart valve is quite larger for an artificial heart valve design as shown in Figure 6. Formation of vortex is not favourable for an artificial heart valve that may lead to cavitation thereby might damaging the heart valve [8].

3.3. Doppler Velocity Index of Left heart valve Stenosis.

One of the criteria to determine the mitral stenosis is through the Doppler velocity index (DVI). From Figure 7, the normal DVI value for aortic valve and mitral valve should be more than 0.30 and less than 2.2.

| Valve structure and motion | Normal | Possible stenosis | Significant stenosis |
|---------------------------|--------|------------------|----------------------|
| Aortic                    | Normal | Often abnormal** | Abnormal**           |
| Mitral                    | Normal | Often abnormal** | Abnormal**           |
| Doppler quantitative parameters |        |                  |                      |
| Peak velocity (m/s)**†   | <3     | 3–4              | >4                   |
| Mean gradient (mm Hg)**† | <20    | 20–35            | >35                  |
| DVI                        | ≦0.30  | 0.25–0.29        | <0.25                |
| Effective orifice area (cm²)** ≤ | 1.2    | 1.2              | <1.2                 |
| Effective orifice area versus normal reference value** ≤ | Reference ±1SD | Reference ±1SD | <Reference–1SD | <Reference–1SD | <Reference–2SD | <Reference–2SD |
| Contour of the transprosthetic jet† | Triangular, early peaking | Triangular to intermediate | Rounded, symmetrical |
| Acceleration time (ms)** | <80    | 80–100           | >100                 |
| Pressure half time (ms)** | <130   | 130–200          | >200                 |

**Figure 6.** Allowable DVI in mitral valve[9]

![Figure 6. Allowable DVI in mitral valve[9]](image)

**Figure 7.** Parameters involved to calculate DVI

For mitral valve:  Doppler Velocity Index (DVI) = \( \frac{V_{jet}}{V_{LVO}} \)

**Table 2.** Average velocity of blood flow and Doppler velocity index depicted from computational simulation when the valve is fully open.

| Inlet velocity (m/s) | Outlet velocity (m/s) | DVI |
|----------------------|------------------------|-----|
| 1                    | 1                      |     |
| 2                    | 2                      |     |
| 3                    | 3                      |     |
| 4                    | 4                      |     |
| 5                    | 5                      |     |
| Average              | Average                |     |
| 0.11                 | 0.12                   |     |
| 0.13                 | 0.14                   |     |
| 0.14                 | 0.12                   |     |
| 0.12                 | 0.201                  |     |
| 0.16                 | 0.23                   |     |
| 0.17                 | 0.215                  |     |
| 0.1952               | 1.55                   |     |

From Table 3, DVI value of artificial heart valve is the 1.55 which is still within allowable range for left heart valve as shown in Fig. 7. Hence, the artificial heart valve is within the permissible limit and the artificial heart valve for this work is safe to be used.
4. Conclusion
For this research work, the effect of blood flow pattern, velocity and vorticity of the artificial heart valve design has been analyzed. The peak velocity shows in flow analysis is 0.2329 m/s. The stress analysis shown that higher stress, strain and deformation is occurring at the hinge of the both leaflets. Besides, the artificial heart valve design shows that it has a Doppler velocity index that is 1.55 which is less than the allowable standards for the left heart with values of more than 0.30 and less than 2.2. Therefore, from this value of DVI, the artificial heart valve in this research work is safe to be used as replacement of the human heart valve.

5. Acknowledgement
The work was partly supported by the Short Term Grant 60313020 from the Division of Research and Innovation, Universiti Sains Malaysia, and FRGS Grant 6071322 from the Ministry of Higher Education

References
[1] “Heart.” [Online]. Available: https://www.nationalgeographic.com/science/health-and-human-body/human-body/heart/
[2] “Anatomy of Heart.” [Online]. Available:https://www.nhlbi.nih.gov/health/health-topics/topics/hhw/anatomy Another reference
[3] “Heart valve disease.” [Online]. Available:https://www.bhf.org.uk/heart-health/conditions/heart-valve-disease
[4] Dasi, L. P., Simon, H. A., Sucosky, P., & Yoganathan, A. P. (2009). Fluid Mechanics Of Artificial Heart Valves. Clinical and Experimental Pharmacology & Physiology, Volume 36 Issue 2, pp 225–237.
[5] Martin C., Sun W. (2011) Bio-prosthetic Heart Valve Stress Analysis: Impacts of Leaflet Properties and Stent Tip Deflection. In: Proulx T. (eds) Mechanics of Biological Systems and Materials, Volume 2. Conference Proceedings of the Society for Experimental Mechanics Series. Springer, New York, NY
[6] A.C. Benim, A. Nahavandi, A. Assmann, D. Schubert, P. Feindt, S.H. Suh. (2011) Simulation of blood flow in human aorta with emphasis on outlet boundary conditions, In Applied Mathematical Modelling, Volume 35, Issue 7, pp 3175-3188.
[7] H. Kim, J. Lu, M.S. Sacks, and K.B. Chandran (2008). Dynamic Simulation of Bioprosthetic Heart Valves Using a Stress Resultant Shell Model. Annals of Biomedical Engineering, Vol. 36, No. 2.
[8] Avrahami, I., Rosenfeld, M., Einav, S. et al. Med. Biol. Eng. Comput. (2000). Can vortices in the flow across mechanical heart valves contribute to cavitation?. Volume 38, Issue 1, pp 93-97.
[9] P. Pibarot and J. G. Dumesnil. (2012) Doppler echocardiographic evaluation of prosthetic valve function. Heart, vol. 98, no. 1, pp. 69–78.
[10] M. Engineering. (2012). Prediction of Blood Flow Velocity and Leaflet. Volume 2, No. June, pp. 217–225.