EFFECT OF VORTEX GENERATOR ON BLOOD FLOW CHARACTERISTIC ON IDEALIZED PROSTHETIC HEART VALVE

LIM BOON HONG

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

EFFECT OF VORTEX GENERATOR ON BLOOD FLOW CHARACTERISTIC ON IDEALIZED PROSTHETIC HEART VALVE

LIM BOON HONG

This report is submitted
in fulfillment of the requirement for the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

JUNE 2020

DECLARATION

I declare that this project report entitled " Effect of Vortex Generator on Blood Flow Characteristic on Idealized Prosthetic Heart Valve" is the result of my own work except as cited in the references

Signature : ....

Name : ....

Date : ....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :. ....

Name of Supervisor : ....

Date : ....

DEDICATION

To my beloved mother and father

ABSTRACT

Bi-leaflet Mechanical Heart Valve (BMHV) is widely used in surgically heart valve replacement in worldwide. The main complication of the BMHV is that BMHV leaded to the formation of blood clotting known as thrombosis. Vortex Generator (VG) is used to improve the performance of the BMHV by delaying the turbulence that activated the platelet and hemolysis. This paper presents various configuration of VG to enhance the performance of BMHV. In this Computational Fluid Dynamic (CFD) simulation, a simplified prosthetic heart valve is used to investigate the performance of BMHV with different orientation of VG. As a result, the fluid is passed through the leaflets with VG. The pressure drop is decreased between the position of after leaflets and before leaflets. In the present study, four different configurations of VG are reviewed, which are without VG, Co-counter Equally Spaced VG, Straight Equally Spaced VG and Counter-rotating Far Spaced VG. In the other hand, this present study also investigates the pulsatile turbulent transient flow in simplified prosthetic heart valve with no VG and the best configuration of VG in the previous study. In the present study, Co-counter Equally Spaced VG is the best configuration and it contributed 42.62% of improvement in pressure drop across the leaflets. Besides that, Co-counter Equally Spaced provided 52.96% and 7.82% reduction in Turbulence Shear Stress and Turbulence Kinetic Energy respectively. In the summary, the pressure drop, turbulence kinetic energy and turbulence shear stress are significantly reduced due to the existence of VG. VG is a crucial device to enhance the performance of BMHV by delaying early separation and thus turbulence reduced.

ABSTRAK

Bi-leaflet Mechanical Heart Valve (BMHV) digunakan dalam penggantian injap jantung pembedahan di seluruh dunia. Terdapat masalah yang serius dengan penggunaan peralatan ini adalah peralatan ini boleh membawa kepada pembentukan pembekuan darah dalam jantung kita. Vortex Generator (VG) adalah peranti yang dapat digunakan untuk menambahbaikkan prestasi BMHV. VG dapat melambatkan pergolakan dalam aliran darah di jantung. Projek ini dijalankan untuk menyiasatkan beberapa konfigurasi VG untuk meningkatkan prestasi BMHV. Dalam Computational Fluid Dynamic (CFD) simulasi, satu prostetik injap jantung digunakan untuk menyiasatkan prestasi BMHV dalam konfigurasi VG yang berbeza. Darah disimulasikan dalam injap jantung prostetik tersebut yang mempunyai pemasangan VG. Dalam simulasi ini, hasilnya dijankakan tekanan dapat dikurangkan selepas pemasangan VG di dalam prostetik injap jantung Terdapat empat konfigurasi yang berbeza dalam projek ini iaitu kes yang tidak mempunyai VG, Co-counter Equally Spaced VG, Straight Equally Spaced VG dan Counter-rotating Far Spaced VG. Selain itu, projek ini juga menjalankan penyiasatkan aliran pendenyutan dalam prostetik injap jantung. Perbandingan juga dilaksanakan antara kes yang tidak mempunyai VG and konfigurasi VG yang terbaik. Dalam projek ini, Co-counter Equally Spaced ialah konfugurasi yang terbaik dalam perbandingan beberapa reka cipta yang lain. Terdapat 42.62% pengurangan tekanan dengan penggunaan konfigurasi Co-counter Equally Spaced VG. Selain itu, Co-counter Equally Spaced VG dapat menambahbaikkan tenaga kinetik tubulensi dan tekanan tubulensi sebanyak 52.96% dan 7.82%. Konklusinya, VG dapat mengurangkan tekanan dan tenaga kinetik pergolakan dengan berkesan. VG adalah sesuatu peralatan yang sangat penting dalam penambahbaikan prestasi BMHV.

ACKNOWLEDGEMENT

It was an excellent opportunity to be able to have final year project related to bio-mechanical engineering during my final year period. I gained abundance of hands on experiences and knowledge. I am glad to meet many individuals and keen parties who had guided me through execution of project work.

Firstly, I would like to take this opportunity to express my gratitude to my supervisor, Dr. Mohamad Shukri bin Zakaria from Faculty of Mechanical Engineering, University Teknikal Malaysia Melaka (UTeM) for his altruistically teachings and support towards my project.

I would also like to express my deepest sense of gratitude to my Computational Fluid Mechanic lecturer, Dr. Suhaimi bin Misha from Faculty of Mechanical Engineering for his precious guidance of CFD simulation in my project work. Furthermore, I would like to express my profound gratitude to my peers who helped me in the critical situation during my project work.

Finally, I would also like to express my special thanks to my family and siblings for their impartial and selfless moral support. Without them, this project work would not be able to finish in time. I am thankful to all the people who involved in my project work, and I am lucky enough to have such encouragement, guidance, and support from them.

I will cherish this opportunity as a steppingstone for my future career's development. I will strive to achieve my desired career objectives with the skills and knowledge learnt.

CONTENT

CHAPTER	CONTENT	PAGE
	SUPERVISOR'S DECLARATION	**ii**
	TABLE OF CONTENT	**viii**
	LIST OF FIGURES	**xi**
	LIST OF TABLES	**xiii**
	LIST OF SYMBOLS	**xiv**
	LIST OF ABBREVIATIONS	**xv**
CHAPTER 1	**INTRODUCTION**	**1**
	1.1 Background	1
	1.2 Problem Statement	5
	1.3 Objective of Project	6
	1.4 Scope of Project	6
CHAPTER 2	**LITERATURE REVIEW**	**7**
	2.1 Mechanical Heart Valve	7
	2.2 Hemodynamic Blood Clot	9
	2.3 Vortex Generator	12
	2.3.1 Vortex Generator Effect on Bluff Body	12
	2.3.1.1 Influence of the Angle of Vortex Generator	13
	2.3.1.2 Influence of the Spacing of Vortex Generator	14
	2.3.1.3 Influence of the Reynolds Number	15

2.3.1.4 Influence of the Distribution of Vortex Generator along the Width of a Bluff Body 16
2.3.2 Vortex Generator Effect on Wind Turbine 17
2.3.3 Vortex Generator Effect on Car 18
2.3.4 Vortex Generator Effect on Prosthetic Heart Valve 20
2.4 CFD in Mechanical Heart Valve 22

CHAPTER 3 METHODOLOGY 23
3.1 Introduction 23
3.2 Idealized Prosthetic Heart Valve 26
3.3 Vortex Generator 27
3.4 Boundary Condition 27
3.5 Governing Equation 31
3.5.1 Navier-Stokes Equation 31
3.5.2 Turbulence Model 33
3.6 Vortex Generator Configuration 34
3.7 Turbulence Shear Stress 36
3.8 CFD Simulation Setup 36
3.8.1 Boundary Named Selection 36
3.8.2 Meshing 37
3.8.3 Solver 39
3.9 Grid Independent Test 40
3.10 Validation 41

CHAPTER 4 RESULTS AND DISCUSSION 43
4.1 Pressure Drop 43
4.2 Turbulence Kinetic Energy and Turbulence Shear Stress 46
4.3 Contours and Streamlines 48
4.4 Comparison of Different Phase in Pulsatile 51

CHAPTER 5	**CONCLUSION AND RECOMMENDATION**	**54**
	REFERENCE	**56**

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Anatomy of human heart.	2
1.2	Statistics of Causes of Death in Malaysia (2018).	3
1.3	(a) Caged ball valve (b) Bjork-Shiley tilting disk valve (c) Medtronic Hall tilting disk valve (d) St. Jude Medical Regent bileaflet valve. (Zakaria *et al.*, 2017).	4
1.4	Bioprosthetic heart valve.	5
2.1	SJM Bileaflet Mechanical Heart Valve.	8
2.2	Axial Velocity Contour for functioning valve with 1.25m/s blood inlet velocity.	10
2.3	Velocity Contour for malfunctioning valve with 1.25m/s blood inlet velocity.	10
2.4	Description of VGs geometry with typical parameters used in the experiment.	12
2.5	Influence of position in VGs line on drag and lift coefficients for both angles.	13
2.6	Influence of spacing between VGs with λ=0.015m instead of λ=0.02m.	14
2.7	Drag reduction obtained for three different free stream velocities for Uo = 20m/s, 30m/s and 40m/s.	15
2.8	Three different arrangements of VGs along the width of the bluff body for s = 0.20m.	16
2.9	Aerodynamic Flow Pattern over Wind Turbine without VG.	17
2.10	Aerodynamic Flow Pattern over Wind Turbine with VG.	18
2.11	The differences of velocity profile generated between car (a) with VGs and (b) without VGs.	19

2.12	Velocity Contour of a Body without VG.	19
2.13	Velocity Contour of a Body with VG.	19
2.14	(a) Co-rotating Equally Spaced of VG and (b) Counter Rotating Closely Spaced on Bi-leaflet Mechanical Heart Valve.	20
3.1	Flow Chart of the Methodology.	25
3.2	Computational Model of the Idealized Prosthetic Heart Valve.	26
3.3	Parameters of a Rectangular Vortex Generator Design.	27
3.4	Parabolic Velocity Profile in UDF C Programming Code.	29
3.5	Pulsatile Velocity Profile in UDF C Programming Code.	30
3.6	Pulsatile Velocity Profile.	30
3.7	Boundary Named Selection in Idealized Geometry.	34
3.8	Tetrahedral meshing grid.	35
3.9	Topology of the grid.	36
3.10	The Graph of Grid Independent Test – Velocity Differences against Grid Quality.	38
3.11	Illustration of validation location.	39
3.12	The Velocity Profile Comparison Result at x = 2.2mm.	40
3.13	The Velocity Profile Comparison Result at x = 10.3mm.	40
3.14	The Velocity Profile Comparison Result at x = 20.1mm.	40
4.1	(a) The several points across leaflets. (b) The points chosen for comparison.	41
4.2	Six lines located at leaflets for comparison purpose.	44
4.3	Velocity contour in non-VG case.	46
4.4	Velocity contour in VG case.	46
4.5	Turbulence kinetic energy contour in non-VG case.	47
4.6	Turbulence kinetic energy contour in VG case.	47
4.7	Streamlines pattern across leaflets in Non-VG case.	48
4.8	Streamlines pattern across leaflets in VG case.	48
4.9	The position of line at X = -0.004m.	49
4.10	The Velocity Profile in Acceleration Stage.	50
4.11	The Velocity Profile in Peak Systole Stage.	50
4.12	The Velocity Profile in Deceleration Stage.	51

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Summary of Hemodynamic Data in Different VGs Arrangements	21
3.1	Simulation Parameters of Steady Flow-through Idealized Geometry.	28
3.2	Details of Vortex Generator Arrangement Used in this Study.	33
3.3	Statistics of meshing grid.	35
3.4	The Solution of Discretization.	37
3.5	Grid Independent Test	38
4.1	Simulation Result in Pressure Drop	42
4.2	Simulation turbulence kinetic energy and turbulence shear stress result	44

LIST OF SYMBOLS

α	-	Angle of Attack
λ	-	Wavelength between two VG
C_d	-	Drag Coefficient
U_o	-	Velocity of Flow
S_{min}	-	Minimum spacing between two VG
Re	-	Reynolds number
ρ	-	Density
V	-	Mean Velocity
D	-	Diameter of tube
μ	-	Dynamic Viscosity
ν	-	Kinematic Viscosity
W_n	-	Womersley number
ω	-	Angular Velocity
P	-	Pressure
I	-	Turbulence Intensity
C_μ	-	Turbulence Model Contact
l	-	Turbulence Length Scale
η	-	Eddy Viscosity

LIST OF ABBREVIATION

SJM	-	St. Jude Medical
RBC	-	Red Blood Cell
BHV	-	Bioprosthetic Heart Valve
MHV	-	Mechanical Heart Valve
BMHV	-	Bi-leaflet Mechanical Heart Valve
VG	-	Vortex Generator
EOA	-	Effective Orifice Area
CFD	-	Computational Fluid Dynamic
UDF	-	User-Defined Function
RHS	-	Right Hand Side
LHS	-	Left Hand Side
TKE	-	Turbulence Kinetic Energy
RSS	-	Reynolds Shear Stress

CHAPTER 1

INTRODUCTION

1.1 Background

Heart failure is a life-threatening illness and it indicated that a current worldwide wellbeing priority. Approximately 26 million people worldwide are living with heart failure (Ponikowski *et al.*, 2014). The heart diseases are included coronary artery disease, transplants and ventricular assist devices (VADs) for heart failure congestion or valve replacement (James, Papavassiliou and O'Rear, 2019).

The general structure of the heart is shown in Figure 1.1 below. Heart valve is used to provide unidirectional blood flow through the heart (Sotiropoulos, Le and Gilmanov, 2016). The heart valve failure happened when the valve does not close completely, caused the blood to start to flow backward. This condition occurred will lead to the heart started to pump harder and became less efficient. In heart valve disease treatment, patients have 2 main treatment options which are heart valve repair and replacement. For the first option, the patients can keep their valve and leaflets but only used for mitral and tricuspid valve regurgitation. Besides that, valve replacement required a new valve to be inserted surgically in the heart.

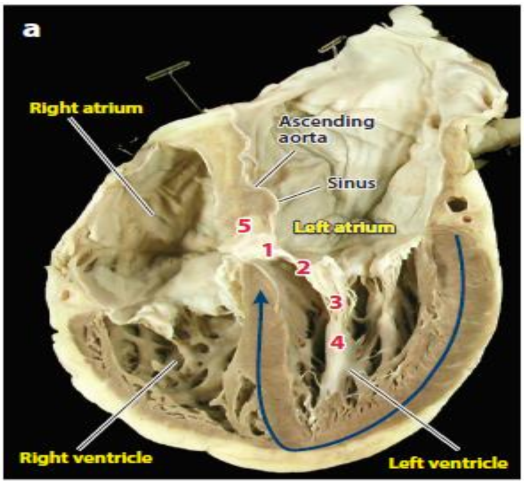

Figure 1.1: Anatomy of the human heart (Sotiropoulos, Le and Gilmanov, 2016)**.**

According to the Department of Statistics Malaysia, Ischaemic heart disease is the highest causes of death facing by Malaysians in the last year 2018. About 15.6% of Malaysian are suffering from the Ischaemic heart diseases as shown in Figure 1.2 below. Ischaemic heart diseases also known as coronary heart diseases. The waxy substances inside the coronary arteries is a factor to cause Ischaemic heart diseases. These waxy substances are partially or totally block the blood flow through the heart. Many Malaysians do not notice that they suffer from ischaemic heart disease until they experience some complications such as heart attack (*Ischemic Heart Disease | National Heart, Lung, and Blood Institute (NHLBI)*, no date).

In the category of Ischaemic heart diseases, a total of 12,510 men is suffered Ischaemic heart diseases. It showed that the men have higher chances to get diseases compared to women which are about 36.97%. From the perspective of races, the Bumiputera has contributed the highest total of amount (11,350 of people) who are suffering from the Ischaemic heart diseases followed by Chinese (4,243 of people) and Indian (2,240 of people). The average of causes of death for Ischaemic heart diseases is about 50 persons per day in Malaysia. On the other hand, the principal causes of death for Ischaemic heart diseases are mostly in the age of 60 years and above. It means that the golden ages of people have larger chances to have Ischaemic heart diseases.

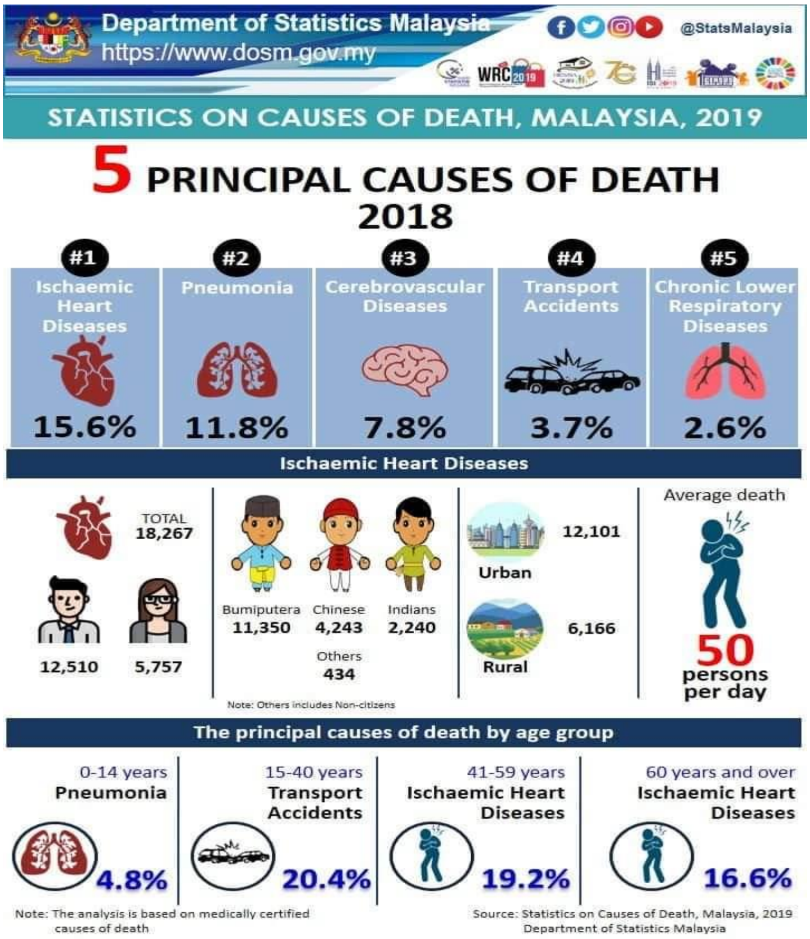

Figure 1.2: Statistics on Causes of Death in Malaysia, 2019.

The prosthetic heart valve is commonly surgically implanted for the occurrence of valvular heart disease. In current existing commercial, the prosthetic heart valve is divided into 2 major type which is the mechanical heart valve and bioprosthetic heart valve. Over 300000 heart surgical heart valve replacement operation is carried out worldwide annually, where 40~60% of the operations are using bioprosthetic heart valve produced by using glutaraldehyde-fixed animal tissues. The advantages of implantation of bioprosthetic heart valve are durable, particularly in older patients for more than 60 years old (Li, 2019). Second, it does not have thrombosis complication. The most crucial point is that the bioprosthetic heart valve does not last long and has a shorter life span of about 7 to 10 years compared to a mechanical heart valve. On the other hand, high durability is the main advantage of mechanical heart valve. The mechanical heart valve can last throughout the entire life cycle of the patient. But the main complication of mechanical heart valve is the formation of blood clotting known as thrombosis (Zakaria *et al.*, 2017).

Both Zakaria et al. (2017) and Hatoum and Dasi (2019) stated that tremendous progress has been made in the development of MHVs over the past 60 years to improve their stability and performance in reducing complications of blood clotting. There are several types of design in MHV’s family which are shown in Figure 1.3. In this study, St. Jude Medical (SJM) mechanical heart valve was selected to investigate the impact of turbulent flow in this idealized geometry design. Computational simulation of flow through idealized mechanical heart valve is included in this study. Turbulent flow are well-established factors that contribute to the hemolysis of the valve and the activation of platelets. Consequently, any new mechanical heart valve design aims to minimize the risk of activation of platelets and hemolysis by increasing the turbulent pressure (Hatoum *et al.*, 2018). To achieve the goals, a vortex generator installed with an ideal configuration in an idealized mechanical valve is investigated in this study.

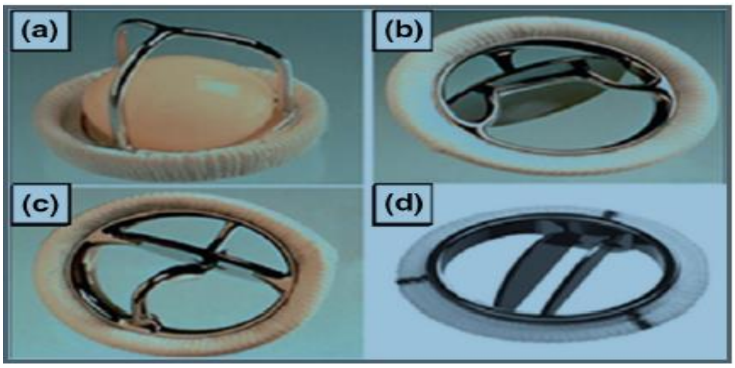

Figure 1.3: (a) Caged ball valve (b) Bjork-Shiley tilting disk valve (c) Medtronic Hall tilting disk valve (d) St. Jude Medical Regent bileaflet valve. (Zakaria *et al*., 2017).

Figure 1.4: Bioprosthetic heart valve (Pibarot and Dumesnil, 2009).

1.2 Problem Statement

Artificial heart valve can expose blood to flow that condition in unnaturally high blood cell pressure and damage as well as thrombosis (James, Papavassiliou and O'Rear, 2019). For current main concern is that the installation of foreign objects which is either a mechanical heart valve or bioprosthetic heart valve may lead to the blood flow in unnatural condition. According to the research of Hund, Antaki and Massoudi (2010), it stated that foreign objects such as artificial heart valves are generated turbulent flow. The turbulent stress of non-physiological flow is harm to the RBC and platelets. This will lead to the occurrence of blood clotting. Besides that, a high-speed leakage jet experienced high shear stresses, separation of flow to increase the formation of blood clots (Zakaria *et al.*, 2017).

Despite strong anticoagulation treatment, thromboembolism is the most common complication linked with mechanical heart valves. Around 0.1-5.7 percent per patient per year (Hatoum and Dasi, 2019). Clinical studies found that patients with mechanical valves had been reduced half-lives of RBC and platelets. However, given the potential for thromboembolism complications, mechanical heart valve recipients must take anticoagulant medication. Such complication are believed to cause high blood shear stress, turbulent flow and overall difficulty of hemodynamic in the mechanical heart valve (Ge *et al.*, 2003).

Besides that, the mechanical heart valve without the vortex generator may increase the risk of thrombosis. Hatoum and Dasi (2019) stated that the presence of vortex generators removes the inflection point indicating the direction of the boundary layer separation. This indicated that the separation has reduced significantly. Downstream pressure recovery is significantly improved when separation and recirculation is decreased.

1.3 Objective of Project

The main objective of research is to reduce the formation of blood clotting and thrombosis in terms of reducing the pressure gradient and shear stress in bi-leaflet mechanical heart valve. Hence, the specific aims are:

a) To investigate the effect of turbulent flow in an idealized prosthetic heart valve.

b) To analyze the effect of vortex generator on blood flow in an idealized prosthetic heart valve.

1.4 Scope of Project

The scopes of present study as followed below:

a) Using numerical simulation only. (ANSYS Workbench 16.1)

b) 3D geometry of aorta. (Idealized Geometry)

c) Laminar flow and Turbulent flow inside the aorta.

d) St. Jude Medical Standard of Mechanical Heart Valve.

e) Leaflets are placed 5° to the horizontal. (Fully Opened)

f) Turbulence model k-ε is used.

CHAPTER 2

LITERATURE REVIEW

This chapter introduces the theories and related scientific knowledge in this research topic. Previous works related to this research were reviewed to obtain ideas and references for current work.

2.1 Mechanical Heart Valve

In this era modern world, prosthetic system substitution remains a major therapy option for heart disease patient. Although bioprosthetic heart valve (BHV) remains the most common replacement heart valve in the medical field, its durability still limited. This is, therefore, an ongoing requires to establish a general understanding of the mechanisms that restrict BHV durability to facilitate the production of a more durable prosthetic (Zakerzadeh, Hsu and Sacks, 2017). In this regard, a mechanical heart valve (MHV) is introduced and to overcome the BHV complications. On the other hand, MHV has its complications. In recipients of MHV, thrombus development is a major concern which allows them to take anticoagulant medicine for the rest of their life (Hedayat, Asgharzadeh and Borazjani, 2017). Many patients required to take anticoagulants for the entire life after MHV has been installed. Anticoagulant is used to slow down the formation of thrombus, preventing complications on the artificial valve. If the anticoagulant drugs ignored by recipients, it would enhance the valve obstruction and causing a stroke.

BHV has a shorter life span (10-15 years) than MHV (entire life), whereas MHV is less biocompatible and vigorously rejected by human body. The foreign object exposed to the blood; a turbulent flow condition can be generated. In a high shear stress condition, the activation of platelets is increased. Hemolysis due to prosthetic heart valve has been discussed since the 1960s (James, Papavassiliou and O'Rear, 2019).

Choosing a substitute for MHV or BHV is a significant decision, affected by the interchanges between potential need for reaction due to BHV degradation and the risk correlated with anticoagulation in long term for MHV (Zakerzadeh, Hsu and Sacks, 2017). The current design of bi-leaflet valve is significantly different from the natural valve. Compared to the natural heart valve, the flow field is completely different in the bi-leaflet valve. In previous study, it showed that the heart valve design is a crucial impact on the aortic flow area (Akutsu and Matsumoto, 2010). According to Hatoum and Dasi (2019), St. Jude Medical (SJM) mechanical valve as shown in Figure 2.1 below, well known for its excellent hemodynamic quality and low relative thrombogenicity. The layout design valve of SJM is made up of two semi-circular leaflets pivoting on hinges. This provides a good central flow relative to other mechanical valve prostheses such as ball and cage, and the pressure drop across the valve is negligible (Mohammadi, Jahandardoost and Fradet, 2015).

Figure 2.1: SJM Bi-leaflet Mechanical Heart Valve.