EFFECT OF VORTEX GENERATOR ON BLOOD FLOW CHARACTERISTIC ON REAL PATIENT SPECIFIC DATA

NURSYASYA AMANINA BINTI MOHD FIZAL

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

EFFECT OF VORTEX GENERATOR ON BLOOD FLOW CHARACTERISTIC ON REAL PATIENT SPECIFIC DATA

NURSYASYA AMANINA BINTI MOHD FIZAL

A report is submitted
in fulfilment of the requirements for the degree of
Bachelor of Mechanical Engineering with Honours

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2020

DECLARATION

I declare that this project “Effect of Vortex Generator on Blood Flow Characteristic on Real Patient Specific Data” is the result of my own work except as cited in the references.

Signature : ....

Name : Nursyasya Amanina Binti Mohd Fizal

Date : ....

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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 :Dr. Mohamad Shukri Bin Zakaria

Date :..............................

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ABSTRACT

Blood clot coagulation is the main concerned for people who are using Bileaflet Mechanical Heart Valve to replace the ruptured valve. Different design of vortex generator can affect the blood flow at the vicinity of the mechanical heart valve and therefore the velocity, pressure drops and wall shear stress are needed to be investigated. The study only includes steady state condition during peak systole at the aorta. The blunt edges vortex generators (without the aorta) showed lower average velocity with value of 0.80 m/s compared with the sharp edges of vortex generator. The blunt edges of vortex generator also improved the pressure gradient of the blood flow and the result was found 3.64 mmHg compared to the previous study which shows pressure gradient of 10.45 ± 0.94 mmHg. Meanwhile, the wall shear stress was found 10.24 Pa which shows some reduction compared with the sharp edges of vortex generator. A blunt edges of Co-rotating vortex generator is considered a good application as it reduce the flow separation at the vicinity of the leaflets as well helps in reducing the formation of thrombosis. However, to compare with the mechanical heart valve with aorta, the result with the aorta is less prone to blood clotting. A reduction with results of 2.3955 mmHg and 8.845 Pa in pressure drop and wall shear stress respectively indicates more delayed flow separation compared with the mechanical heart valve without aorta. This shows the simulation with the aorta needs to be included to investigate the reduction in blood clot.

ABSTRAK

Pembekuan darah beku adalah kebimbangan utama bagi orang yang menggunakan Injap Jantung Mekanik Bileaflet untuk menggantikan injap yang rosak. Reka bentuk penjana pusaran yang berbeza boleh mempengaruhi aliran darah di sekitar injap jantung mekanikal dan oleh itu halaju, penurunan tekanan dan tekanan ricih dinding perlu diselidiki. Kajian ini hanya merangkumi keadaan stabil semasa puncak sistol di aorta. Penjana pusaran berbucu tumpul (tanpa aorta) menunjukkan halaju purata yang lebih rendah dengan nilai 0.80 m/s berbanding dengan penjana pusaran berbucu tajam. Bucu tumpul penjana pusaran juga meningkatkan kecerunan tekanan aliran darah dan hasilnya didapati 3.64 mmHg berbanding kajian sebelumnya yang menunjukkan kecerunan tekanan 10.45 ± 0.94 mmHg. Sementara itu, tegasan ricih dinding dijumpai 10.24 Pa yang menunjukkan sedikit pengurangan berbanding dengan penjana pusaran berbucu tajam. Bucu tumpul penjana pusaran yang berbentuk berpusing bersama dianggap sebagai aplikasi yang baik kerana ia mengurangkan pemisahan aliran di sekitar injap jantung dan juga membantu mengurangkan pembentukan trombosis. Namun, jika dibandingkan dengan injap jantung mekanikal dengan aorta, hasilnya dengan aorta kurang terdedah kepada pembekuan darah. Pengurangan dengan keputusan 2.3955 mmHg dan 8.845 Pa pada tekanan kecerunan dan ricih dinding menunjukkan pemisahan aliran yang lebih lambat berbanding dengan injap jantung mekanikal tanpa aorta. Ini menunjukkan simulasi dengan aorta perlu disertakan untuk menyiasat pengurangan pembekuan darah.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ACKNOWLEDGEMENT

Praise to Allah S.W.T, the Almighty on whom ultimately we depend for substance and guidance and for the strengths and His blessing in completing this report.

Special appreciation goes to my supervisor, Dr. Mohamad Shukri Bin Zakaria, whose continuous guidance, constructive comments and useful advices was very valuable to me and have contributed to the success of this report Certainly, not to forget Faculty of Mechanical Engineering, UTeM for giving me the opportunity to do researches in order to complete my degree in Bachelor of Mechanical Engineering.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Sincere thanks to my friend, Edzzry Indrawan Bin Faizal Edzuan, Muhammad Nazhiim Bin Mohd Nazri, Yew Sin Wei, Nur Syahirah Binti Ahmad, Aina Nazira Binti Abdul Muttalib and Nur Batrisyia Husna Binti Zainurin for the support in helping me with my final year project. Not to forget other friends that support and encourage me continuously in completing my study.

Last but not least, my deepest gratitude goes to my beloved family for their endless love, support and encouragement especially to my parent; Mr. Mohd Fizal Bin Abd Dzubir and

Mrs. Junaidah Binti Yusof. To those who indirectly contributed in this research, your kindness means a lot, thank you.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

TABLE OF CONTENTS

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF FIGURES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF APPENDICES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF TABLES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF ABBREVIATIONS

BMHV	Bileaflet Mechanical Heart Valve
MHV	Mechanical Heart Valve
RSS	Reynolds Shear Stress
VG	Vortex generators
CFD	Computational Fluid Dynamics
WSS	Wall Shear Stress
CT	Computerized Tomography
MRI	Magnetic Resonance Imaging
Re	Reynolds number
SCCH	Swept Constant Chord Half-model
PG	Pressure Gradient
CAD	Computer-Aided Design

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF SYMBOLS

ρ	Density of fluid
g_i	Body force in i-direction
μ	Dynamic viscosity of the fluid
u	velocity

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 1

INTRODUCTION

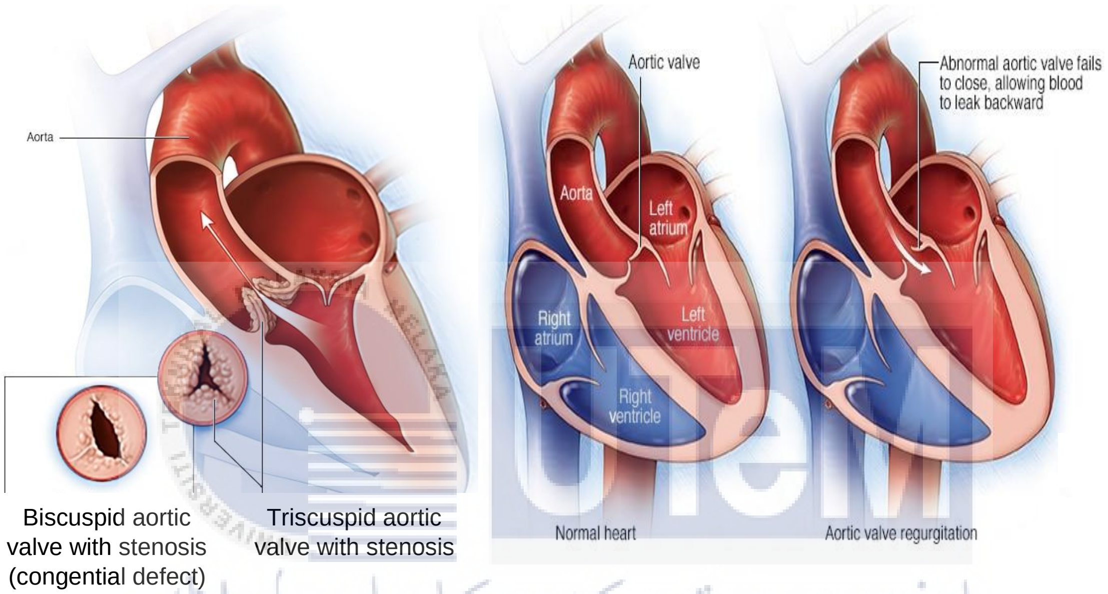
1.1 Background of Study

Heart valve replacement surgery is a one kind of surgery that quit popular these days. This surgery involves patient that happen to have damaged heart valve due to some diseases, infections or accidents (Zakaria et al., 2017). If the heart valve disease is uncured, people can suffer from stroke, chest pain, or even die due to heart attack. Aortic valve stenosis is one of the heart valve diseases which causes the heart's aortic valve become narrow and soon can prevent the blood from flow through the aorta. A clear diagram of aortic valve stenosis is shown in Figure 1.1 (a). According to a research, about 400,000 people died due to cardiovascular disease which major on heart valve disease in between 1998 and 2004 in Germany (Bongert et al.,2008). In 2006, the heart valve surgery became popular for the local and demand on skilled heart surgeon increased (Bongert, M., Geller, M., Pennekamp, W., Roggenland, D., & Nicolas, V., 2008). Meanwhile, an estimated 2.9 to 5.8 million more adults in the U.S. experienced aortic valve disease in 2016 as the percentage of people having the heart valve disease increase at the age of 65 years old and above (Evans, F. & Vinod H. Thourani, 2018).

Other than stenosis, aortic valve regurgitation also contributes in heart valve failure. Regurgitation is a backflow of blood during diastole (phase when heart muscles relaxes), where the blood flow backwards from the aorta to the left ventricle (Armstrong, G. P.,

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018). Based on American Heart Association (2016), this disease can occur mostly due to aging, infection at the heart tissue and high blood pressure. It can make a person become exhausted and make them feel breathless due to the low oxygen being pumped through the heart as there are leakage occurs at the aortic valve where the blood will flow backwards from the aorta to the left ventricles.



(a) (b)

Figure 1.1 (a) Aortic valve stenosis (M. C. S, 2018). (b) Aortic valve regurgitation (M.C. S, 2017)

Due to the leakage, the aortic valve did not operate efficiently and can lead to heart failure. Figure 1.1 (b) shows how the aortic valve regurgitation can occur.

There are two types of prosthetic heart valve that can be used to treat the uncured heart valve, which are Mechanical Heart Valve (MHV) and Bio-prosthetic Heart Valve (BHV). Mechanical Heart Valve is made of pyrolytic carbon and is the most preferable prosthetic heart valve among the patients as it is last long and only need to undergo replacement surgery once in a life time (Zakaria et al., 2017). Meanwhile, Bio-prosthetic heart valve is made of animal tissues and only last long for several years as it will degenerate due to calcification. Therefore, another surgery needs to be done to replace the damaged valve with the new one which make this prosthetic heart valve less preferable compared to MHV. However, despite of being the most preferable prosthetic heart valve, there are few complications occur on having MHV such as thrombosis and bleeding.

Previous study found that blood clot complication is highly risk and can cause stroke or cause the valve to fail itself. If there is some vessel injury occurs at the valve, low dilution of the activated clotting factors due to low cardiac output will trigger the blood coagulation and this can occur based on different anatomical positions. Besides that, the hemodynamic flow characteristic varies with different anatomical positions. Other than that, no current or circulation of the blood flow at Bileaflet Mechanical Heart Valve (BMHV) hinges caused by the sharp geometries, can lead to thrombosis. In contrast, blunt edges at the vicinity of the vortex generator leads to low level of platelet damage (Zakaria et al., 2017).

Besides sharp geometries, thromboembolism and platelet activation are the most crucial complications of having this type of heart valve replacement surgery as it creates a high shear stress caused by the blood flow (Yun et al., 2014).

UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

1.2 Problem Statement

Bileaflet Mechanical Heart Valve (BMHV) is the most common design of MHV and said to be the best design during this century. However, this type of MHV cannot run from the fact of thrombosis complication that can occur in the vicinity of the leaflet due to abnormal flow (Zakaria et al., 2017). Besides that, according to Zakaria et al (2017), current design of Bileaflet MHV has a weakness as there is a gap between hinge and leaflet (150µm), where higher risk of blood clot will occur. In order to reduce the blood clot, patients need to take blood thinner known as warfarin everyday based on doctor's prescription. This could drastically affect the lifestyle of the patients for his future days and also can affect the child mortality for married women. Based on researches, the vorticity in the shear layers disperse directly soon after leave the leaflet surfaces where the fastest streamwise of the vorticity deteriorate. This phenomenon occurs during peak systole, when there is no vortex generator installed at the bileaflet heart valve (Hatoum & Dasi, 2018). Besides that, it is found that the Reynolds Shear Stress (RSS) magnitudes at the peak systole is higher when VGs are not installed compared to the absence of the VGs. In order to reduce the RSS and pressure drop, as well as the velocity of the blood flow, VGs need to be attached to the bileaflet of the valve as it leads to the slowing down of the separation of flow and reduce the unsteadiness of the free shear at the shear layers (Hatoum & Dasi, 2018). Other than that, even though VGs give big impact to reduction of RSS, pressure drop and velocity, different types of VGs will give different value and effect of those parameters. Therefore, a better geometry design of vortex generator by using the Computational Fluid Dynamic (CFD) analysis of the blood flow can help to reduce the aggregation of blood clot.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

1.3 Objectives

Bileaflet Mechanical Heart Valve (BMHV) is the most preferred prosthetic valve during this era, which is symmetrical and relatively non-turbulent in term of blood clot influence, compared to other MHV type. The most prospering material used for MHV is pyrolytic carbon as it suits the condition of the body in term of biocompatibility (Helmus, M., & Cunanan, C., 2011). This project is cognate with the geometry design of the vortex generator and the effect on the blood flow which is rigorously scrutinises the blood clot issue. There are few objectives of this study in order to achieve a better result, which are as follows;

1) To develop CFD models of blood flow in vivo at the aortic valve.
2) To improve the current vortex generator design by comparing with previous experimental studies.
3) To analyze the blood flow characteristics such as velocity, pressure drop and wall shear stress by using improved design of vortex generator attached to the real aorta.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

1.4 Scope of Study

This study is focusing primarily on the effect of vortex generator on blood flow characteristic on real patient specific data. Type of prosthetic valve used in this study is Bileaflet Mechanical Heart Valve (BMHV) that resembling St. Jude Medical Regent Bileaflet Valve as it is the most thriving prosthetic valve for the heart valve replacement surgery based on the past research that gives better result compared to other type of prosthetic heart valve. Besides that, this study is also focusing on designing a new geometry of vortex generator in order to reduce the coagulation of the blood clot. Other than that, in this study, only the opening sequence of the leaflet will be covered. However, the effect of angle opening of the vortex generator will not be covered in this study.

General Methodology

In order to achieve the objectives and scopes of this study, there are few actions need to be carried out in a correct sequence as follows:

1) Literature review.

   Scholarly article, journal and past research thesis will be reviewed and summarized to help with the research.

2) Mimics software.

   Mimics/Slicer software will be used to create medical imaging of the real patient's data.

3) SolidWorks software.

   This software will be used to draw the mechanical heart valve with vortex generator.

4) Geomagic X software.

   This software will be used to attach the mechanical heart valve and the medical imaging of the real patient's data.

5) Simulation.

   Simulation of Computational Fluid Dynamics (CFD) models of blood flow in vivo at the aortic valve with vortex generator is simulated by using ANSYS.

6) Analysis and proposed solution.

   Analysis of the blood flow characteristics due to blood clot with the presence of vortex generator will be done in terms of wall shear stress (WSS).

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

7) Report writing.

A full report on this research will be written at the end of the project.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Human Body

Human’s heart has four valve and one valve per chamber of heart which are mitral valve, tricuspid valve, aortic valve and pulmonic valve. Besides, both mitral valve and tricuspid valve are located between atria and ventricles while aortic valve and pulmonic valve are located between the ventricles and main blood flows in and out of the body respectively (“4 Valves,” 2018).

Tricuspid valve is a valve that works by prevents the backflow of the blood from right ventricle to the right atrium. Furthermore, mitral valve works by open the valve to allow the oxygenated blood coming from the lung. Next, Pulmonary valve or pulmonic valve is a valve that open to allow the deoxygenated blood being pumped from the right atrium to the right ventricle and out of the lung through the pulmonary artery (American Heart Association, 2016).

Meanwhile, aortic valve works by open the valve to allow the oxygenated blood flows from the left ventricles to the aorta (contraction) and throughout the whole body. During relaxing of the ventricle, the valve will close to prevent the backflow of the blood from the aorta to the left ventricle, which may lead to heart failure. Aortic valve is one of the valves that maintain the flow of the blood through the heart and it ensures the blood flows in a right way. If the aortic valve did not work efficiently, it will intrude the blood flow and cause the heart to force itself to pump harder which is not a normal phenomenon for a normal heart to operate (American Heart Association, 2016).

2.1.1 Blood Circulatory System

The basic principle of circulatory system is to carry fluid or substances from certain part to other part of the body. The fluid medium of the transportation process in the body is blood while the blood vessels secure the path of the blood to its targeted place. 'Cardiovascular system' is a term best describes the heart and vessels. It is purposely to provide nutrients and oxygen to the cells throughout the body (Saladin, K. S., 2010).

There are two type of circulations involve in cardiovascular system which are systemic circulation and pulmonary circulation. According to the Institute for Quality and Efficiency in Health Care (2010), systemic circulation is a circulation where blood is transported to the organs, tissues, cells and other crucial parts of the body including other parts of the lungs to get enough oxygen. Meanwhile, pulmonary circulation is a process where deoxygenated blood is exchanged with the oxygen at the lung and before undergoes systemic circulation process (Boyette LC & Burns B., 2019).

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Systemic circulation begins when oxygenated blood enters the left atrium, travels to the left ventricles and transferred to the main artery called aorta through aortic valve. Then it travels to the capillary network, drops oxygen and some other substances throughout the body. After circulate throughout the body, the deoxygenated blood will enter the main vein called vena cava and will be delivered to the lung to exchange for fresh oxygen through the lung capillaries (Padsalgikar, A. D., 2017).

Pulmonary circulation starts when the deoxygenated blood is pumped from the right ventricle through the pulmonary artery. At the capillaries in the alveoli, the process of gas exchanges occurs where the deoxygenated blood is replaced with the new oxygenated blood (Rogers, K., 2018). Then, the oxygenated blood is returned to the left atrium. The process of blood circulation in human body is visualized in Figure 2.1.

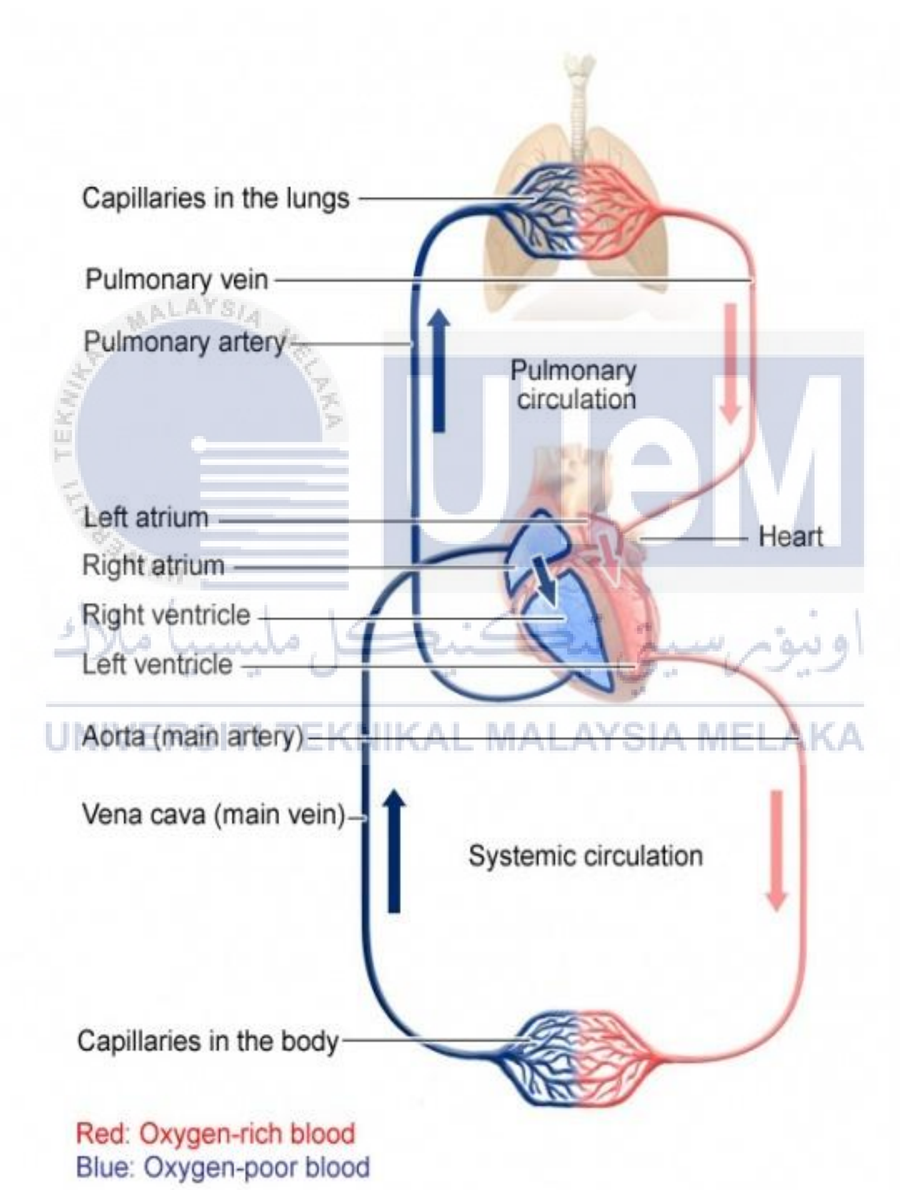


Figure 2.1 Blood Circulatory System ("How Does the Blood Circulatory System Work?," 2019)

2.1.2 Anatomical Structures of Aorta

Aorta is known or commonly called as the largest artery in the body. It functions as to keep on supplying oxygenated blood to all arteries in the body and it starts from the left ventricle where the heart undergoes systole which is the pumping state of heart (Hoffman, 2017). Aorta is divided into 4 regions named ascending aorta, aortic arch, descending thoracic aorta and abdominal aorta.

Ascending aorta is part where the oxygenated blood starts to enter which covers the part from the left ventricles through the aortic valve until the aortic arch. Aortic arch is the curved part of the aorta that delivers the oxygenated blood to the brachiocephalic artery to the head, neck and arm regions (Regina, 2019). It has this bend-backward-structure-look which connected both of the ascending and descending parts of the aorta (Regina, 2017). The anatomical structure of aorta can be referred to Figure 2.2 and the position of mechanical heart valve in aorta can be referred to Figure 2.3.

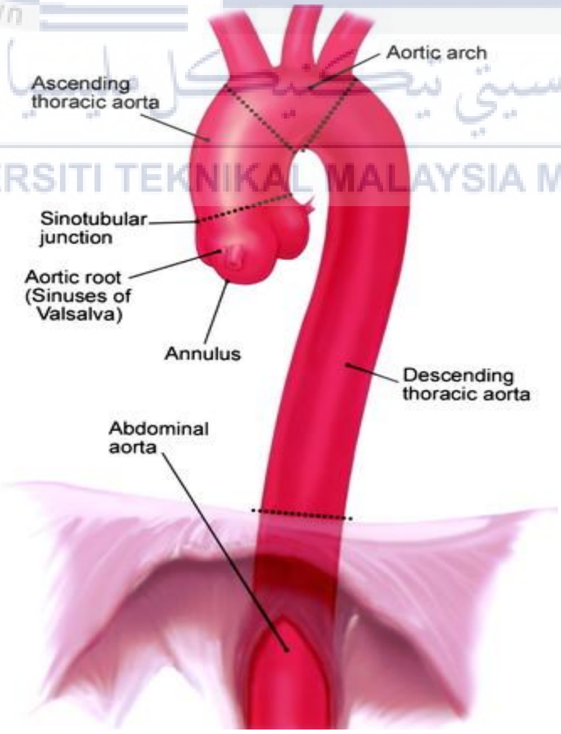


Figure 2.2 Anatomical structure of aorta (Isselbacher, 2005)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

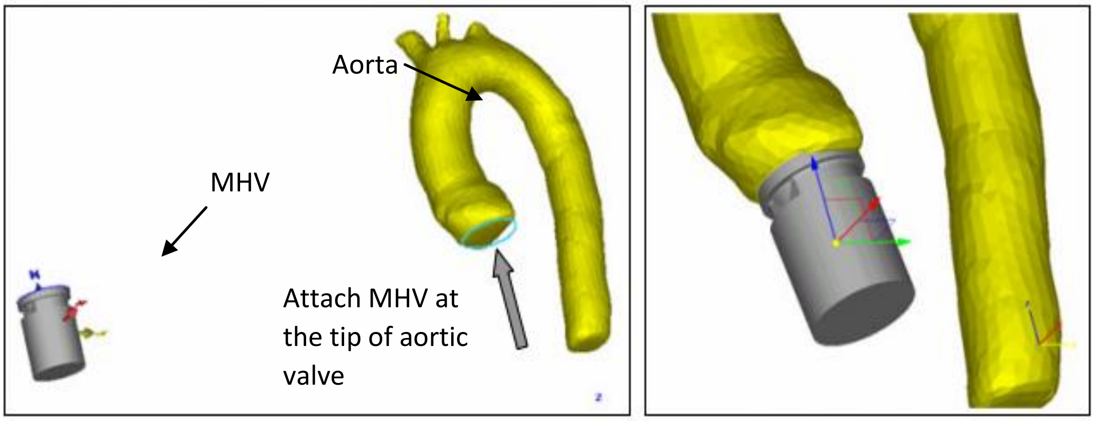


Figure 2.3 Position of MHV in the aorta (Bongert et al., 2008)

The next regions are the regions of the lower part of the aorta which are descending thoracic aorta and abdominal aorta. Descending thoracic aorta is the region where the oxygenated blood is delivered to the area of the chests which are to the ribs and chest structure. Meanwhile, the abdominal aorta is the region where the oxygen-rich blood is transported to the lower abdomen, starts from the diaphragm to the paired iliac arteries which are the pelvic regions and the legs (Hoffman, 2017). The overview of aorta structure in human body is shown in Figure 2.4.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

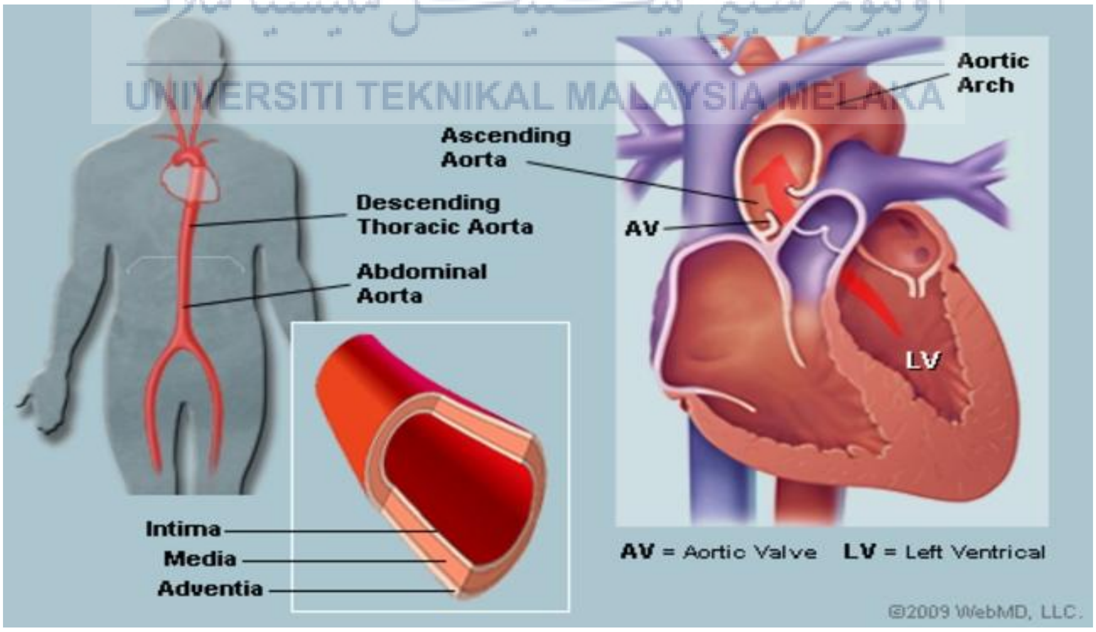
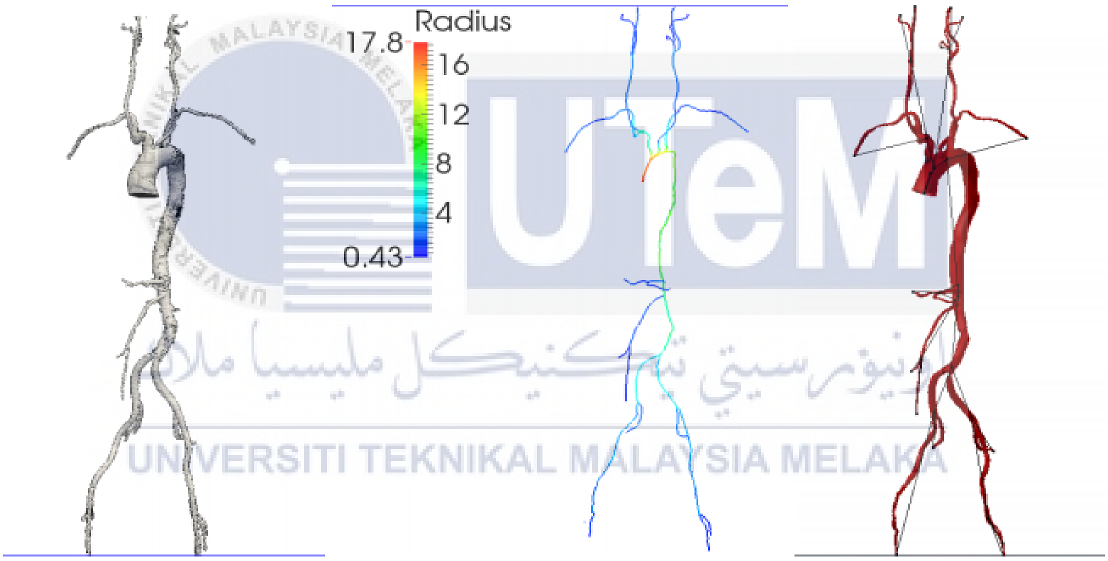


Figure 2.4 Overview of aorta structure in the human body (Hoffman., 2017)

2.2 Modelling Blood Flow in Cardiovascular System

The blood flow modelling will be in three-dimensional part where the wall of the vessels will be assumed as rigid model. The modelling of cardiovascular system is to determine the blood vessels in the body and hemodynamic part which make it easier for estimation on patients that having cardiovascular diseases. Mathematical and computational should take place in order to do the modelling process where it starts from the patient's medical imaging data until the last process which is the computational results (Marsden, 2015). Therefore, 3D Navier-Stokes equation is used to determine the hydrodynamic part of the model.



(a) (b) (c)

Figure 2.5 Network reconstruction of blood modelling by stages: (a) vascular segmentation, (b) centrelines extraction, (c) 3D graph generation (Bessonov et al., 2015)

Figure 2.5 shows the network reconstruction of blood modelling where the first stage in Figure 2.5 (a) is the segmentation of vascular system which extracted from the CT or MRI data. The second stage is the extraction of centrelines and the final stage is the generation of 3D graph which characterized the vascular network.

2.2.1 Properties of Fluid Flow

The properties of fluids were explained in Fluid Dynamics where it explains on the behaviour of the fluid where each property can affect and cause things differently. There are numerous properties of fluids such as density, viscosity and surface tension. The density basically based on the mass and volume of the fluid while viscosity is prone to the effect of resistance when shear stress occurs (Wilkes, 2017). The fluid that is going to use in this study is blood with some properties based on previous research which is shown in Table 1.

Table 1 Properties of blood (Ge et al., 2005; Zhou et al., 2016)

Parameter	Value
Density	1060 kg/m^3
Dynamic viscosity	0.0035 kg/m.s

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

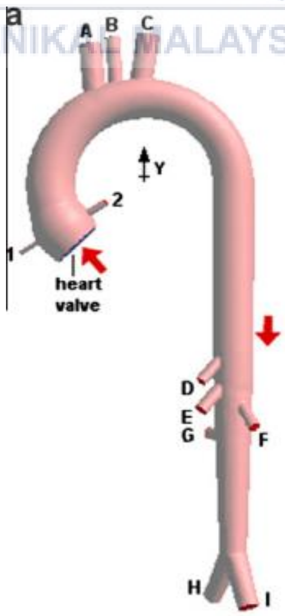


Figure 2.6 Geometry of physiologic circulation (Benim et al., 2011)

The modelled geometry of aorta for physiologic circulation is shown in Figure 2.6. The arrows in the figure indicate the main flow of blood in the aorta where the inlet boundary is selected at the position of where the MHV is placed. In this study, the type of blood flow is assumed to be Newtonian flow based on the past research. During time-averaged, the inlet velocity at the inlet boundary is 0.098 m/s while the Reynolds number is 1140, where it shows the blood flow is in laminar flow (Benim et al., 2011). Meanwhile, during pulsatile flow at the aorta, turbulence state is occurred due to higher velocity and Reynolds number during the cardiac cycle. The pulsatile computation can be seen in Figure 2.7 below.

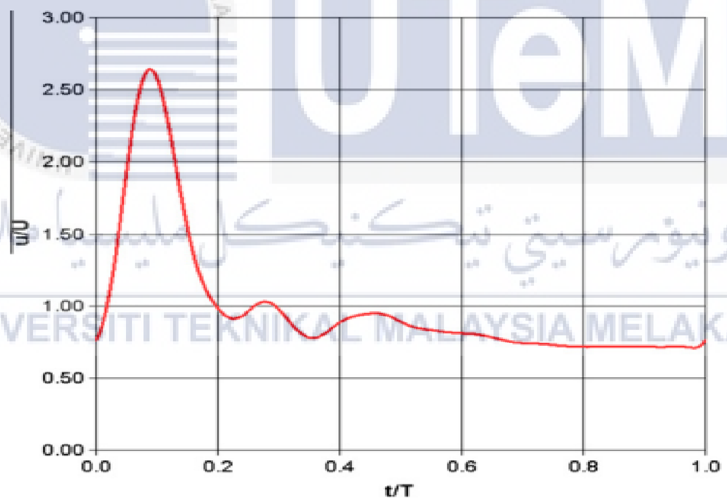


Figure 2.7 Pulsatile flow of physiologic circulation by using inlet velocity (Benim et al., 2011)

2.2.2 Model of Wall Aorta

The model that is going to use in this study is a rigid model type of aorta. Each layer can be seen has different Young's Modulus as shown in Figure 2.8. Subtleties of the stream patterns in the specific blood vessel areas of specific physiological such as at bifurcations, at aortic arch, at the abdominal aorta or cerebral aneurysms can be taken through the rigid walls models. Besides that, in most studies, rigid wall needs to be assumed in order to diagnose the fluid flow, where any movement will not affect the stream (Reymond et al., 2013).

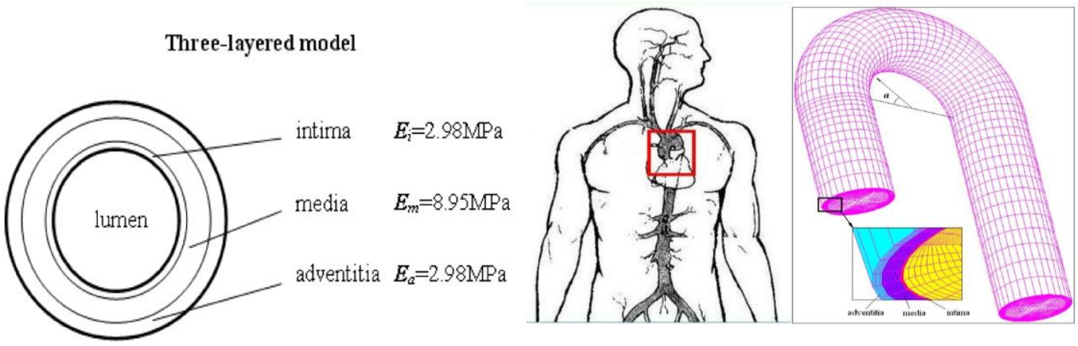


Figure 2.8 Model of rigid wall aorta (Gao et al., 2006)

2.3 Mechanical Heart Valve (MHV)

In this study, we will focus on Bileaflet Mechanical Heart Valve (BMHV) as it is the type of prosthetic heart valve that will be used and analyze in this study. Basically, MHV can be classified based on the reduction of thrombus complications. They are:

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

- Starr-Edwards caged ball valve
- Bjork-Shiley tilting disk valve
- Medtronic Hall tilting disk valve
- St. Jude Medical Regent bileaflet valve

Starr-Edwards caged ball valve is made of stellite and silastic material. It is designed based on caged-ball valve concept where the ball will open during forward flow and close during the reverse flow. Other than that, they happened to have both excellent durability and haemodynamics, which lead to last long structure of prosthetic heart valve and lower risk of having blood clot complications respectively (Amrane, Soulat, Carpentier

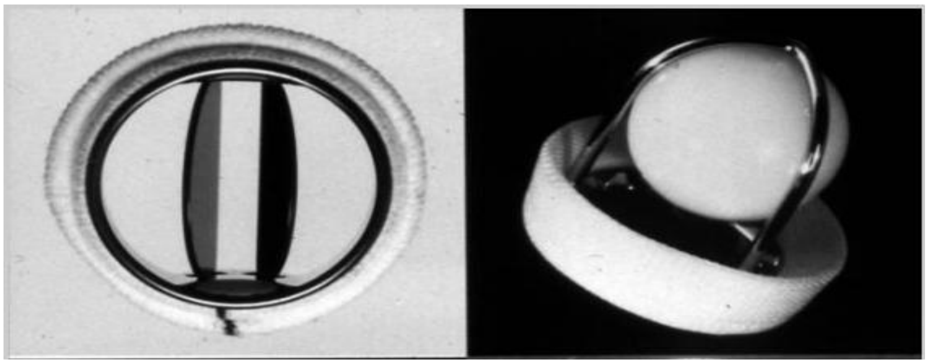
& Jouan, 2017). Based on Zakaria et al. (2017) the blood clot was affected due to high pressure drop and high turbulence state that suddenly occurred because of the barrier of flow by the ball.

Bjork-Shiley tilting disk valve has became a successful tilting disk valve during 1969 and it was primarily made for clinical practise during the year (Sansone et al., 2012). This tilting disk valve was made of thermoplastic, acetyl resin (Delrin). Based on the characteristics of Delrin, this type of valve is synergic to the human body which make it can last long for 37 years (Sansone et al., 2012). Although this prosthetic valve can last long for over 40 years, it still comes with blood clot complications such as maximum shear stress around the disk at certain parts and at the vicinity of the entrance at the valve chamber and huge path of the blood flow where it halts the blood flow separation (Zakaria et al., 2017).

Medtronic Hall tilting disk valve was designed by a surgeon named Karl V. Hall and an engineer named Robert L. Kaster where they called them Hall-Kaster. It started to establish at 1977 for clinical use and the creation of this valve is to increase the valve lifespan besides to revamp the hemodynamic performance of the valve (Antunes, M. K., 2015). Titanium is the material used to produce this prosthetic valve while the disk is made of different kind of material named tungsten-impregnated graphite and coat with pyrolytic carbon (Svennevig, J. L., Abdelnoor, M., & Nitter-Hauge, S., 2007). Based on analysis and research, this valve shows positive response towards younger age patients while the performance slowly going down as their age increases (in the range of middle-aged and elderly) (Svennevig, J. L., Abdelnoor, M., & Nitter-Hauge, S., 2007). The effect of blood clot when using this prosthetic valve is higher as the blood clot aggregates at the hinge and the pivot (Zakaria et al., 2017). Figure 2.9 shows types of heart valves prostheses which

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

include St.Jude Medical bileaflet valve, Bjork-Shiley tilting disc, Starr-Edwards ball and cage, and Medtronic-Hall tilting disc valve.



(a) (c)

(b) (d)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 2.9 Types of heart valve prostheses. (a) St.Jude Medical bileaflet, (b) Bjork-Shiley tilting disc, (c) Starr-Edwards ball and cage (Bloomfield, 2002), (d) Medtronic-Hall tilting disc valve (Yadav et al., 2018)

In this study, the valve that is going to use is St.Jude Medical bileaflet valve or BMHV. As discussed in chapter 1, BMHV is the best valve that is being used and preferred until now due to the design and the lifespan of the valve. However, despite of being the most preferred valve, blood clotting problem is still being the biggest problem. Therefore, in order to reduce the accumulation of blood cloth, vortex generator will be designed and added to the leaflet of the valve. Based on research (Zakaria et al., 2017), sharp geometries will lead to serious blood clot and this problem need to be solved. A modification of geometries should be done, where the geometries need to be a blunt type to avoid the presence of blood clot at the edges of geometries.

2.4 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is the application that used for calculation and numerical strategies to tackle liquid stream issues (Wills and Finch, 2016). According to other research, CFD is a branch of science that use computerized computer to predict fluid flow with the consent of conservation laws such as mass, momentum and energy that control the movement of the fluids (Hu, 2012). Flow of fluids (liquids or gases) can be numerous things and it can occur whenever structures contact with the air or water encompassing them. Besides that, CFD can help engineer in doing feasibility study on building something or in automotive, impact of natural disaster to houses and etc (Nasir, 2018).

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Next, to obtain the desired simulation results, CFD analysis processes are needed to be followed. The first process is pre-processing where it involves in determining the flow problems, generating geometry and generating mesh grid. Objectives, type of fluid, material that will be used will be done in this part as well as choosing a correct method for meshing. The second process is solving where in this section, boundary conditions and initial conditions will be determined in order to get the expected results. Besides that, the calculation will be run based on the iterations set until the calculation achieves convergence. The last process will be post-processing where the useful results will be extracted and use for the research (Slater, 2008). Details on the process of CFD analysis will be discussed in Chapter 3 and 4.

There are many application of CFD that is widely used in the industry, such as in aircraft application where CFD is used to simulate the effect of propellers with the aircraft's main body section (Bhaskaran & Collins, n.d.). For example, CFD is used to obtain the pressure affect by those two interactions as mentioned above. It is much easier to do a simulation compared to real situation where it consumes high cost to prepare all the tools needed. Another example is CFD is used in Bio-Medical Engineering where it is used to examine the blood flow in heart system or other system in the body (Bhaskaran & Collins, n.d.). The simulation can be used to study the pressure or velocity at the valve. CFD is used in this Medical field as it is more effective and also can save cost.

2.4.1 Governing Equation

The governing equations involve in this study are the fluid dynamics equation, 3D unsteady incompressible continuity (shows mass enter the system equal to mass going out of the system) and Navier–Stokes equations. The equation is shown as below:

For continuity equation,

$$\nabla . u = 0 \tag{1}$$

where,

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2}$$

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

For Navier-Stokes equation,

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\rho g_x+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{3}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\rho g_y+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{4}$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\rho g_z+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{5}$$

where ρ represents the density of fluid, u, v, w indicates the velocity in x, y, z direction, while g_i indicates the body force in i-direction and μ represents the dynamic viscosity of the fluid. The left side of the Navier-Stokes equations is the inertia forces, where it is balanced by the right side of the equation which is pressure force, body force and viscous force (Kadhim et al., 2017).

2.5 Vortex Generator Application

In this section, vortex generator on basis applications with multipurpose functions will be discussed which include the application of vortex generator on mechanical heart valve.

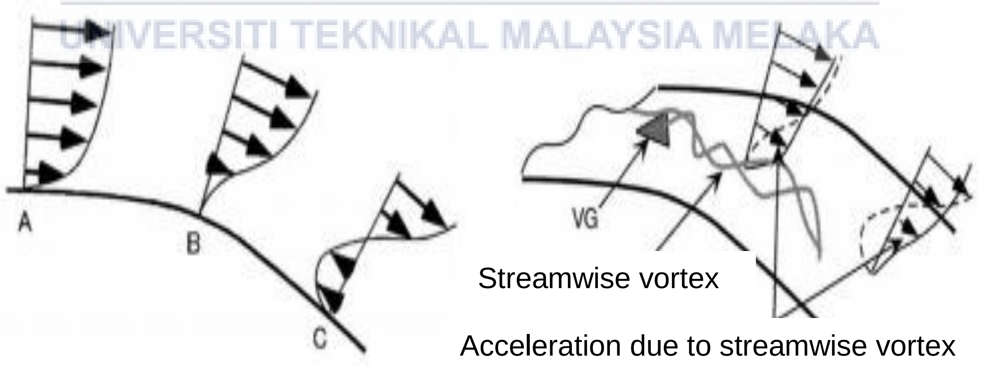
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2.5.1 Effect of vortex generator on hatchback type cars

The problem with the hatchback cars was stated to be high in drag force and the flow separation, where the drag force occurs to be the main defiance of car slowing down while the flow separation most occurs at the back of the car. The function of VG attached at the roof of a hatchback car is to reduce the aerodynamic drag and increase the time of flow separation on the car (Yadav, Rawal & Mishra, 2018). Based on past research, VG is designed to be installed on the roof, above the windshield at the back of the car. Even though the rear end car is designed to be aerodynamic to reduce drag force, it creates high pressure which will increase the backflow at the back of the car. The aerodynamic design at the rear end car causes the increasing in the flow area which will lead to reduction of velocity as the air started to flow separately.

Based on Figure 2.10 (a), the reverse flow of boundary layer can be seen at point ‘C’ because the pressure is higher at the downstream which is contra from the upstream (point ‘A’) where the pressure is lower and this will create a high drag . At point ‘A’, contradicting stream does not occur as the momentum of the boundary layer can prevail over the pressure gradient. At point ‘B’, it shows the balance or equal on the momentum and pressure gradient of boundary layers. Therefore, to avoid the reverse flow as at point ‘C’, vortex generator is needed as it acts as the medium to balance the momentum and pressure gradient of boundary layer between the flow at point ‘A’ and point ‘C’ by creating the vortices at the vicinity of the rear end car. It shows that vortex generator controls the flow separation efficiently. Figure 2.10 (b) shows the depiction of flow around the VG (Yadav et al., 2018).

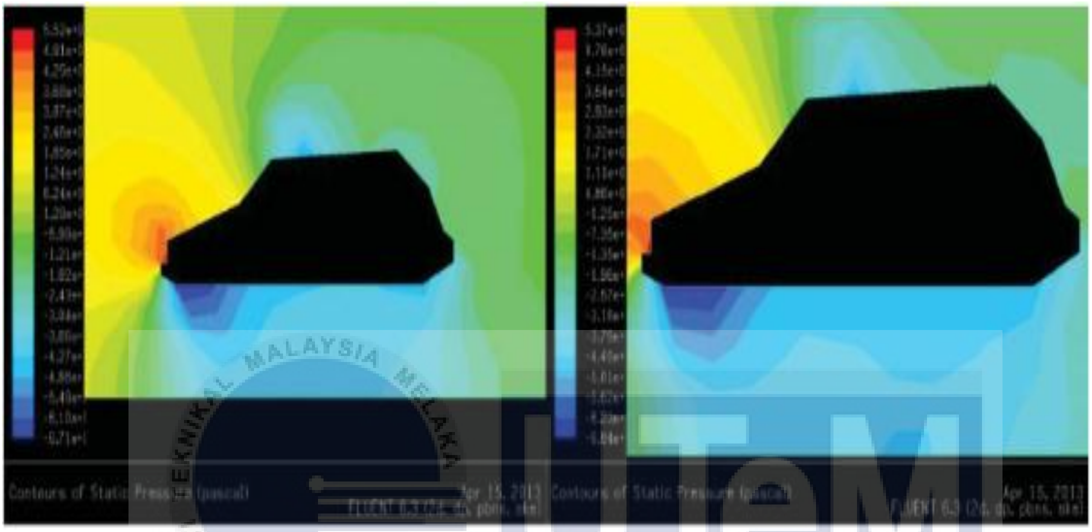
UNIVERSITI TEKNIKAL MALAYSIA MELAKA



(a) (b)

Figure 2.10 (a) Velocity profile at the rear end car, (b) air flow around the VG (Yadav et al., 2018)

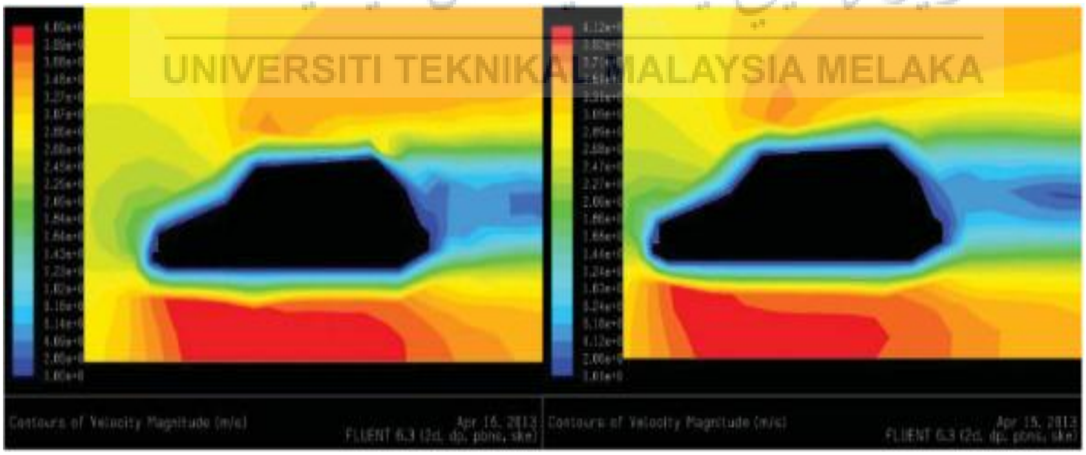
Figure 2.11 shows the pressure distribution over the hatchback car with and without VG. It can be seen on Figure 2.11 (b) that the pressure decreases with the presence of vortex generator at the rear end car compared to the normal car without VG installed as in Figure 2.11 (a). Furthermore, it can be seen that the flow area is narrowing based on the velocity increase at the vicinity of the back of the car with VG based on Figure 2.12 (b). Therefore, VG can be used to reduce the drag force and flow separation of the hatchback car (Kumar et al., 2013).



(a) (b)

Figure 2.11 Pressure distributions over hatchback car, (a) without VG, (b) with VG (Kumar et al., 2013)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA



(a) (b)

Figure 2.12 Velocity distributions over hatchback car, (a) without VG, (b) with VG (Kumar et al., 2013)

2.5.2 Effect of vortex generator on Swept Constant Chord Half-model

Swept Constant Chord Half-model (SCCH) is a basic replica that is being used to determine the aerodynamic force of high-lift system. The schematic views of SCCH can be seen in Figure 2.13 and it should be formed by the main wing, leading edge slat and trailing edge flap. High lift system is needed to increase the efficiency of the aircraft during landing, take-off and in term of flow separation (Chu, Zhang, Chen, Li & Mao, 2012). The maximum lift and lift-to-drag ratio of the system needed to be improved to ensure the efficient aerodynamic performance. However, during the turning of the plane, the flow separation increases at the trailing edge flap which will decrease the lift force, and increase the lift drag and noise surge. Thus, it will decrease the performance of the aerodynamic drag force of high-lift system.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 2.13 Swept Constant Chord Half-model schematic views (Chu et al., 2012)

Therefore, vortex generator is introduced to the system in order to improve the aerodynamic efficiency by decrease the flow separation at the trailing edge flap during the turning of the plane. It helps to delay the flow separation by creating vortices at the vicinity of the VGs. Thus, the lift force can be increased, and the drag force followed by the noise surge can be reduced. When the flow separation is controlled by the VGs, the aerodynamic efficiency of the system will be improved during the aircraft landing and take-off. Based on Figure 2.14, it shows that the flow separation increases as the flow starts to separate immediately at the trailing edge flap when there are no VGs attached before the separation region. In contrast, the flow separation is narrowed when there are VGs attached to the flap as in Figure 2.15 due to the presence of vortices created by the VGs. Both experiments conducted are based on the common angle of attack used for landing configuration which is α =8° (Chu et al., 2012).

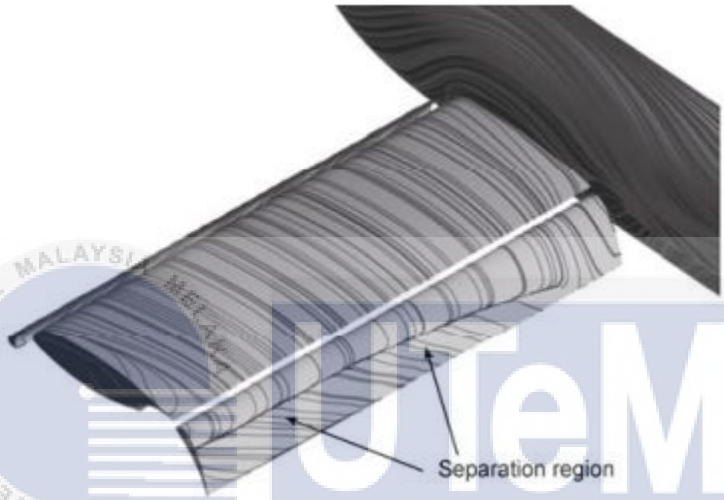


Figure 2.14 Surface streamlines of SCCH without VGs (Chu et al., 2012)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

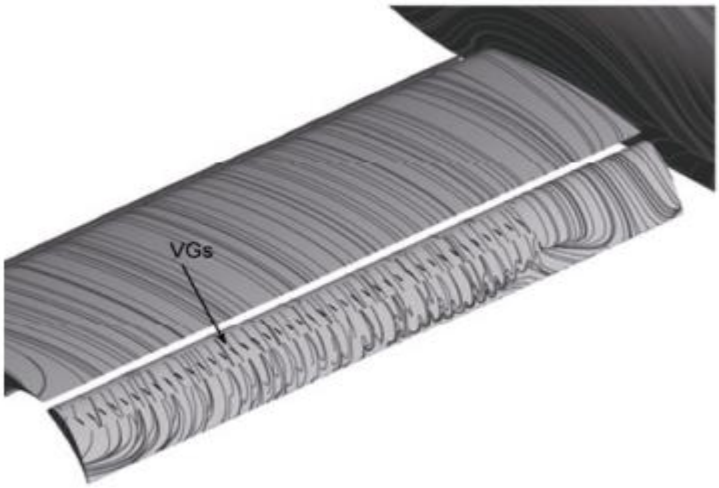


Figure 2.15 Surface streamlines of SCCH with VGs (Chu et al., 2012)

The adding of VGs at the trailing edge flap does not only improve the flow separation, but also improve the pressure distribution of the whole parts of SCCH. In Figure 2.16, it shows the comparison of the pressure distribution of SCCH with and without VGs, where it results in good condition. Consequently, the effect from the good results in pressure distribution does affect the improvement of the lift performance during the landing configuration as shown in Figure 2.17.

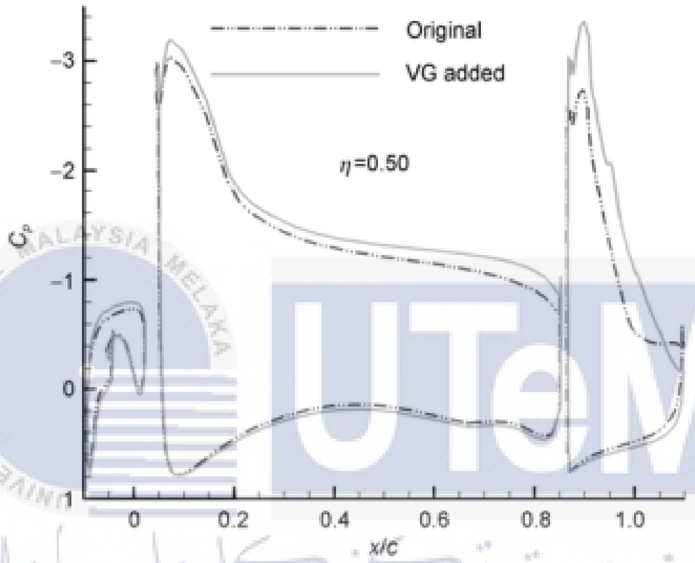


Figure 2.16 Pressure distribution of SCCH with and without VGs (Chu et al., 2012)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

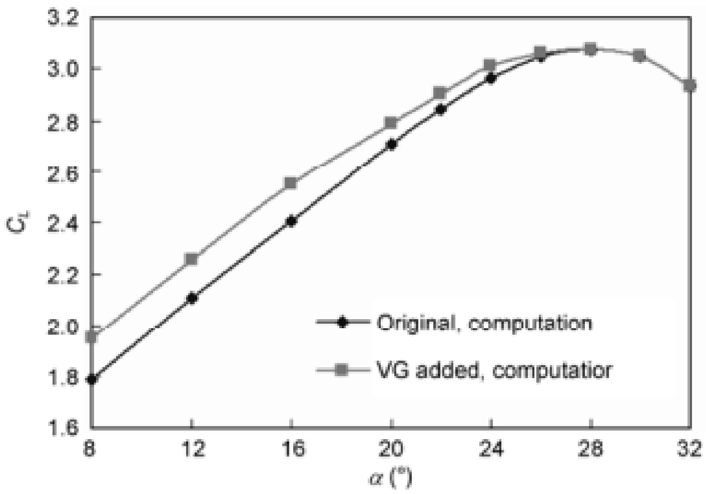


Figure 2.17 Effect of VGs on lift performance (Chu et al., 2012)

2.5.3 Effect of vortex generator on mechanical heart valve

Mechanical heart valve is a prosthetic valve that is designed and being used in this decade to replace the failure valve inside of the human's heart such as aortic valve (Harris, Croce & Cao, 2015). It is made of pyrolytic carbon which suits the condition of the blood flow in terms of biocompatibility (Helmus et al., 2011). Even though it was a success on replacing the valve, however the consequences by having this MHV can lead to serious blood clot due to turbulent stresses occur at the valve which can cause fatal to the patient. The blood clot occurs due to the activation of platelets made by the turbulent flows at the valve closure (Hatoum et al., 2018).

Therefore, vortex generator is needed to reduce the turbulence flow which causes the blood clot by include some parameters such as pressure gradient (PG), flow velocity and Reynolds shear stress (RSS). Based on Hatoum et al., 2018, the PG of the heart valve with no vortex generator is 14.88 ± 0.40 mmHg, where the PG is more higher compared to PG of co-rotating vortex generator attached to the leaflet of the MHV which is 10.45 ± 0.94 mmHg. The summary of hemodynamic data can be seen in Table 2. The highest and fastest flow separation occurs to the MHV with no vortex generator as the vortices disperse fully right after passing through the leaflet during the peak systole. Meanwhile, for co-rotating VGs, the flow separation is narrowed and this can be seen in Figure 2.18 where during deceleration, the flow separation of co-rotating VGs are the final one to separate after the leaflet.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Table 2 Summary of hemodynamic data of MHV with and without VGs (Hatoum et al., 2018)

	Control valve	Co-rotating VGs
Pressure gradient (mmHg)	14.88 ± 0.40	10.45 ± 0.94
Effective orifice area (cm^2)	1.43 ± 0.04	2.26 ± 0.17

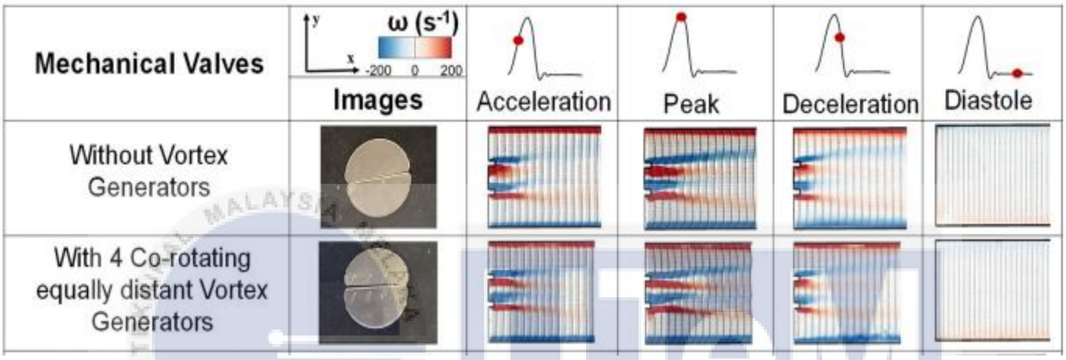


Figure 2.18 Velocity vectors and vorticity contours at four different phases during cardiac cycle with and without VGs (Hatoum et al., 2018)

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

For Reynolds shear stress cases, MHV with VGs shows positive result as the value is much lower than the MHV with no VGs. During acceleration, the RSS of valve with no VGs is 19.3 ± 0.72 Pa whereas for co-rotating VGs is 9.76 ± 0.13 Pa. Furthermore, the RSS during the peak systole for no VGs is quit high compared to co-rotating VGs which the values are 38.13 ± 0.89 and 12.95 ± 0.32 Pa respectively (Hatoum et al., 2018). The comparison of RSS contour at four different phases is shown in Figure 2.19. Based on the overall results and comparisons made, MHV with VGs is better than with no VGs. The turbulence which causes the platelet activation and blood damage, which will produce blood clot can be reduced by include those three parameters such as pressure gradient, velocity and Reynolds shear stress.

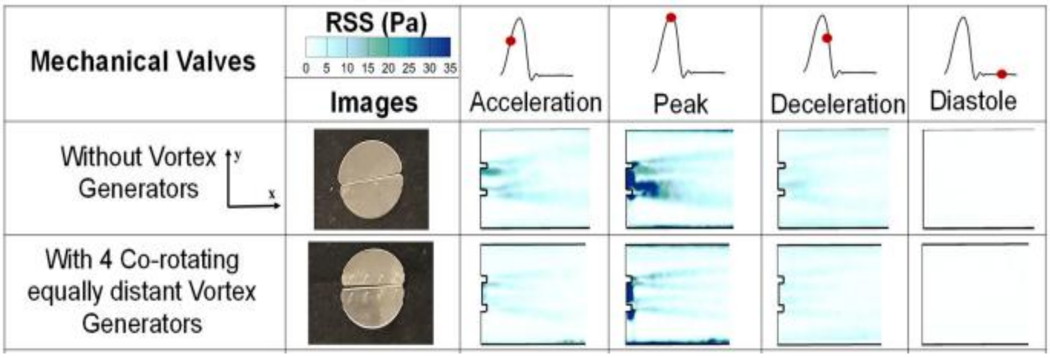


Figure 2.19 RSS contour at four different phases with and without VGs (Hatoum et al., 2018)

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 3

METHODOLOGY

3.1 Introduction

This section explains in details about the method use to achieve the objectives. The flowchart of the study is shown in Figure 3.1. This study starts by studying about the mechanical heart valve with vortex generator where the MHV is drawn in SOLIDWORKS software and simulate the CFD model of blood flow with the real medical imaging of the patient's data by using the ANSYS software. After suspected the accumulation of blood clot does affect the blood flow when there is sharp geometries of vortex generator added, modelling of MHV with a new geometry design of vortex generator is created. Then, the CFD simulation on the blood flow is performed to ensure the parameters such as velocity, wall shear stress and the pressure drop decrease. Otherwise, a new design of geometry is needed to decrease those parameters. The methodology of the study is summarized in a form of flowchart as in Figure 3.1:

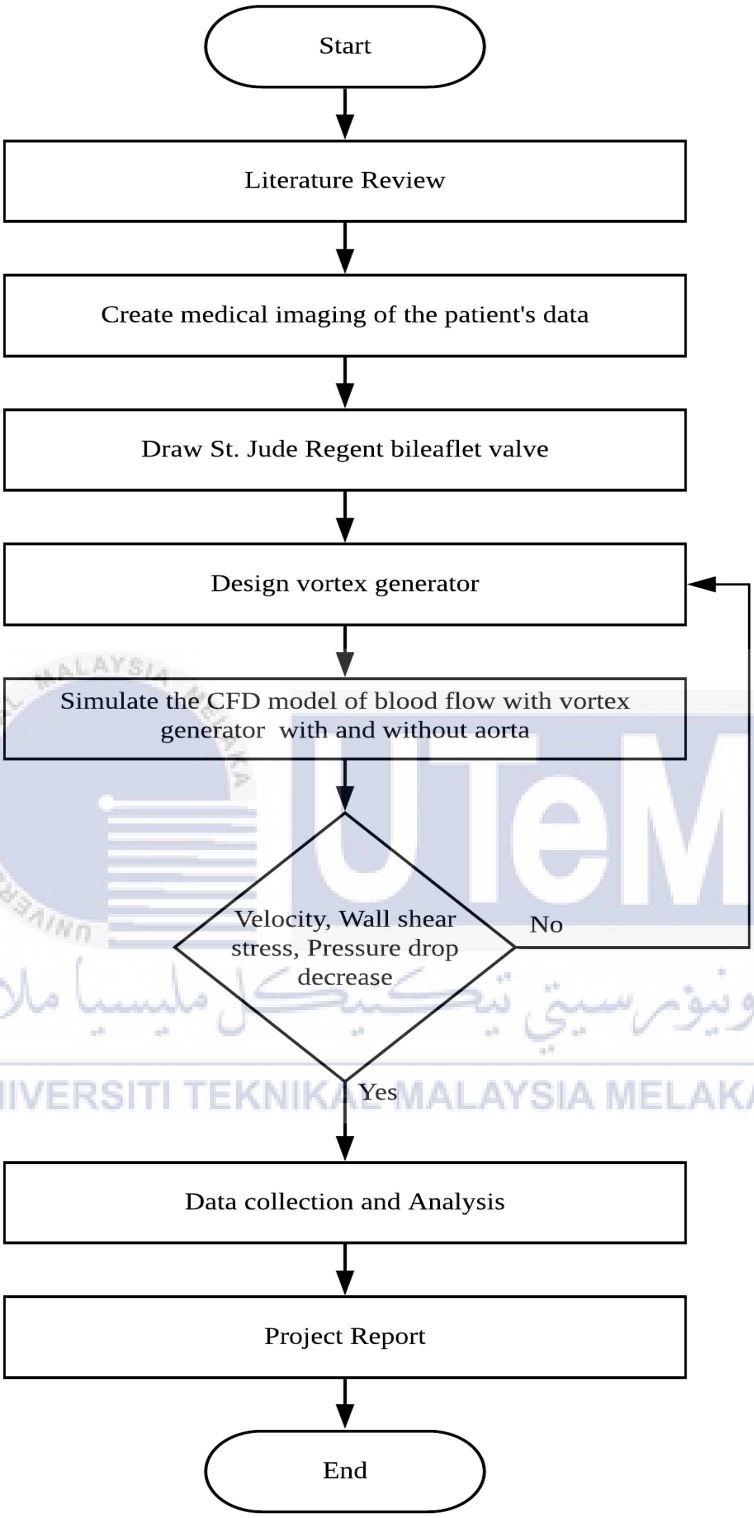


Figure 3.1 Flowchart of methodology of the study

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

3.2 Software

3.2.1 Mimics Medical 21.0

The first software used is Mimics Medical 21.0 where it will be used to extract aorta from the medical imaging of the real patient's data. The processes started by determine the threshold of the heart at the segment tab. Then, at the same tab, split mask is used to split between the area needed and not needed such as the heart (needed) and the spine (not needed). Next, unnecessary tissues around the heart are erased by using edit masks function. After that, the model is converted in CAD format ''STL'' (Stereolithography format). Figure 3.2 shows the X-ray images of patient's heart with the 3D image while Figure 3.3 shows the aorta extracted from the imaging and attached with the mechanical heart valve drawn in SOLIDWORKS software.

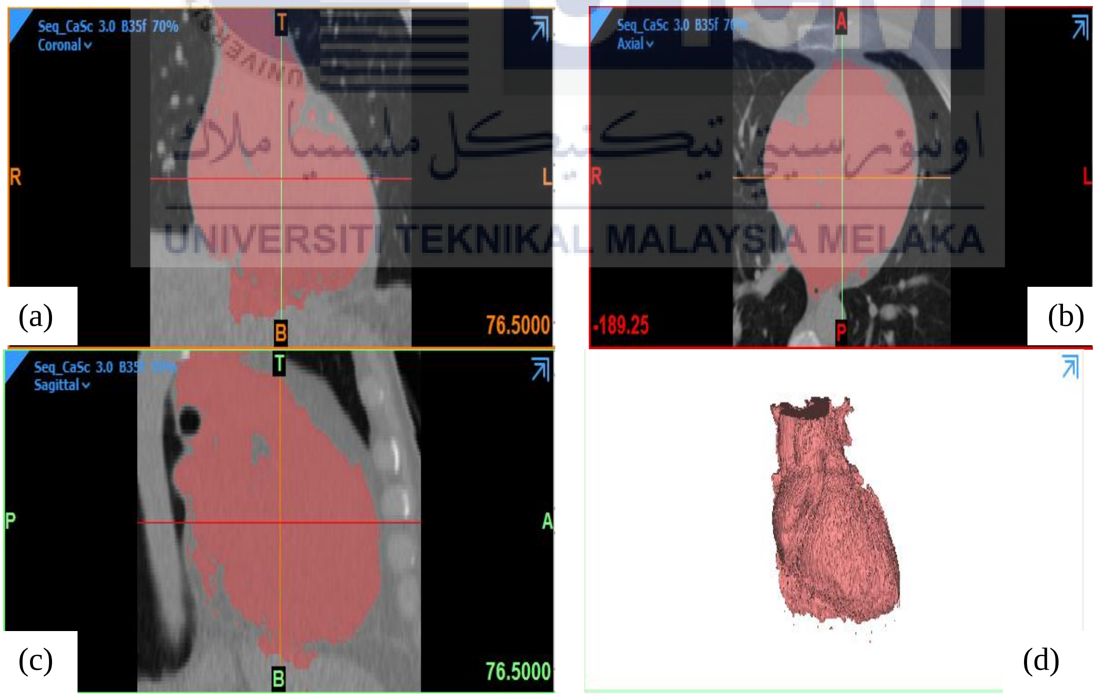


Figure 3.2 X-ray images of patient's heart. (a) Coronal view, (b) Axial view, (c) Sagital view, (d) 3D anterior view of patient's heart

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

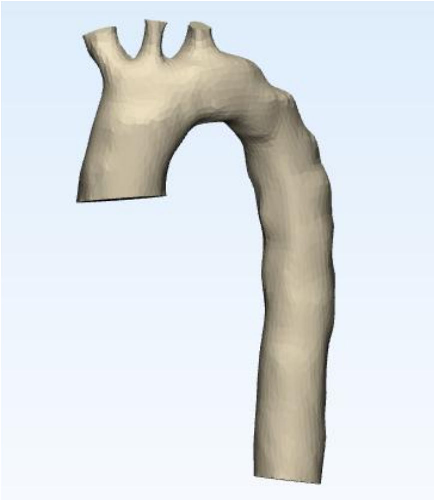


Figure 3.3 Image of aorta extracted from the X-ray images of patient's heart

3.2.2 SOLIDWORKS

The second software that is being used is SOLIDWORK. This software will be used to draw the mechanical heart valve with vortex generator. The mechanical heart valve then will be attached with the aorta from the medical imaging of the patient. The dimensions for the prosthetic heart valve are shown in Table 3. The leaflet is left hanging with 1.5 mm from the inner wall of the valve which the hinge part, where the hinge drawing is not covered in the study. The drawing of 3D mechanical heart valve is shown in Figure 3.4, followed by the 3D drawing of the vortex generator shown in Figure 3.5. The location of vortex generator is shown in Figure 3.6.

Table 3 Dimensions of prosthetic heart valve and VGs (Ge et al., 2005; Hatoum et al., 2018)

Parameters	**Dimension**
Outer diameter of MHV	25.40 mm
Inner diameter of MHV	23 mm
Length of MHV	65.05 mm
Diameter of leaflet	20 mm
Length of VG	2.80 mm
VG radius	0.50 mm
Height of VG	1 mm
Spacing between VG	5 mm
Leaflet thickness	1 mm
Angle between center of MHV to leaflet	5°

UTeM
اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

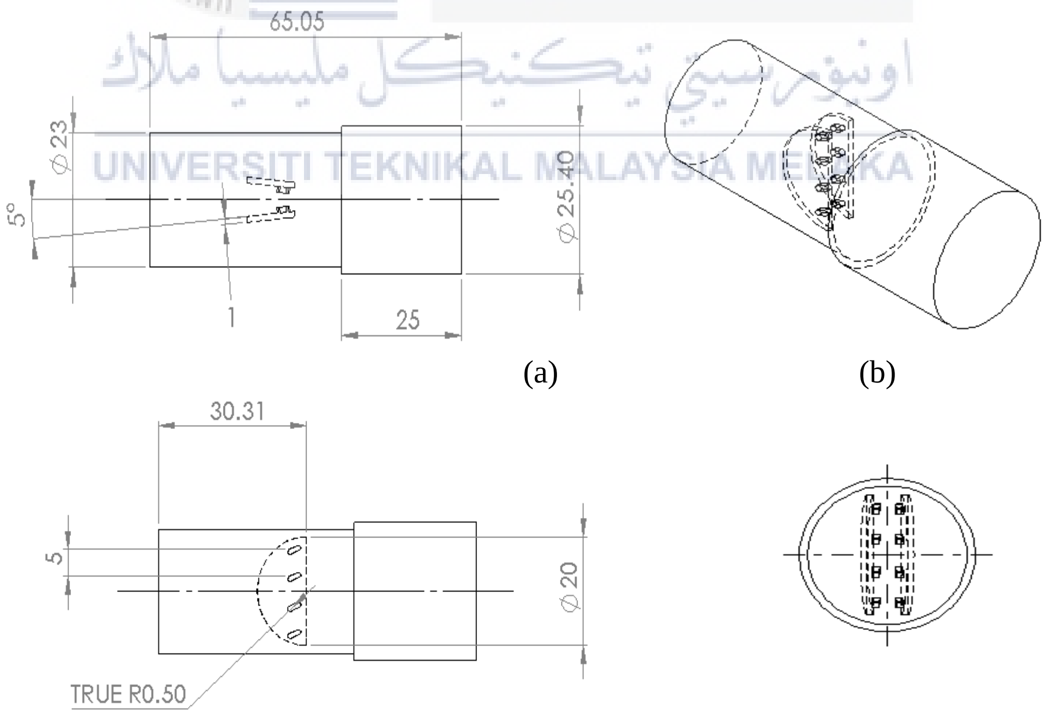


Figure 3.4 3D CAD drawing of mechanical heart valve. (a) Top view, (b) Isometric view, (c) Front view, (d) Side view

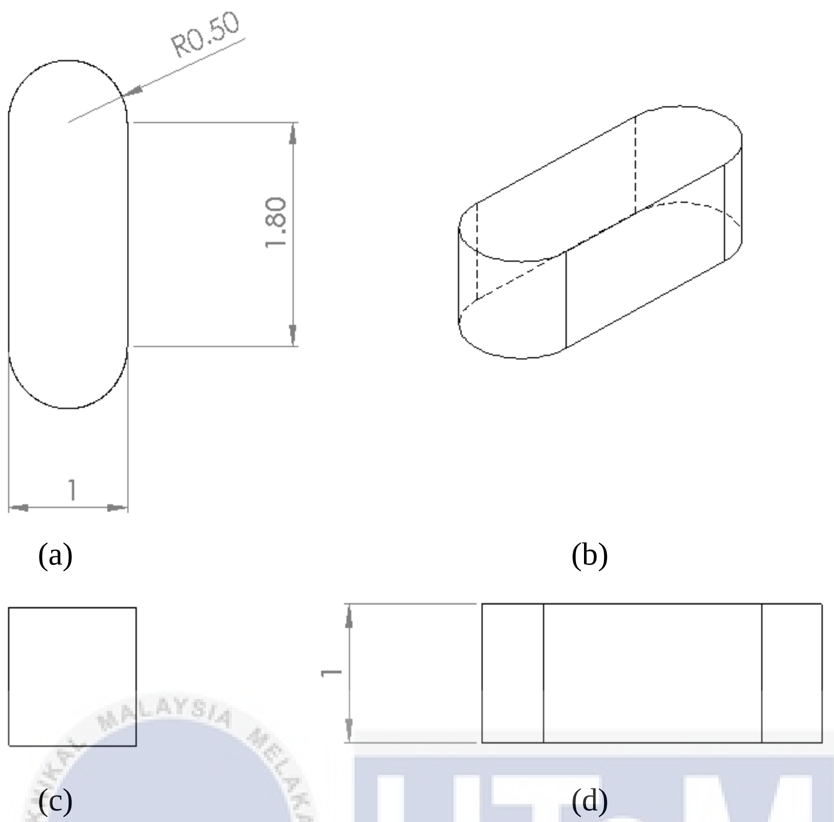


Figure 3.5 3D CAD drawing of vortex generator. (a) Top view, (b) Isometric view, (c) Front view, (d) Side view

UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

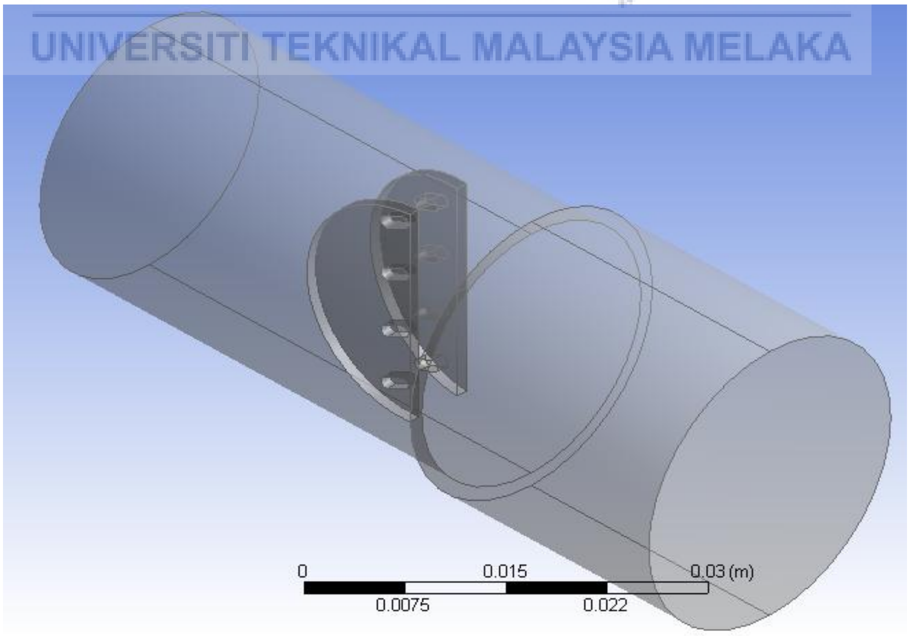


Figure 3.6 Location of VGs in mechanical heart valve

3.2.3 Geomagic Design X

After finished drawing the mechanical heart valve, this software will be used to assemble the mechanical heart valve and the aorta. This process started by importing the files which is saved in '.igs' format. Then, the transform body feature is used in model section to assemble the mechanical heart valve with the aorta. Figure 3.7 shows the assembled mechanical heart valve with the aorta.

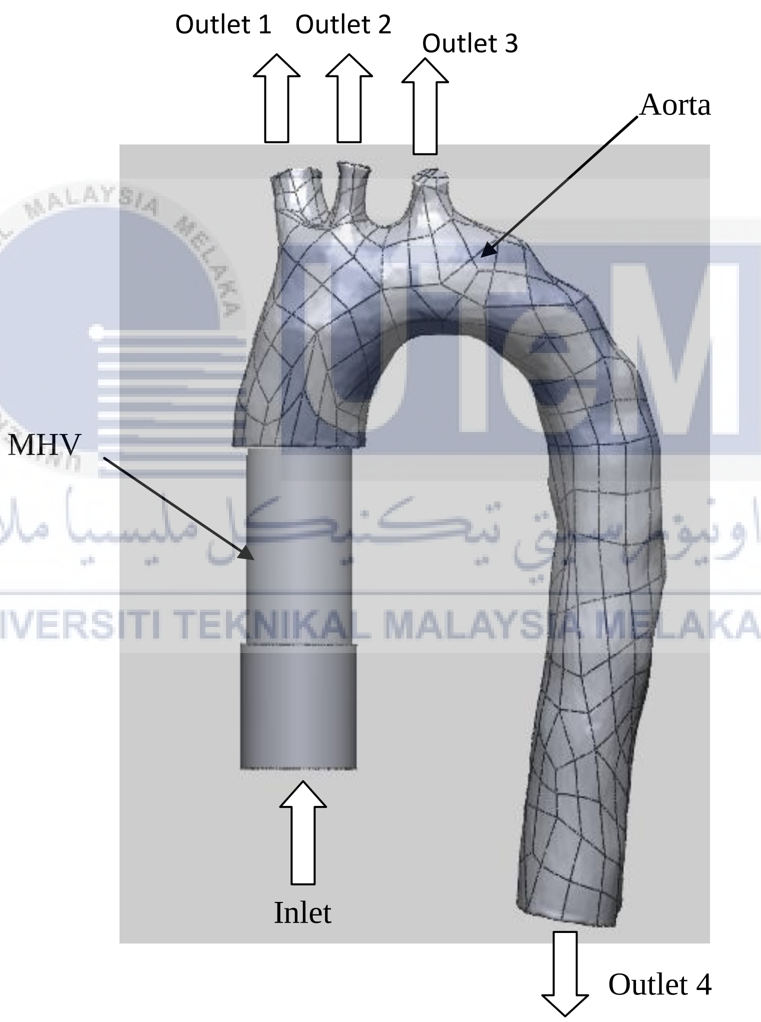


Figure 3.7 Assembled mechanical heart valve

3.2.4 ANSYS

The final software is ANSYS where it will be used as final method of this study to determine the final result of the study. It involves the simulation of Computational Fluid Dynamics (CFD) models of blood flow in vivo at the aortic valve with vortex generator.

3.3 CFD Simulation Process (MHV without Aorta)

This section will illustrate the CFD simulation processes for mechanical heart valve started with pre-processing and solver execution. Meanwhile, post-processing will be discussed in chapter 4.

3.3.1 Pre-Processing

This process consists of geometry modelling and mesh generation. Geometry modelling is drawn in SOLIDWORKS software and imported to design modeller in ANSYS Workbench. The details of the geometry are shown in Table 3 followed by the 3D CAD drawing in Figure 3.4.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Grid Generating

The next step was to produce mesh generation of the model. Figure 3.8 shows the generated meshing of mechanical heart valve with the meshing details in Figure 3.9. The geometry is meshed by a polyhedral mesh grid as it is the simplest method.

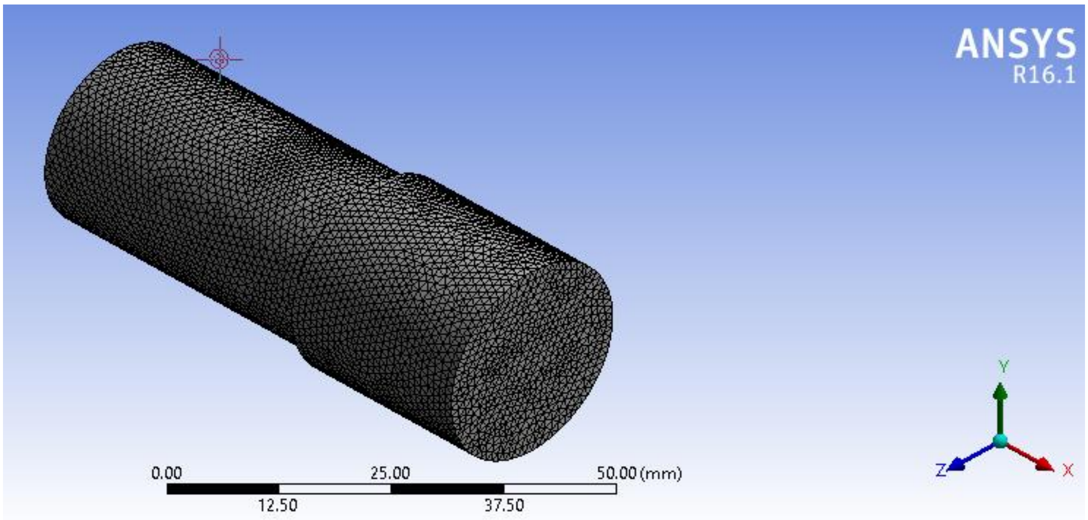


Figure 3.8 Polyhedral meshing grid of mechanical heart valve

Statistics	
Nodes	53614
Elements	284537
Mesh Metric	Skewness
Min	8.6469e-007
Max	0.83364
Average	0.22761
Standard Deviation	0.12017
Mesh Metric	Orthogonal Quality
Min	0.26339
Max	0.99693
Average	0.85952
Standard Deviation	8.3521e-002
Mesh Metric	Aspect Ratio
Min	1.158
Max	9.4429
Average	1.8454
Standard Deviation	0.46093

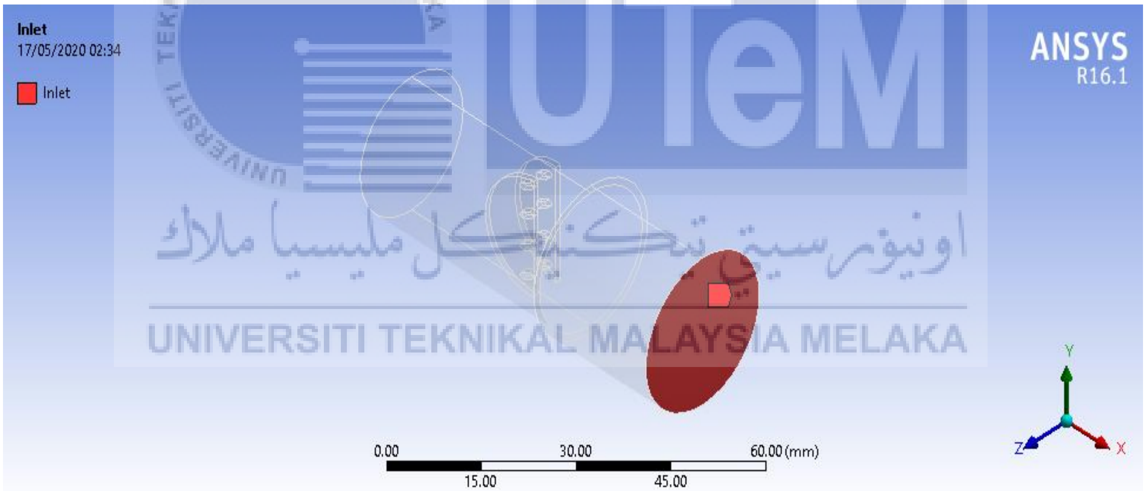
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 3.9 Details of generated mesh

Based on the mesh statistics, the number of nodes is 53614 and the number of elements is 284537. For the mesh metric details, the average value of skewness, orthogonal quality and aspect ratio are 0.22761, 0.85952 and 1.8454 respectively. The value of skewness is considered excellent as it lies between the ranges of 0-0.25, while the orthogonal quality is considered very good as it lies between the good range standard. Meanwhile, the aspect ratio is acceptable as the value is near to 1, where it indicates the quality of element shape.

Named Selection

After meshing process, named selections are created for inlet, outlet, leaflet 1 and leaflet 2 of the geometry to send to the solver as shown in Figure 3.10, 3.11, 3.12 and 3.13.



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 3.10 Named selection for inlet

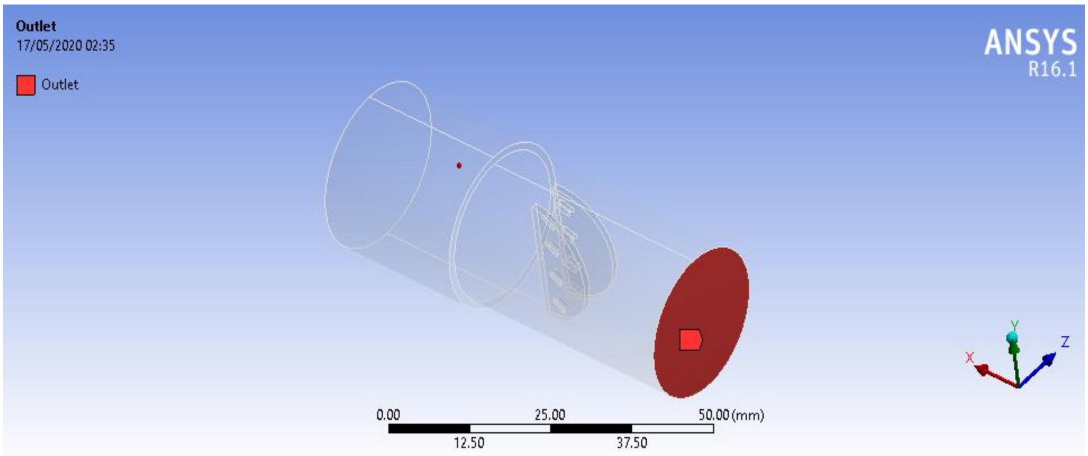


Figure 3.11 Named selection for outlet

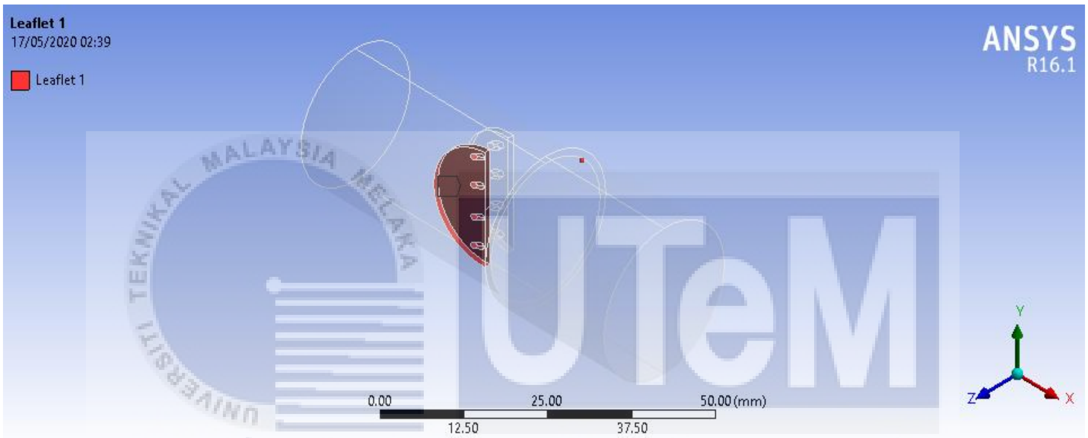


Figure 3.12 Named selection for leaflet 1

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

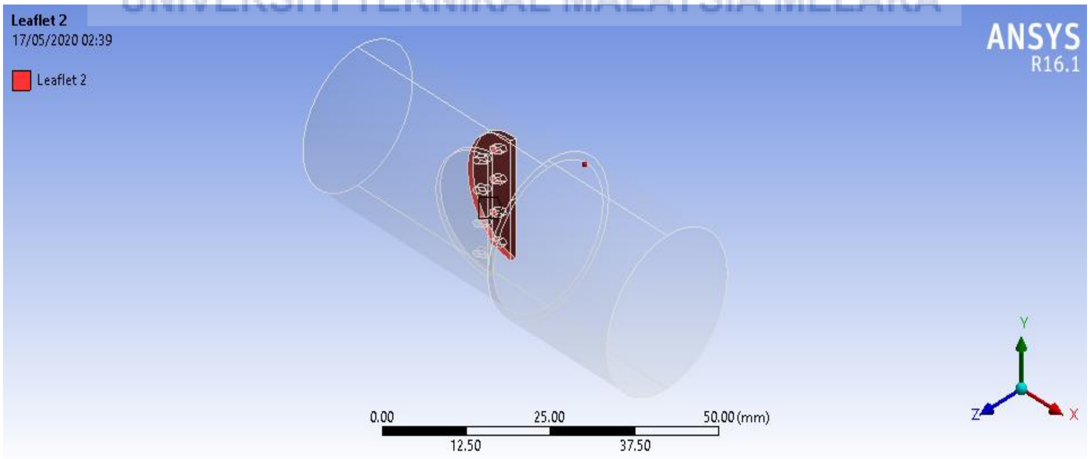


Figure 3.13 Named selection for leaflet 2

3.3.2 Solver Execution

In this section, there are two parts which are numerical model set up and solution compute and monitor. The first part consists of four processes which are defining type of solver, defining physical model, setting material properties and defining boundary and initial conditions. The solver chosen in this study is Pressure-Based type. In the solution setup, the geometry was solved for Navier-Stokes equation by using realizable k-epsilon model with a standard wall functions.

Next, material properties of the mechanical heart valve are determined as fluid which uses blood properties, while the material properties of leaflets are determined as solid which uses pyrolytic carbon properties. Then, the blood properties need to be set up as illustrated such in Table 1, whereas the pyrolytic carbon needs to be set up with density 2200 kg/m^3. Next, boundary conditions are defined based on the zone type shown in Table 4. The velocity of 0.9 m/s is set as the initial boundary condition at the inlet of mechanical heart valve which is referred to Hatoum (2018).

Table 4 Zone type of boundary conditions

Boundary conditions	Zone type
Inlet	Velocity-inlet
Interior-MHV	Interior
Leaflet 1	Wall
Leaflet 2	Wall
Outlet	Pressure outlet
Wall-MHV	Wall

The second part of solver execution is solution compute and monitor. A SIMPLE pressure-velocity coupling scheme was used with the Green-Gauss Cell Based gradient.

The solution is initialized by using hybrid initialization method where it is environment programmed. Then, the number of iteration was set to 500.

3.4 CFD Simulation Process (MHV With Aorta)

This section will illustrate the CFD simulation processes for mechanical heart valve with aorta where it started with pre-processing and solver execution. Meanwhile, post-processing will be discussed in chapter 4.

3.4.1 Pre-Processing

This part will show the mesh generation of the mechanical heart valve with the aorta. It starts with the grid generating and continues with creating named selection to determine boundary conditions.

Grid Generating

The process started with mesh generation of the model as shown in Figure 3.14. The aorta is meshed by using path independent method with tetrahedrons mesh grid while the mechanical heart valve is meshed by using MultiZone method with hexa mesh grid. The detail of generated mesh is shown in Figure 3.15.

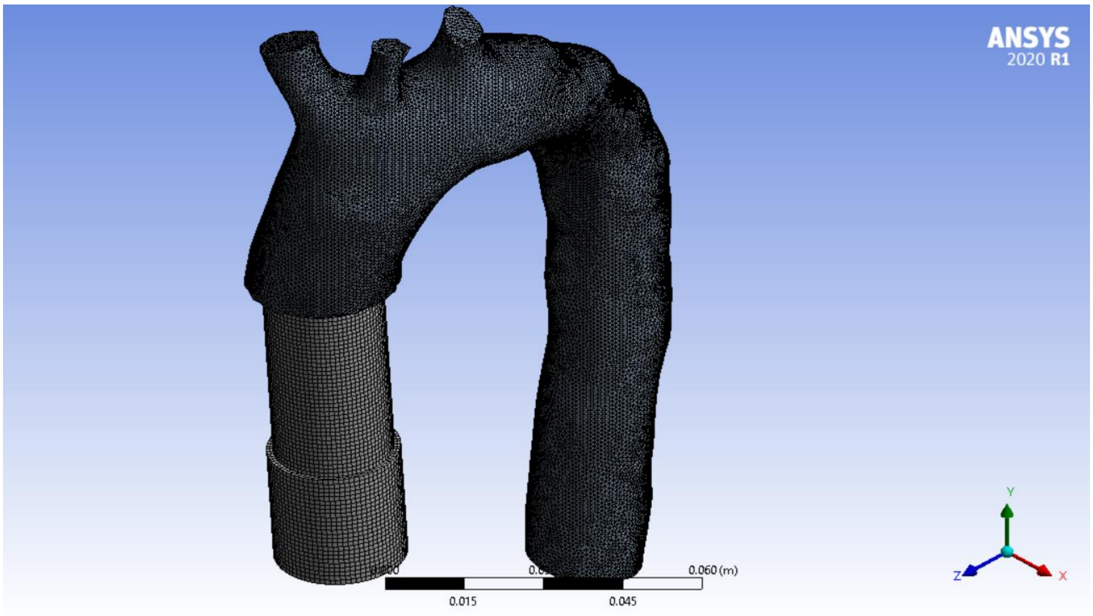


Figure 3.14 Generated meshing of mechanical heart valve with aorta

Statistics	
Nodes	171552
Elements	912484
Mesh Metric	Skewness
Min	2.4208e-005
Max	0.91384
Average	0.23427
Standard Deviation	0.12446
Mesh Metric	Orthogonal Quality
Min	8.6155e-002
Max	0.99538
Average	0.76376
Standard Deviation	0.12294
Mesh Metric	Aspect Ratio
Min	1.1595
Max	16.986
Average	1.8615
Standard Deviation	0.47122

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 3.15 Details of generated mesh

Based on the mesh details, the number of nodes is 171552 and the number of elements created is 912482. The mesh metric shows the average value of skewness, orthogonal quality and aspect ratio are 0.23427, 0.76376 and 1.8615 respectively. The value of skewness is considered excellent where it lies between the ranges of 0-0.25, whereas the orthogonal quality is considered very good as it lies between the good range standard. Meanwhile, the aspect ratio is considered acceptable.

Named Selection

Next, named selections are created for inlet, outlet 1, outlet 2, outlet 3, outlet 4, leaflet 1, and leaflet 2. The named selections are created as shown in Figure 3.16, 3.17, 3.18, 3.19, 3.20, 3.21 and 3.22.

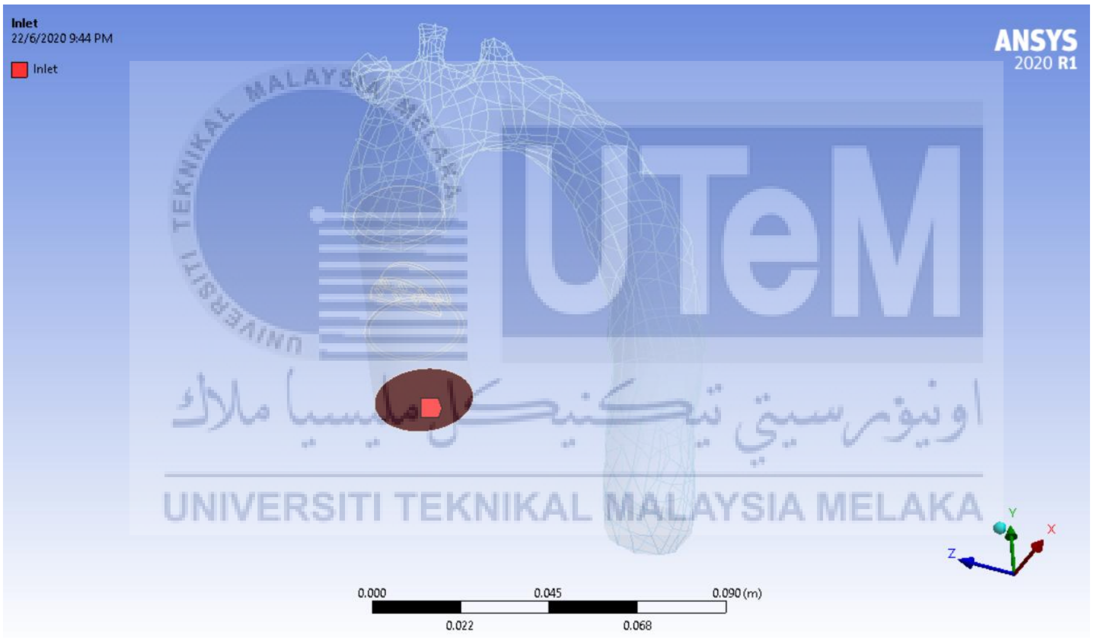


Figure 3.16 Named selection for inlet

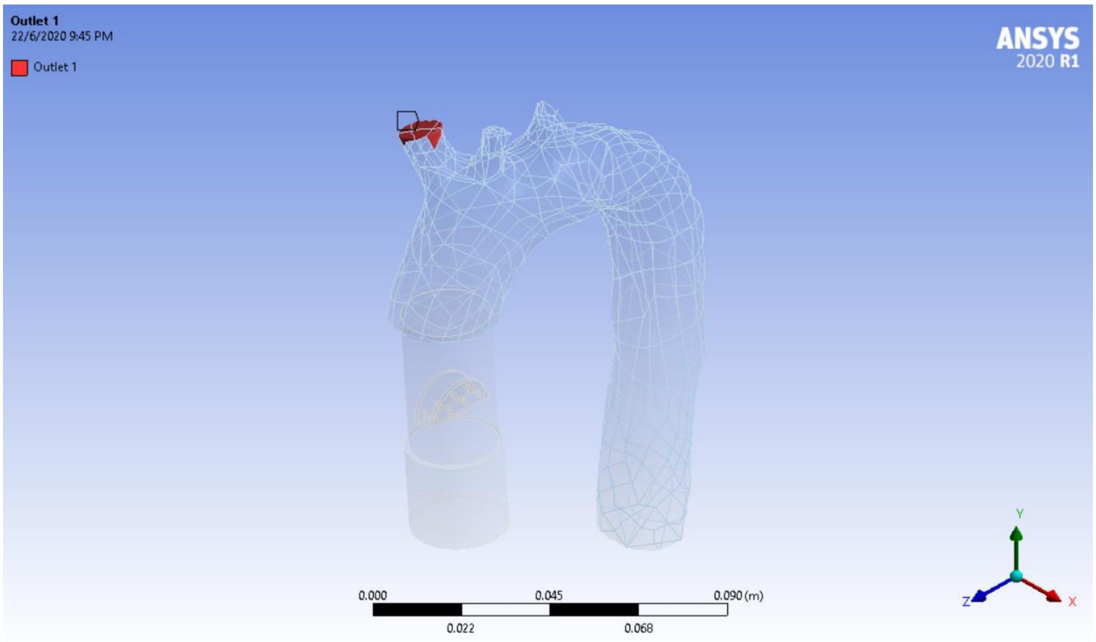


Figure 3.17 Named selection for outlet 1

Figure 3.18 Named selection for outlet 2

UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

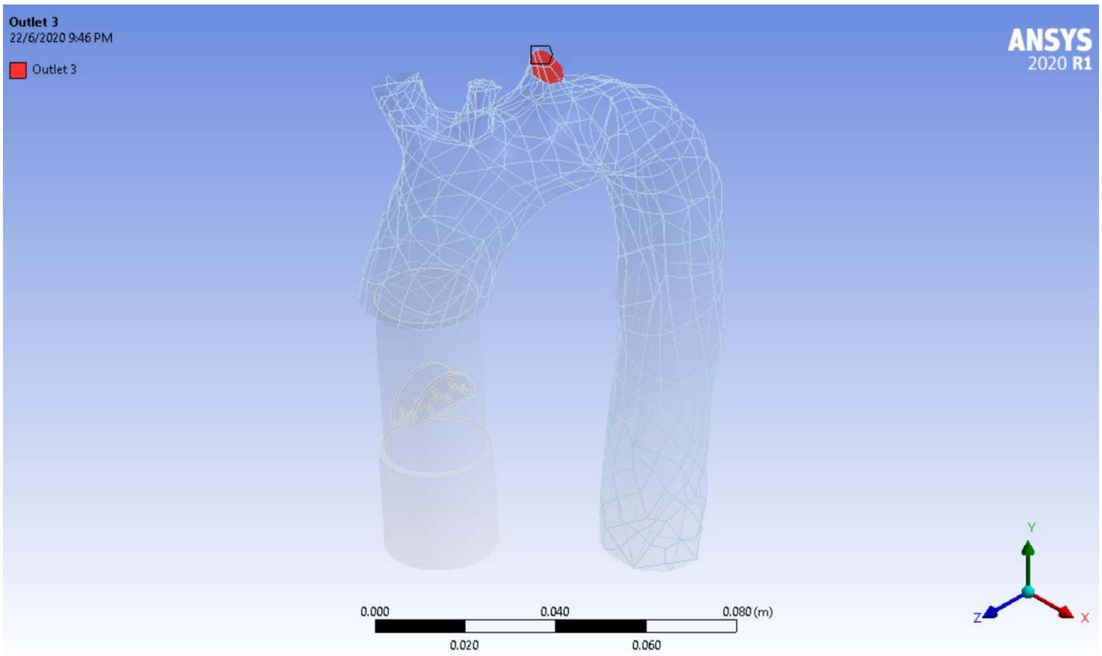


Figure 3.19 Named selection for outlet 3

Figure 3.20 Named selection for outlet 4

UTeM
اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

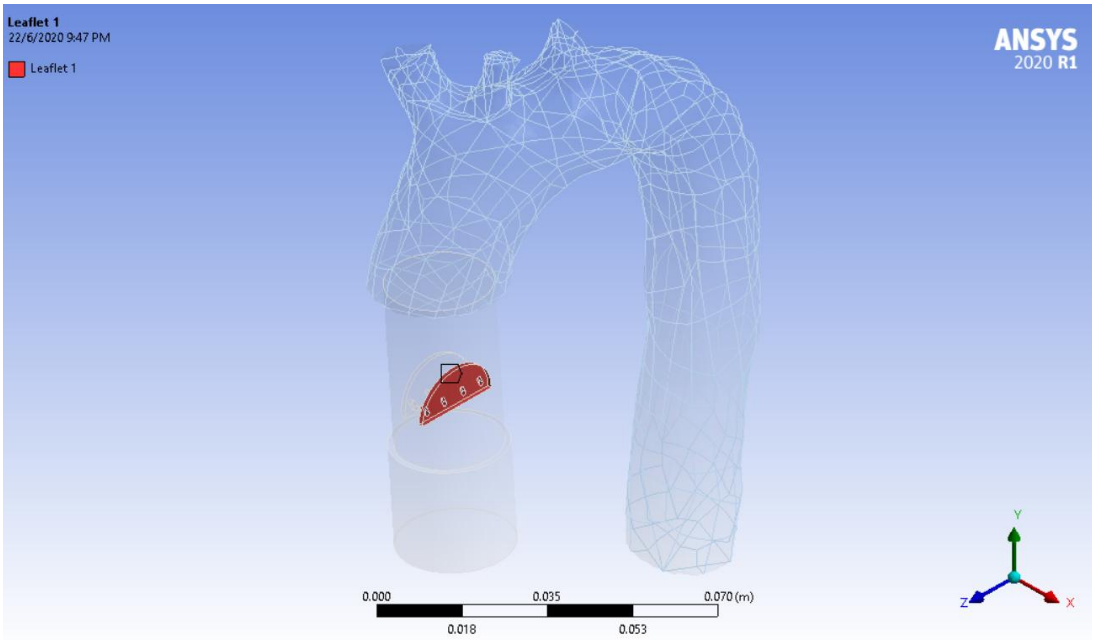


Figure 3.21 Named selection for leaflet 1

اونيۏرسيتي تيکنيکل مليسيا ملاک
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

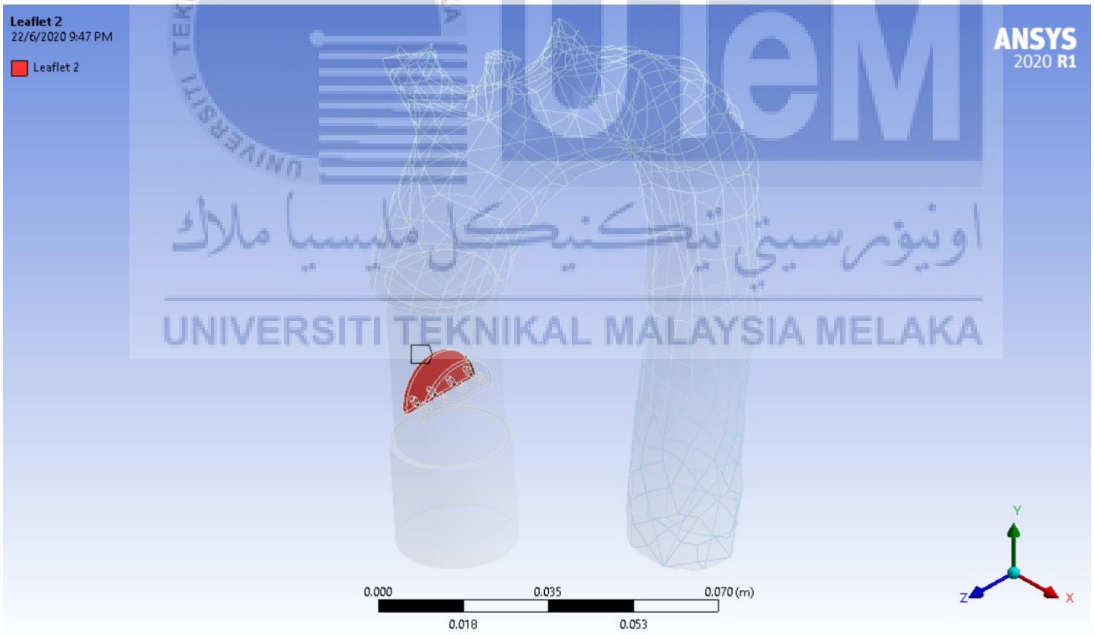


Figure 3.22 Named selection for leaflet 2

3.4.2 Solver Execution

In this section, the details of solver execution will be discussed. The solver chosen in the setup is Pressure-Based type. In solution setup, this geometry was solved for Navier-Stokes equation by using realizable k-epsilon model with a standard wall functions.

Then, the material properties of the mechanical heart valve are determined as fluid by using blood properties as shown in Table 1, while the pyrolytic carbon is set up with density 2200 kg/m^3. The boundary conditions are defined based on the zone type as shown in Table 5. The velocity was set same as previous set up of mechanical heart valve without the aorta.

Next, in solution methods, a SIMPLE pressure-velocity coupling scheme was used with the Green-Gauss Node Based gradient and initialized by using the hybrid initialization method. The number of iteration was set to 7000.

Table 5 Zone type of boundary conditions

Boundary conditions	**Zone type**
Inlet	Velocity-inlet
Contact_region-src	Interface
Contact_region-trg	Interface
Interior-aorta	Interior
Interior-MHV	Interior
Outlet 1	Pressure-outlet
Outlet 2	Pressure-outlet
Outlet 3	Pressure-outlet
Outlet 4	Pressure-outlet
Leaflet 1	Wall
Leaflet 2	Wall
Wall-aorta	Wall
Wall-MHV	Wall

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

3.5 Geometry of Vortex Generator

The vortex generator was designed in co-rotating VG where the design was improvised from Hatoum (2018). Co-rotating VG design is chosen because the results shown in the study is greater than other shape of vortex generator. The edge of the vortex generator was drawn in blunt shape as sharp edge can lead to increase in blood clot. Therefore, a new design of vortex generator is produced. The designed vortex generator on both of the leaflet can be seen in Figure 3.5. The direction of the blood flow is shown in Figure 3.23.

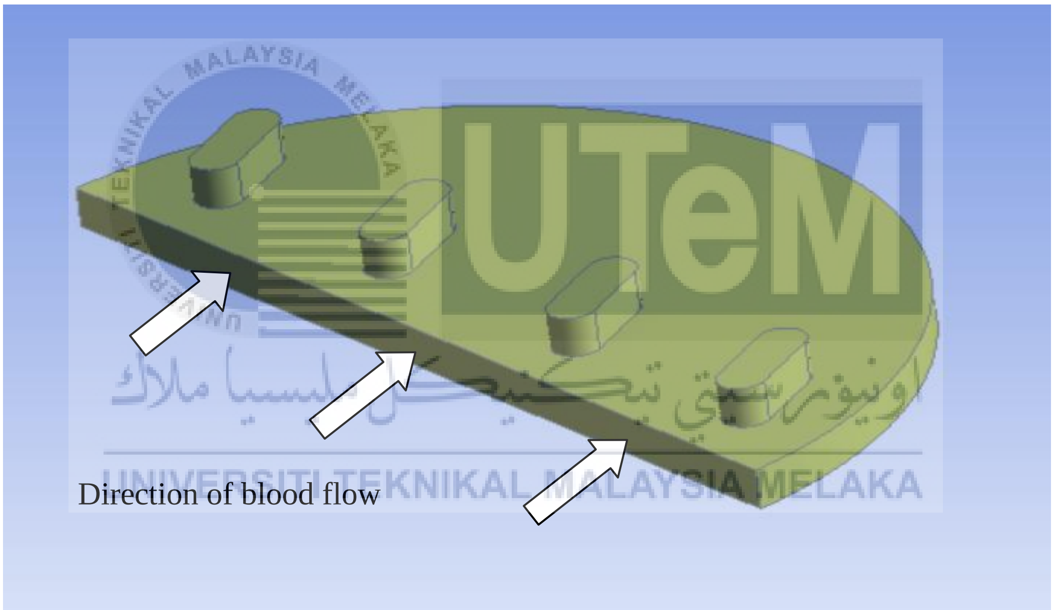


Figure 3.23 Direction of blood flow through the leaflet

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Results and Discussion of Mechanical Heart Valve without Aorta

This section will be discussed about the results and discussion on mechanical heart valve with vortex generator without aorta. It starts with the grid independency test, and then continues with the simulation results and finally the comparison of mechanical heart valve between previous study and present study.

4.1.1 Grid Independency Test

After meshing process, grid independency test is needed to be done in order to get a better result of the mass flow rate at the outlet of mechanical heart valve. This test was done to check whether the outcomes rely upon the grid or not. In order to get the accepted level of tolerance, the mesh needs to be varied in relevance of coarse, medium and fine by using polyhedral meshes. This mesh test was executed in steady-state condition with the comparison of the mass flow rate as the references between the three meshes generated. When it comes to the point where the mesh does not affect the results, then this mesh can be selected to find the output solution. After this test is done, the simulation will be proceeded. The results of mass flow rates for three different elements are recorded in Table 6. Based on Figure 4.1, it shows that the mass flow rate of the three generated meshes is becoming constant after 50k iterations.

Table 6 Grid Independency Test for mechanical heart valve

Type of mesh	**Number of element**	**Mass flow rate (kg/s)**
Coarse	80k	0.48281491
Medium	100k	0.48281622
Fine	200k	0.48281819

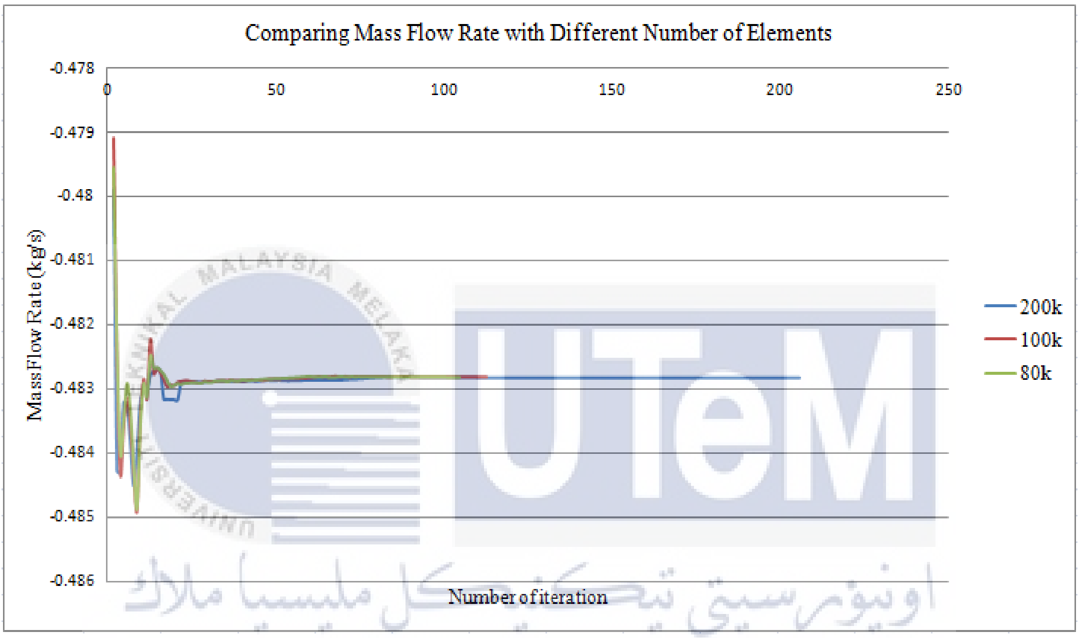


Figure 4.1 Grid Independency Test for mechanical heart valve without aorta

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

4.1.2 Simulation Results

This part will illustrate the simulation results of the mechanical heart valve. Figure 4.2 shows the convergence results of the mechanical heart valve with iterations that were set to 500 iterations and the convergence was achieved at 206 iterations. Next, Figure 4.3 illustrates the velocity contour at the centre plane of the MHV. The contour indicates the magnitude of the velocity with the colour bands that illustrates the different in velocity magnitude of the blood flow in the mechanical heart valve. From the contour, the highest velocity magnitude can be seen occurred after blood pass through the leaflet (peripheral jet). Full view of velocity streamline can be seen in Figure 4.4 and Figure 4.5 below shows the 3D velocity streamline and velocity vector of mechanical heart valve.

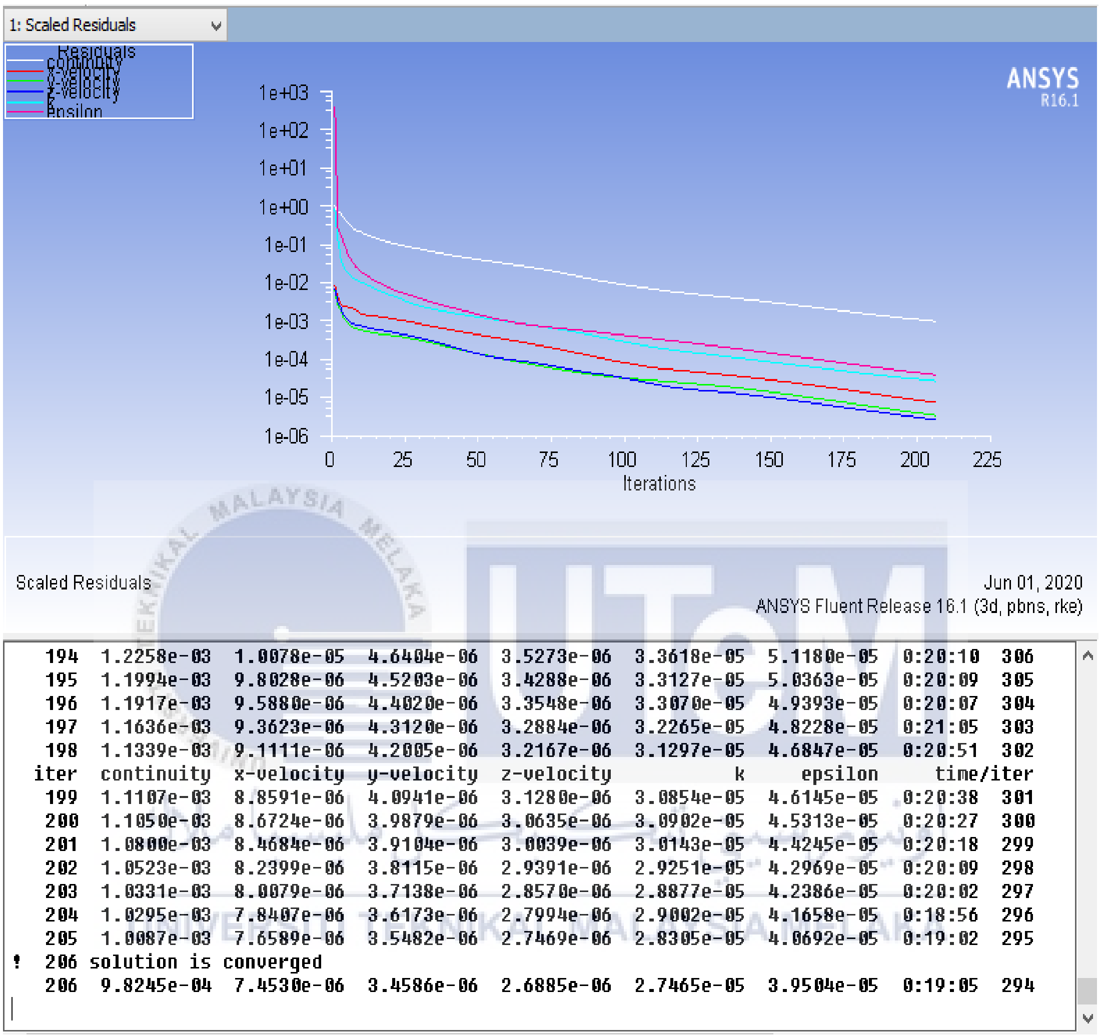


Figure 4.2 Convergence result of mechanical heart valve

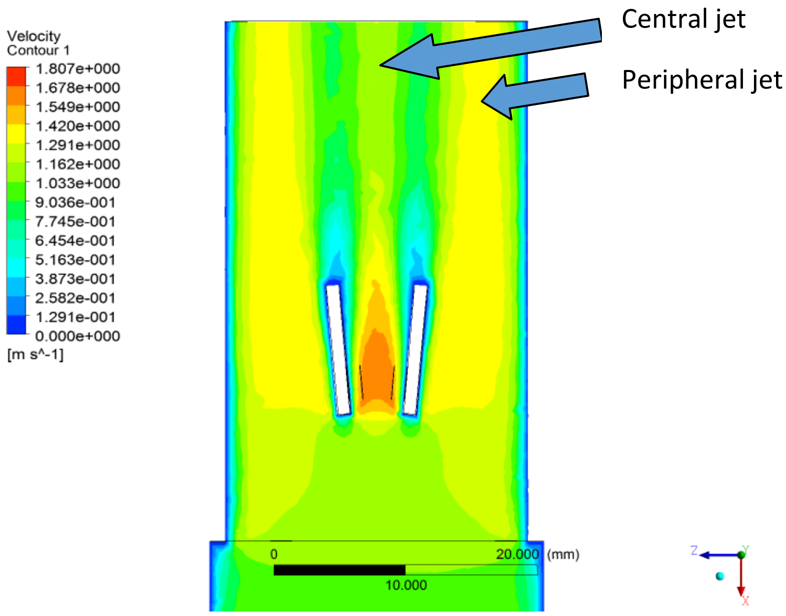


Figure 4.3 Velocity contour at the centre plane of the MHV

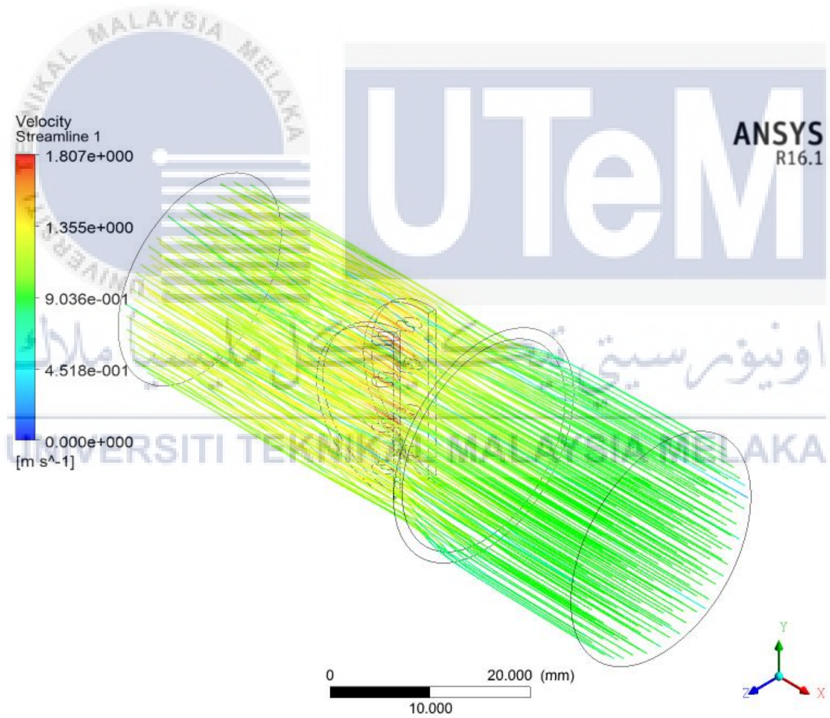


Figure 4.4 3D velocity streamline of the MHV

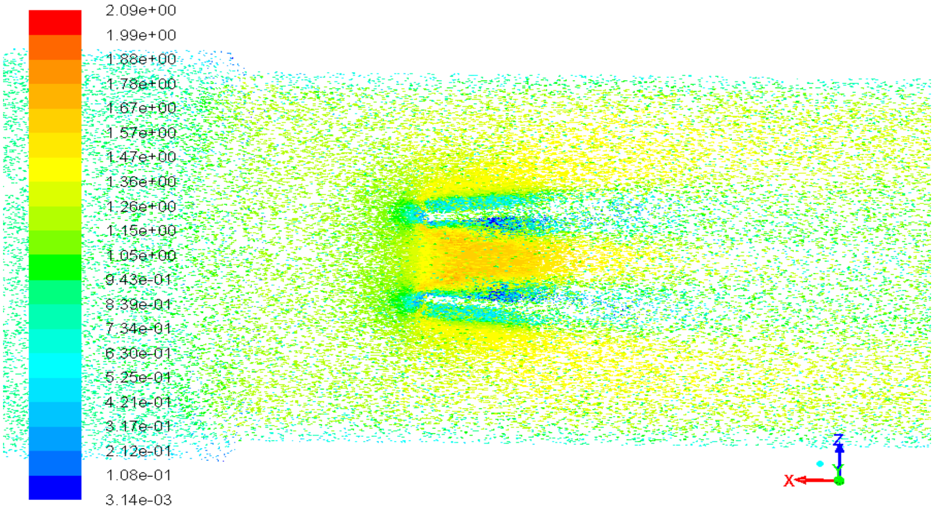


Figure 4.5 Velocity vector of the MHV

4.1.3 Comparison of Flow Characteristics with Previous Study

In order to ensure the results were valid, the present results were compared with the previous journal results during peak systole. The objective of the study is to reduce the blood clot aggregation at the leaflet by using the improved design of VGs. Therefore, the characteristics of the flow that will be compared are velocity, pressure drop and wall shear stress by following the boundary conditions provided from previous study which is Hatoum (2018).

Table 7 summarizes the comparison of hemodynamic parameter of Co-rotating VGs heart valve of the improved design of VGs and the previous study. Based on the results, it shows that the Co-rotating VGs of present studies yields the pressure drop with 3.64 mmHg which is lower than the previous study results. This is due to the slow flow separation that occurred when adding the vortex generator at the leaflet of the mechanical heart valve. Therefore, the streamwise of the vortices does not deteriorate directly after passing through the leaflet during peak systole. From previous studies, it stated that lower pressure drop helps in reducing the blood clot aggregation at the vicinity of the heart valve (Hatoum, 2018).

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Table 7 Comparison of pressure drop with previous study

	Hatoum (2018)	Present study
Pressure drop (mmHg)	10.45 ± 0.94	3.64

In term of flow velocity, the results were only observed during the peak systole. Figure 4.6 shows the velocity profile of the blood flow versus Z direction at X = 20 mm. It can be seen that the highest velocity at the peripheral jet is approximately 1.35 m/s, while the velocity at the central jet is approximately 1.16 m/s. Based on Zakaria (2017), the sharp geometry is to be said can lead to the forming of thrombosis at the vicinity of the leaflet where this problem needs to be solved. Therefore, a new design of VGs was drawn in order to solve the problem. The velocity of the blood flow based on Hatoum (2018) at X = 0 mm is 1.21 m/s approximately. Meanwhile, the velocity based on present study at X = 0 mm is recorded at average velocity 0.80 m/s.

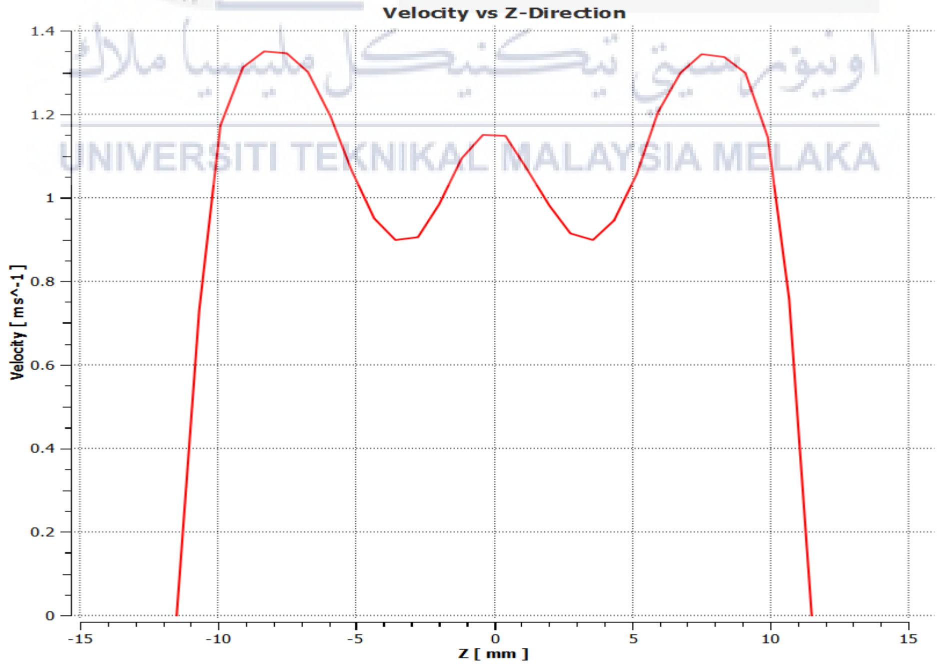


Figure 4.6 Graph of Velocity vs. Z-Direction at X = 20 mm

At X = 20 mm, the velocity is recorded at average velocity 1.029 m/s in present study compared to previous study which is 1.17 ± 0.05 m/s.

Based on previous researches, higher velocity occurs when the VGs design was in sharp edges shape and this can lead to formation of thrombosis that leads to blood clot. One of the ways to solve this problem is to redesign the VGs with blunt edges shape. After attached with the new VGs design, the flow velocity is reduced. The result shows the reduction in velocity in both distance X = 0 mm and X = 20 mm by 0.41 m/s and 0.141 m/s respectively. This shows that the blunt VGs design does affected the reduction in velocity of the blood flow in the mechanical heart valve. The improved design of VGs has lead to slower separation flow of the blood where it reduces the unsteadiness of free shear at the shear layers.

Figure 4.7 illustrates the wall shear stress contour of the mechanical heart valve. Based on Zhou et al. (2016), the accumulation of blood platelets can occur due to high wall shear stress, where this problem can put the patient's life in danger as this kind of stress enhance the formation of blood clot. Based on the wall shear stress contour, the maximum wall shear stress is detected 37.12 Pa at beginning of the leaflet area.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

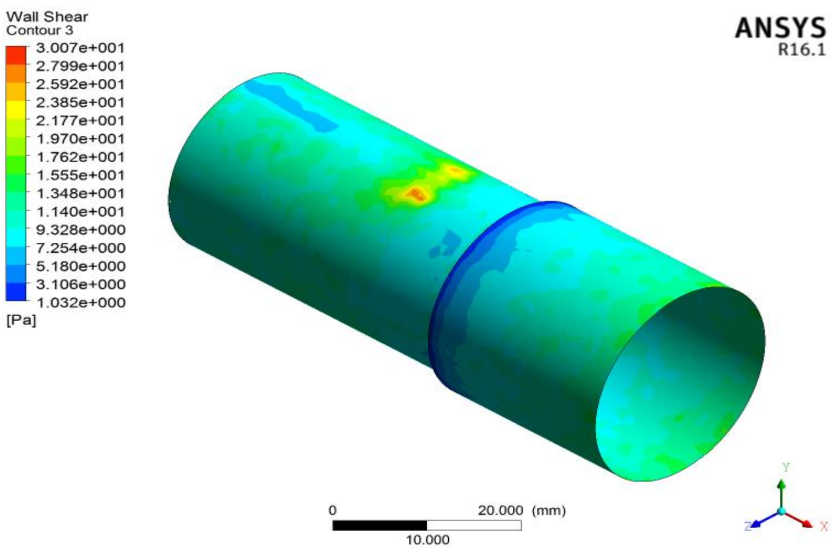


Figure 4.7 Wall shear stress of mechanical heart valve

This phenomenon can induce the formation of thrombosis at the area. However, in terms of average wall shear stress, the average WSS from previous study is higher than present study where the result is computed in Table 8. From Table 8, it shows that the overall wall shear stress of present study is 10.24 Pa which is lower than previous study. This occur when the blunt shape edges of the vortex generator is attached at the leaflet of mechanical heart valve as the blunt edges of VGs does not damage the blood platelet compared to the sharp edges. Sharp edges can cause the blood platelet to damage where it will create a stagnation and recirculation region at the vicinity of the leaflets, and create a backflow of the blood flow (Zakaria et al., 2017).

Table 8 Comparison of average wall shear stress with previous study

	Hatoum (2018)	Present study
Wall shear stress (Pa)	12.95 ± 0.32	10.24

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

4.2 Results and Discussion of Mechanical Heart Valve with Aorta

This section will be discussed on the results and discussion of mechanical heart valve with vortex generator with aorta. The sequences are as same as section 4.1 where it starts with the grid independency test, and then continues with the simulation results and finally the discussion on the simulation results.

4.2.1 Grid Independency Test

The independency test for the mechanical heart valve with the aorta is varied with three different types of mesh which are fine, medium and coarse. After carrying out grid test for the three mesh settings, there is little to no discrepancy between the flow rates for different meshing grids. The number of element for fine mesh is the highest where the grid size of the mesh is much smaller compared to other two types of meshes. The results should be more accurate due to finer mesh. Therefore, grid size of fine mesh is taken due to high accuracy. The results are shown in Table 9 where it shows the mass flow rate of the three types of mesh with the number of elements. Based on Figure 4.8, the mass flow rate started to become constant after 200k iterations.

Table 9 Grid Independency Test for mechanical heart valve with aorta

Type of mesh	Number of element	Mass flow rate (kg/s)
Coarse	400k	0.4829023
Medium	800k	0.4829011
Fine	900k	0.4829426

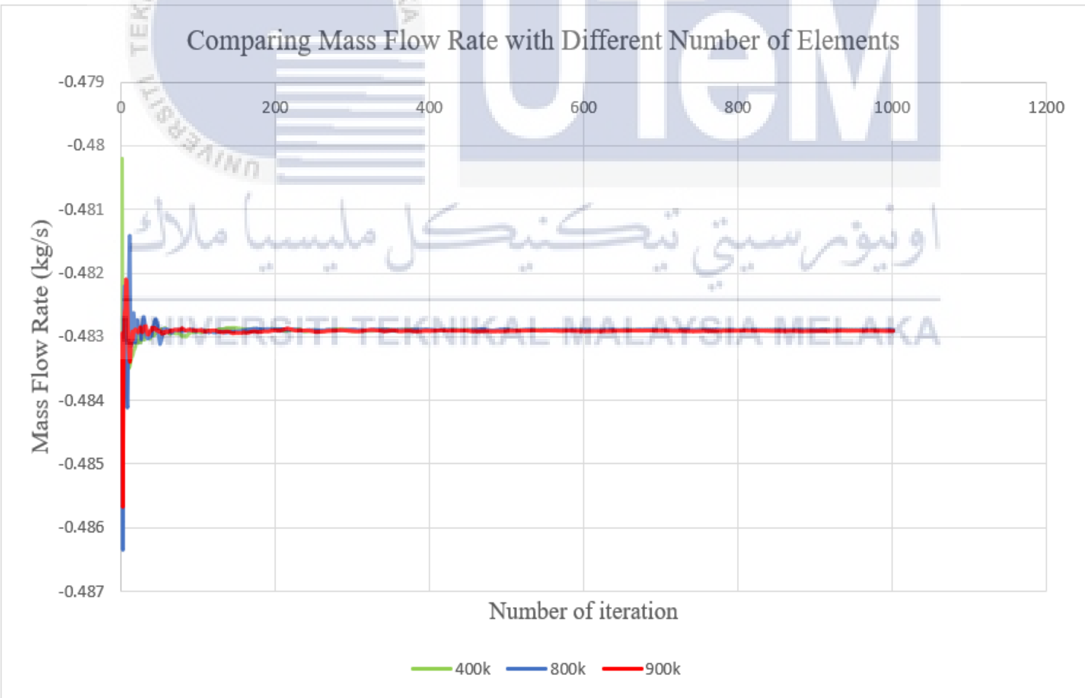
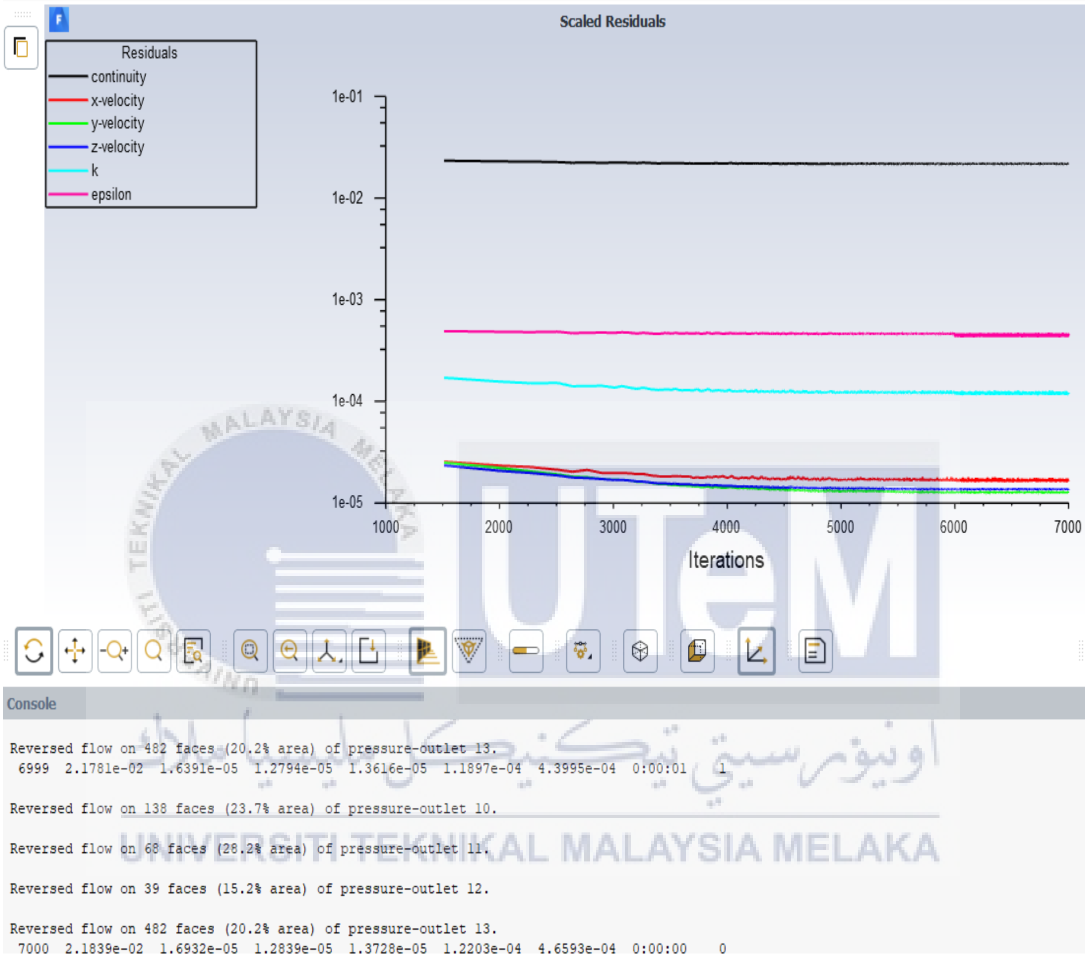


Figure 4.8 Grid independency test with aorta

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

4.2.2 Simulation Results

This section will discuss on the simulation results of mechanical heart valve with aorta. The results achieved the convergence at iteration 7000 as it converges at continuity of 2.1839e-02 where the graph in Figure 4.9 shows the constant value for the residuals.



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Figure 4.9 Convergence result of mechanical heart valve with aorta

Figure 4.10 and 4.11 shows the velocity contour and velocity vector of the mechanical heart valve at the centre plane of MHV respectively. Based on the contour, the highest velocity magnitude can be seen at the peripheral jet where it occurs after the blood passes through leaflet 1 (right leaflet). This shows there is abnormal flow occurs as the blood passes through the mechanical heart valve. Next, the velocity streamline of the mechanical heart valve with aorta is shown in Figure 4.12. Based on the velocity streamlines, the flow of the blood in the aorta can be classified as unstable aorta as there is small recirculation occurred right after the blood passes through the mechanical heart valve. This recirculation such as the backflow of the blood can occur (Zakaria et al., 2017). Referred to the velocity streamlines, velocity magnitude can be seen high at one of the aortic arch branches which are outlet 1 of the aorta.

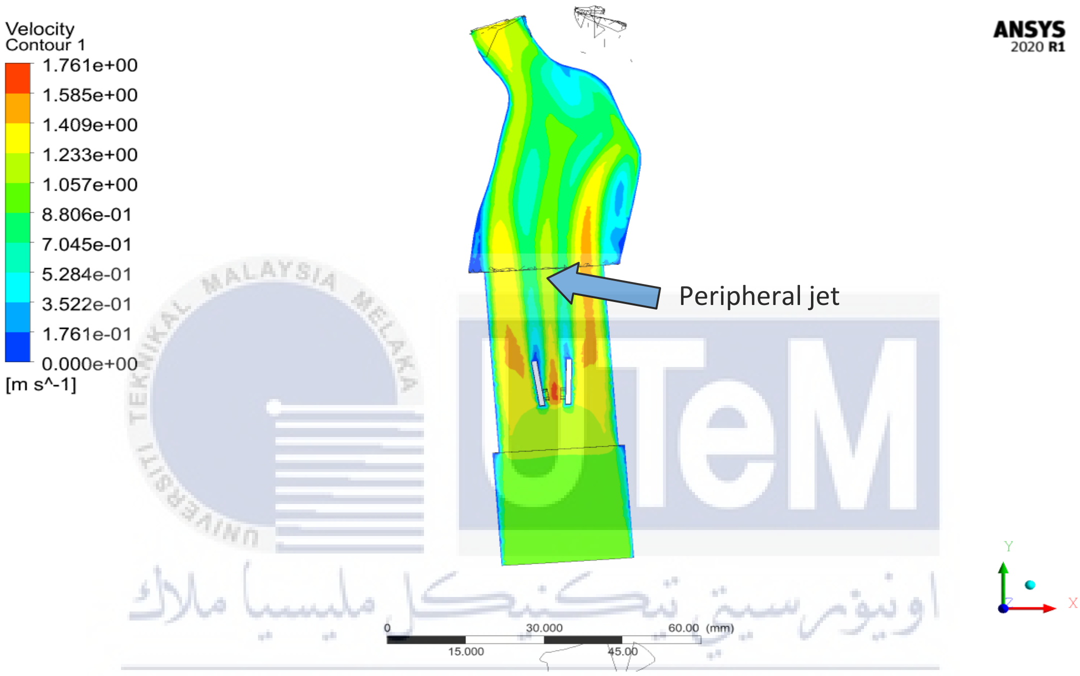


Figure 4.10 Velocity contour of mechanical heart valve attached with the aorta

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

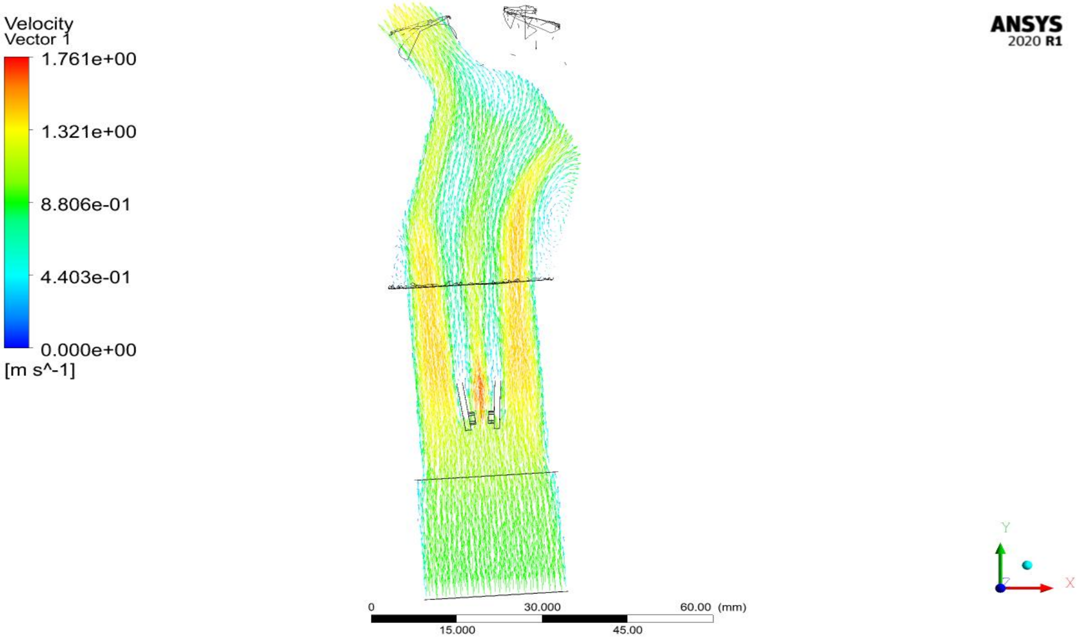


Figure 4.11 Velocity vector of mechanical heart valve attached with the aorta

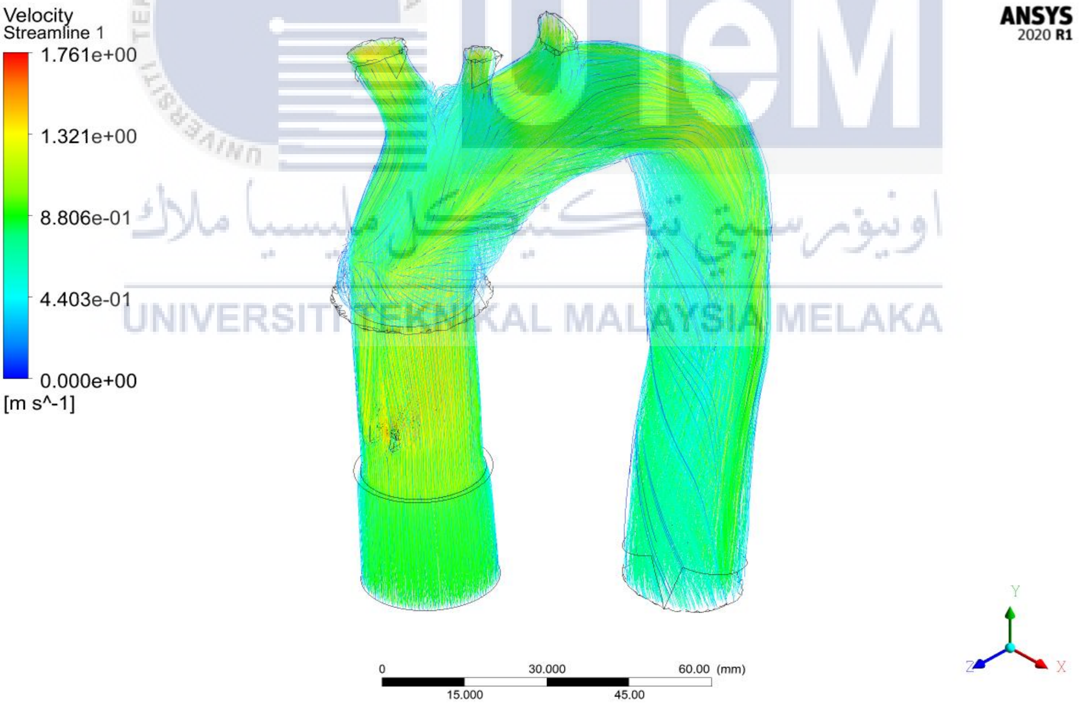


Figure 4.12 3D velocity streamlines of the mechanical heart valve with the aorta

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

The wall pressure distribution of the mechanical heart valve with the aorta is shown in Figure 4.13. This pressure distribution shows the maximum pressure of the MHV with aorta is 1031.882 Pa where the highest pressure occurred at the MHV before the leaflets.

Then, the pressure drops after the blood passes through the leaflet attached with the vortex generator. This reveals that the attached vortex generator helps in reducing the wall pressure of the aorta. Figure 4.14 (a) shows the contour of wall shear stress of the aorta with MHV while Figure 4.14 (b) shows the distribution of the wall shear stress at different side of aorta with MHV. Based on the WSS at the aorta, the maximum value is recorded 33.04 Pa where it is lower compared to the maximum WSS at the mechanical heart valve which is 49.36 Pa. The highest WSS can be seen in Figure 4.14 (b) where it shows the WSS is higher at the vicinity of the leaflet before the blood passes through the leaflet. Then, it shows that the WSS drops after it passes through the leaflet attached with vortex generator. The highest WSS that occurred at aorta is at the vicinity of outlet 1 as shown in Figure 4.15. This indicates there is an abnormal flow of the blood occurred which can contribute to the formation of thrombus (Jiang et al., 2018).

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

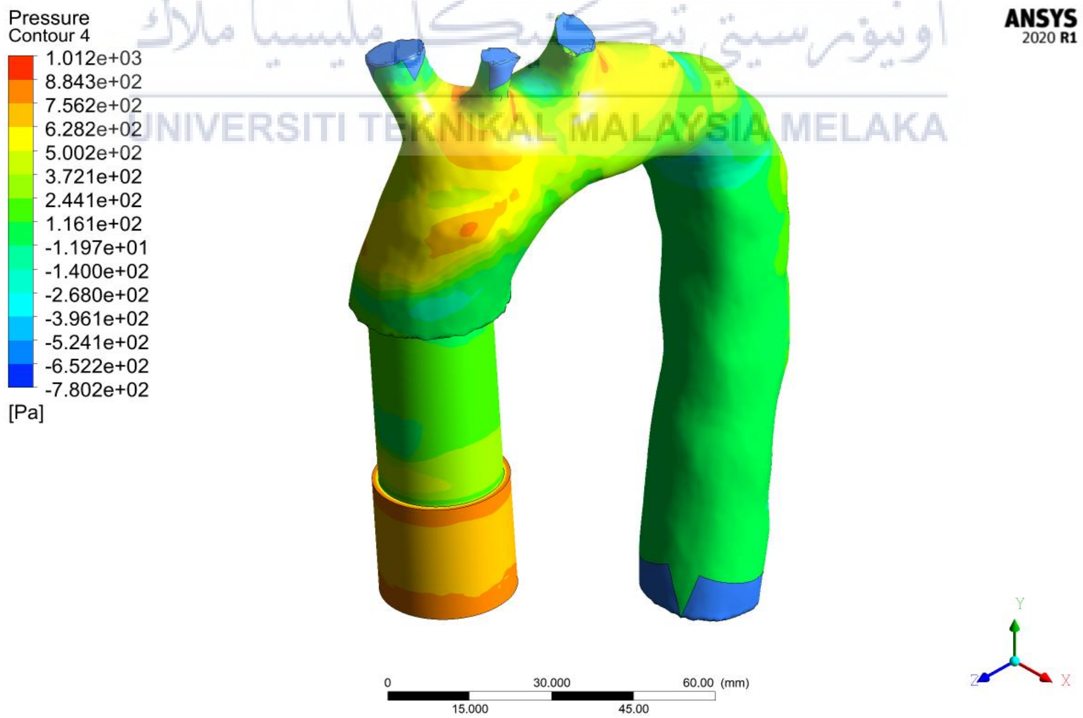
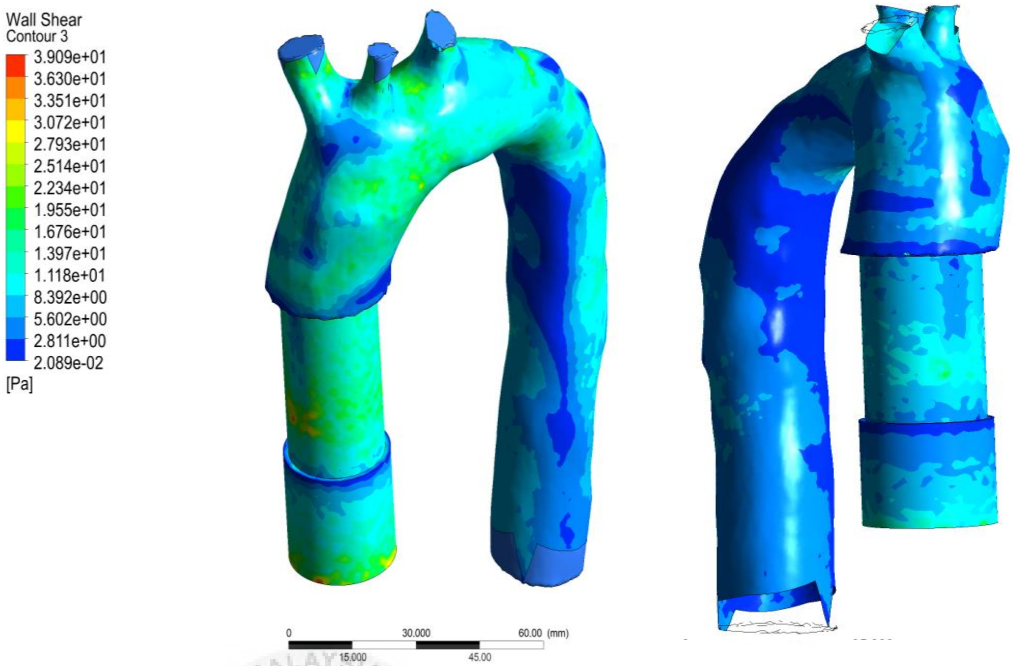


Figure 4.13 Pressure contour



(a) (b)

Figure 4.14 (a) Wall shear stress contour, (b) Wall shear stress contour from the left side

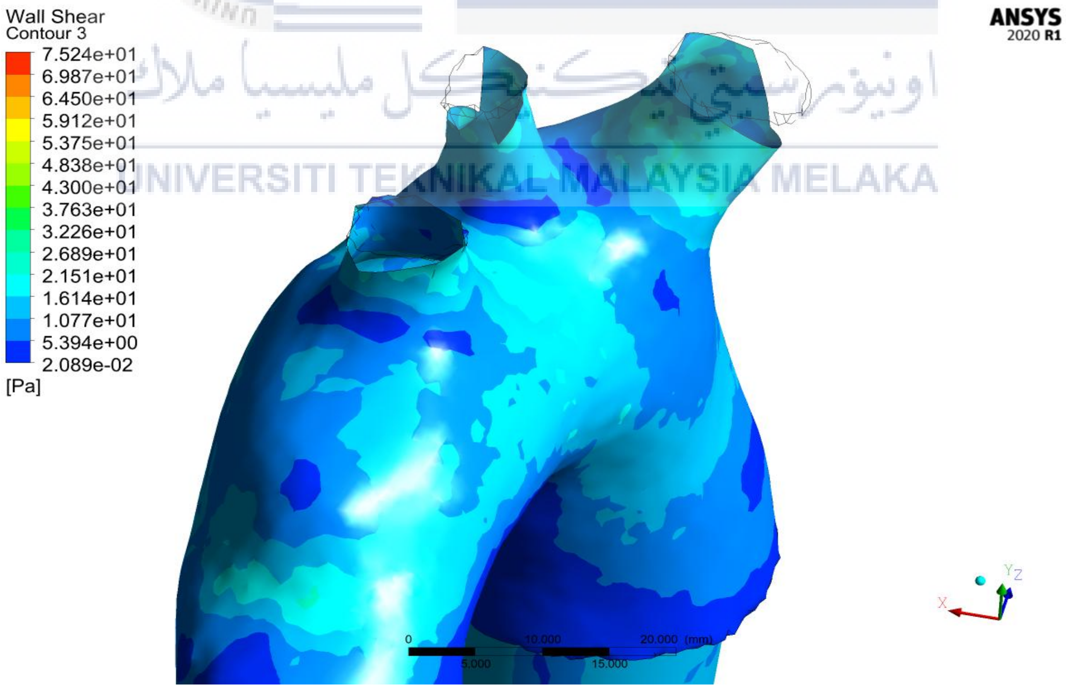


Figure 4.15 Highest WSS at outlet 1

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

4.2.3 Comparison of Flow Characteristics with MHV Results

This section will discuss about the comparison of flow characteristics with present MHV results in terms of velocity, pressure and wall shear stress. The reason to compare with the MHV without attached to aorta result is to determine which results more prone to clotting. The boundary conditions used are based on previous studies which are Hatoum (2018). Table 10 shows the comparison of hemodynamic parameter of mechanical heart valve with and without aorta. The pressure drop is taken before and after the leaflet to determine the reduction of the pressure when MHV is attached with the aorta. Based on Table 10, the differences of the pressure can be seen where the pressure drop of the MHV with aorta is lesser than the MHV without the aorta.

Table 10 Comparison of hemodynamic parameter with and without aorta

	MHV without Aorta	MHV with Aorta
Pressure drop (mmHg)	4.1760	2.3955
Wall shear stress (Pa)	10.24	8.845

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

By reviewing the results, the pressure drop is considered acceptable as it is reduced and still below the pressure drop from previous studies. Slower flow separation was detected occurred when attached with the aorta which contributes in reducing the aggregation of blood clot at the vicinity of the MHV. Meanwhile, in terms of wall shear stress, based on Table 10, the average WSS of the MHV with aorta is lower than MHV without aorta by 1.395 Pa differences. This shows that lower WSS of MHV with aorta is likely to contribute to lower potential of thrombosis formation and therefore leads to lower blood clot accumulation at the vicinity of the MHV.

In term of flow velocity, the results are taken at three different position; before leaflet, after leaflet at Y = 0 mm and after leaflet at Y = 20 mm. This is to compare the velocity results which affected by the presence of vortex generator. The average velocity of the blood flow at Y = 0 is 1.061 m/s which is higher compared to the average velocity of the blood flow without the aorta which is 0.80 m/s. Contra with the velocity of blood flow at Y = 20 mm, where the average velocity is recorded 1.017 m/s which is lower than the velocity of blood flow without aorta by 0.012 m/s difference. This result indicates higher tendency of blood clot aggregation to occur at the end of the leaflet (Y = 0 mm) compared to the MHV without aorta. Figure 4.16 shows the comparison of velocity profile of the blood flow versus Z-direction at Y = 20 mm, with and without aorta.

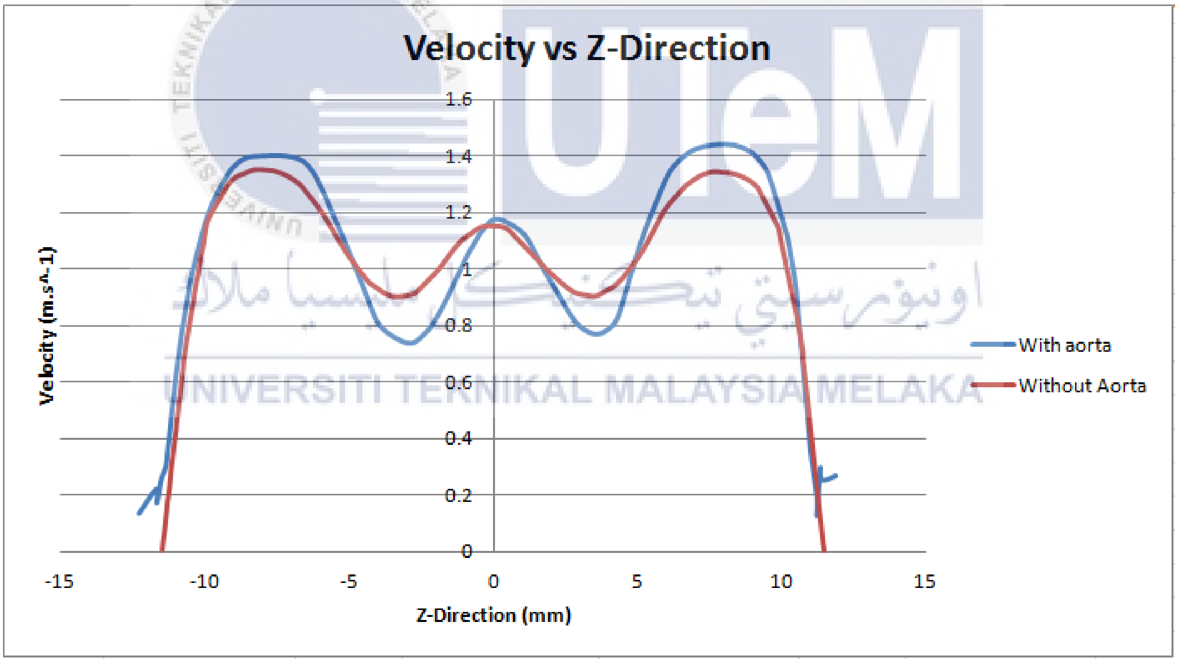


Figure 4.16 Graph of Velocity versus Z-Direction of MHV with and without aorta

The velocity at the left peripheral jet is approximately around 1.4 m/s whereas there is a sudden increase in velocity at the right peripheral jet with velocity of 1.45 m/s approximately. Based on the graph, it shows that the max velocity of blood flow at peripheral jets is higher compared with the MHV without the aorta which is by 0.1 m/s difference. This case may be occurred due to the attachment of the MHV to the aorta. This shows that the vorticity of the shear layer did not disperse directly after passed through the leaflets where this result can reduce the formation of the blood clot at the vicinity of the leaflets. However, to compare with the MHV without the aorta, the results with aorta is more prone to blood clotting. Besides that, the velocity of blood flow at central jet also recorded slightly higher than the results of MHV without aorta with value of approximately 1.19 m/s. Therefore, in term of velocity, the results of MHV with aorta are more prone to blood clotting compared to MHV without aorta.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The CFD models of blood flow in vivo at the aortic valve were developed. A steady state condition is used to simulate the blood flow characteristics during peak systole. An improved geometry of vortex generator was designed with blunt shape edges in order to compare the blood flow of the mechanical heart valve without aorta with the previous experimental studies. Then, the blood flow characteristics; pressure drop, wall shear stress and velocity are recorded and analyzed from the simulation results by attached the MHV with the aorta. Based on the results, it shows that the blunt edges shape of vortex generator contributes in reducing the velocity, pressure drop and wall shear stress. Therefore, this type of vortex generator helps in reducing the aggregation of blood clot at the vicinity of the leaflet.

اونيۈرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Other than that, it is shown that mechanical heart valve without the aorta is less stable compared to mechanical heart valve with the aorta. This is due to higher pressure drop and higher wall shear stress of the model. The high magnitude of these two parameters will lead to the aggregation of blood clot at the vicinity of the MHV. Meanwhile, the average velocity of the blood flow of MHV without aorta (at X = 0) is lower than MHV with aorta (at Y = 0) which indicates low formation of blood clot around the leaflets. Based on the results, it shows that MHV without aorta is more prone to blood clotting as the pressure drop and wall shear stress are higher than MHV with aorta. Therefore, this can be concluded that mechanical heart valve needs to be attached with the aorta for the simulation of the blood flow characteristics as it shows lower potential in formation of blood clotting.

During the process to do this research, there are few recommendations that can be suggested for future improvements and researches. The increase of the number of vortex generator to the leaflet should be done as it helps to reduce the flow separation at the vicinity of the leaflet. This will contribute in reduction of blood clot formation. Therefore, the recommendation is to increase the number of vortex generator attached to the leaflet. Next recommendation is the vortex generator needs to be positioned in closely spaced equally distant as this will help in avoiding the discontinuous of vortices created. This is shown in both velocity contours at the central jet where the vortex generator is attached, and this region has the highest tendency of flow separation to be occurred. Therefore, the recommendation is to position the vortex generator in closely spaced equally distant position and compare with other type of vortex generator position to analyze which is better in reduction of flow separation.

The next recommendation is all the edges of the vortex generator should be in blunt shape which includes every single edge at the vortex generator such as the side edges of the vortex generator that should be fillet. This is to avoid the platelets become damage when it hits the vortex generator which then induced the formation of thrombosis. This case can be seen in Figure 4.6 where the maximum wall shear stress is highest at beginning of the leaflet and it may be due to the sharp side edges of the vortex generator. Therefore, every edges of the vortex generator need to be blunt. The last recommendation will be on the meshing settings and results. In order to get accurate results, it started with the finer mesh in terms of skewness and orthogonal quality where it should be less than 0.25 and more than 0.85 respectively. Therefore, the results will be more accurate.

REFERENCES

Amrane, M., Soulat, G., Carpentier, A., & Jouan, J. (2017). Starr–Edwards aortic valve: 50 years and still going strong: a case report. *European Heart Journal - Case Reports, 1*(2). doi: 10.1093/ehjcr/ytx014

Andersson, B. (2012). *Computational fluid dynamics for engineers*. Cambridge: Cambridge University Press.

Antunes, M. J. (2015). Requiem for a good mechanical heart valve: Farewell to the Medtronic Hall valve. *The Journal of Thoracic and Cardiovascular Surgery*, *149*(6), 1492–1494. doi: 10.1016/j.jtcvs.2015.02.004

Aortic Valve Stenosis (AVS). (n.d.). Retrieved from https://www.heart.org/en/health-topics/congenital-heart-defects/about-congenital-heart-defects/aortic-valve-stenosis-avs.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Armstrong, Guy P. “Aortic Regurgitation - Cardiovascular Disorders.” *MSD Manual Professional Edition*, MSD Manuals, June 2018, https://www.msdmanuals.com/professional/cardiovascular-disorders/valvular-disorders/aortic-regurgitation.

Bailey, R. (2017, March 8). Look at How the Brachiocephalic Artery Is Shaped. Retrieved November 14, 2019, from Articles\brachiocephalic-artery-anatomy-373238.pdf.

Bailey, R. (2019, June 24). What Is the Function of the Aorta? Retrieved November 14, 2019, from https://www.thoughtco.com/anatomy-of-the-heart-aorta-373199.

Benim, A., Nahavandi, A., Assmann, A., Schubert, D., Feindt, P., & Suh, S. (2011). Simulation of blood flow in human aorta with emphasis on outlet boundary conditions. *Applied Mathematical Modelling*, *35*(7), 3175–3188. doi: 10.1016/j.apm.2010.12.022

Bessonov, N., Sequeira, A., Simakov, S., Vassilevskii, Y., & Volpert, V. (2015). Methods of Blood Flow Modelling. *Mathematical Modelling of Natural Phenomena*, *11*(1), 1–25. doi: 10.1051/mmnp/201611101

Bhaskaran, R., & Collins, L. Introduction to CFD Basics. Retrieved 8 June 2020, from https://dragonfly.tam.cornell.edu/teaching/mae5230-cfd-intro-notes.pdf

Bloomfield, P. (2002). Choice of heart valve prosthesis. *Heart*, *87*(6), 583–589. doi: 10.1136/heart.87.6.583

Bongert, M., Geller, M., Pennekamp, W., Roggenland, D., & Nicolas, V. (2008). Patient-Specific Simulation Model To Research The Impact Of Aortic Valve Prostheses On Blood Flow. *Journal of Biomechanics*, *41*. doi: 10.1016/s0021-9290(08)70241-0

Boyette, Lydia C. “Physiology, Pulmonary Circulation.” *StatPearls [Internet]*., U.S. National Library of Medicine, 3 Apr. 2019, https://www.ncbi.nlm.nih.gov/books/NBK518997/#__NBK518997_ai__.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Chu, H., Zhang, B., Chen, Y., Li, Y., & Mao, J. (2012). Investigation of micro vortex generators on controlling flow separation over SCCH high-lift configuration. *Science China Technological Sciences*, *55*(7), 1943–1953. doi: 10.1007/s11431-012-4855-0

"Circulatory Pathways." *Circulatory Pathways | SEER Training*, U. S. National Institutes of Health, National Cancer Institute, https://training.seer.cancer.gov/anatomy/cardiovascular/blood/pathways.html.

Evans, F., & Vinod H. Thourani. *The Silver Book: Valve Disease*. Alliance for Aging Research, 2018.

4 Valves of the Heart: What Are They & How They Work. (2018). Retrieved 24 June 2020, from https://my.clevelandclinic.org/health/articles/17067-heart-valves

Gao, F., Watanabe, M., & Matsuzawa, T. (2006). Stress analysis in a layered aortic arch model under pulsatile blood flow. *BioMedical Engineering OnLine*, *5*(1), 25. doi: 10.1186/1475-925x-5-25

Ge, L., Leo, H.-L., Sotiropoulos, F., & Yoganathan, A. P. (2005). Flow in a Mechanical Bileaflet Heart Valve at Laminar and Near-Peak Systole Flow Rates: CFD Simulations and Experiments. *Journal of Biomechanical Engineering*, *127*(5), 782–797. doi: 10.1115/1.1993665

Gudarzi, Mohammad & Zamanian, Hashem & Oveisi, Atta. (2013). A Steady Flow Analysis of Blood Flow Properties through Some Defective Bileaflet Mechanical Heart Valves. Technical Journal of Engineering and Applied Sciences. 3. 898-903.

Harris, C., Croce, B., & Cao, C. (2015). Tissue and mechanical heart valves. *Annals of cardiothoracic surgery*, *4*(4), 399. doi:10.3978/j.issn.2225-319X.2015.07.01

Hatoum, H., & Dasi, L. P. (2018). Reduction of Pressure Gradient and Turbulence Using Vortex Generators in Prosthetic Heart Valves. *Annals of Biomedical Engineering*, *47*(1), 85–96. doi: 10.1007/s10439-018-02128-6

Helmus, M., & Cunanan, C. (2011). Mechanical and bioprosthetic heart valves. *Biomaterials for Artificial Organs*, 113–162. doi: 10.1533/9780857090843.1.113

Hoffman, M. (2017, November 14). The Aorta (Human Anatomy): Picture, Function, Location, and Conditions. Retrieved November 14, 2019, from https://www.webmd.com/heart/picture-of-the-aorta#3.

Hoffman, M. (2017, November 14). Picture of Aorta (Human Anatomy). Retrieved November 14, 2019, from https://www.webmd.com/heart/picture-of-the-aorta#1.

"How Does the Blood Circulatory System Work?" *InformedHealth.org [Internet]*., U.S. National Library of Medicine, 31 Jan. 2019, https://www.ncbi.nlm.nih.gov/books/NBK279250/.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Hu, H. H. (2012). Computational Fluid Dynamics. *Fluid Mechanics*, 421–472. doi: 10.1016/b978-0-12-382100-3.10010-1

Hussein, Nebras & Khalaf, Taha & Timemy, A.A.. (2009). Velocity analysis of bileaflet artificial heart valve: From opening to near close position. Journal of Applied Sciences Research. 5. 1455-1462.

Isselbacher, E. M. (2005). Thoracic and Abdominal Aortic Aneurysms. *Circulation*, *111*(6), 816–828. doi: 10.1161/01.cir.0000154569.08857.7a

Jiang, M., Ida, N., Louis, A. K., & Quinto, E. T. (2018, September 18). The Proceedings of the International Conference on Sensing and Imaging. Retrieved June 23, 2020, from https://books.google.com.my/books?id=O3dvDwAAQBAJ

Kadhim, S. K., Nasif, M. S., Al-Kayiem, H. H., & Al-Waked, R. (2017). Computational fluid dynamics simulation of blood flow profile and shear stresses in bileaflet mechanical heart valve by using monolithic approach. *Simulation*, *94*(2), 93–104. doi: 10.1177/0037549717712603

Khalili, F. (2017). Hemodynamics of a Bileaflet Mechanical Heart Valve with Different Levels of Dysfunction. *Journal of Applied Biotechnology & Bioengineering*, *2*(5). doi: 10.15406/jabb.2017.02.00044

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Kumar, M., Dubey, A., Chheniya, S. & Jadhav, A. (2013). Effect of Vortex generators on Aerodynamics of a Car: CFD Analysis. International journal of innovations in engineering and technology. 2. 137.

M. C. S. (Ed.). (2017, August 2). Aortic valve regurgitation. Retrieved from https://www.mayoclinic.org/diseases-conditions/aortic-valve-regurgitation/symptoms-causes/syc-20353129.

M. C. S. (Ed.). (2018, March 9). Aortic valve stenosis. Retrieved from https://www.mayoclinic.org/diseases-conditions/aortic-stenosis/symptoms-causes/syc-20353139.

Nasir, Z. (2018, November 19). What Computational Fluid Dynamics Can Do for You. Retrieved November 15, 2019, from https://www.air-worldwide.com/Blog/What-Computational-Fluid-Dynamics-Can-Do-for-You/.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Padsalgikar, A. D. (2017). Cardiovascular System: Structure, Assessment, and Diseases. *Plastics in Medical Devices for Cardiovascular Applications*, 103–132. doi: 10.1016/b978-0-323-35885-9.00005-9

Reymond, P., Crosetto, P., Deparis, S., Quarteroni, A., & Stergiopulos, N. (2013). Physiological simulation of blood flow in the aorta: Comparison of hemodynamic indices as predicted by 3-D FSI, 3-D rigid wall and 1-D models. *Medical Engineering & Physics*, *35*(6), 784–791. doi: 10.1016/j.medengphy.2012.08.009

Rogers, K. (Ed.). (2018, April 5). Pulmonary circulation. Retrieved from https://www.britannica.com/science/pulmonary-circulation.

Roles of Your Four Heart Valves. (2016, May 31). Retrieved from https://www.heart.org/en/health-topics/heart-valve-problems-and-disease/about-heart-valves/roles-of-your-four-heart-valves.

Saladin, K. S. (2918). *Anatomy physiology: the unity of form and function* (5th ed.). New York, NY: McGraw-Hill Education.

Sansone, F., Zingarelli, E., Actis Dato, G. M., Punta, G., Flocco, R., del Ponte, S., & Casabona, R. (2012). The 37-year durability of a Björk-Shiley Delrin-disc aortic valve prosthesis. *Texas Heart Institute journal*, *39*(2), 284–285.

Slater, J. (2008). CFD Analysis Process. Retrieved 8 June 2020, from https://www.grc.nasa.gov/WWW/wind/valid/tutorial/process.html

Svennevig, J. L., Abdelnoor, M., & Nitter-Hauge, S. (2007). Twenty-Five–Year Experience With the Medtronic-Hall Valve Prosthesis in the Aortic Position. *Circulation*, *116*(16), 1795–1800. doi: 10.1161/circulationaha.106.677773

Walker, D K, et al. “The New St. Jude Medical Regent Mechanical Heart Valve: Laboratory Measurements of Hydrodynamic Performance.” *The Journal of Heart Valve Disease*, U.S. National Library of Medicine, Nov. 1999, https://www.ncbi.nlm.nih.gov/pubmed/10616249.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Wilkes, J. O. (2017, November 15). Physical Properties—Density, Viscosity, and Surface Tension. Retrieved November 15, 2019, from http://www.informit.com/articles/article.aspx?p=2832417&seqNum=4.

Wills, B. A., & Finch, J. A. (2016). Modeling and Characterization. *Wills Mineral Processing Technology*, 449–462. doi: 10.1016/b978-0-08-097053-0.00017-0

Yadav, A., Rawal, P., & Mishra, R. K. (2018). Modelling and simulation of aerodynamic performance of Vortex generators for hatch back type cars. *Vibroengineering PROCEDIA*, *21*, 131–136. doi: 10.21595/vp.2018.20399

Yun, B. M., Dasi, L. P., Aidun, C. K., & Yoganathan, A. P. (2014). Highly resolved pulsatile flows through prosthetic heart valves using the entropic lattice-Boltzmann method. *Journal of Fluid Mechanics*, *754*, 122–160. doi: 10.1017/jfm.2014.393

Zakaria, M. S., Ismail, F., Tamagawa, M., Aziz, A. F. A., Wiriadidjaja, S., Basri, A. A., & Ahmad, K. A. (2017). Review of numerical methods for simulation of mechanical heart valves and the potential for blood clotting. *Medical & Biological Engineering & Computing*, *55*(9), 1519–1548. doi: 10.1007/s11517-017-1688-9

Zhou, F., Cui, Y. Y., Wu, L. L., Yang, J., Liu, L., Maitz, M. F., Huang, N. (2016). Analysis of Flow Field in Mechanical Aortic Bileaflet Heart Valves Using Finite Volume Method. *Journal of Medical and Biological Engineering*, *36*(1), 110–120. doi: 10.1007/s40846-016-0106-3

اونيۈرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

APPENDICES A

Gantt chart for PSM 1

	Week																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Gathering general ideas on the topic and study the related article								Mid Term Break								Study Week	Semester Final Examination		Semester Break
Introduction (Background, Problem Statement, Objectives, Scope)																			
Literature Review																			
Methodology																			
Progress Submission Report																			
Create medical imaging of patient's data																			
Model the geometry and flow domain																			
Attach the geometry with the medical imaging																			
Report submission of FYP I																			
Presentation of FYP I																			
Correction of Report																			

اونيۈرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

APPENDICES B

Gantt chart for PSM 2

	Week																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Model the geometry and flow domain																		
Perform the simulation of mhv without aorta																		
Analyze the CFD models of blood flow with mhv without aorta																		
Analyze the velocity, wall shear stress and pressure drop of mhv without aorta																		
Perform the simulation of mhv with aorta								Mid Term Break								Study Week	Final Examination	
Analyze the CFD models of blood flow with mhv with aorta																		
Analyze the velocity, wall shear stress and pressure drop of mhv with aorta																		
Redesign VG if parameters not achieved																		
Project Report																		
Report submission of FYP II																		
Presentation of FYP II																		

اونيۏرسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA