CHAPTER 1

1.0 INTRODUCTION

1.1 BACKGROUND STUDY

1.1.1 Cardiovascular Diseases

Cardiovascular diseases(CVDs) or heart diseases are the class of diseases that involves the blood vessels or heart(veins and arteries) which is caused by disorders of the heart and blood vessels[1].Unhealthy lifestyle such as tobacco use, physical inactivity, and an unhealthy diet are known as the major causes of cardiovascular diseases .According to World Health Organization (WHO),Cardiovascular diseases (CVDs) can be categorized into[2] :

1) Coronary artery disease (CAD) – disease of the blood vessels supplying the heart muscle
2) Cerebrovascular disease - disease of the blood vessels supplying the brain
3) Peripheral arterial disease – disease of blood vessels supplying the arms and legs
4) Rheumatic heart disease – damage to the heart muscle and heart valves from rheumatic fever, caused by streptococcal bacteria
5) Congenital heart disease - malformations of heart structure existing at birth
6) Deep vein thrombosis and pulmonary embolism – blood clots in the leg veins, which can dislodge and move to the heart and lungs.

Heart attacks or strokes are usually acute events which are happened when CVD becomes severe[2].Strokes or heart attacks are caused by a blockage that prevents blood from flowing to the brain or heart. The most common reason for this is a build-up of fatty deposits on the inner walls of the blood vessels that supply the heart or brain. Besides that ,strokes can also be caused by bleeding from a blood vessel in the brain or from blood clots.

There are several symptoms of heart attack or stroke such as pain or discomfort in the centre of the heart and pain or discomfort in the arms, the left shoulder, elbows, jaw, or back . Moreover ,the person may experience difficulty in breathing or shortness of breath; feeling sick or vomiting; feeling light-headed or faint; breaking into a cold sweat; and becoming pale .The most common symptom of stroke is sudden weakness of the face, arm, or leg, most often on one side of the body .Other than that, numbness of the face, arm, or leg, especially on one side of the body; confusion, difficulty speaking or understanding speech; difficulty seeing with one or both eyes; difficulty walking, dizziness, loss of balance or coordination; severe headache with no known cause; and fainting or unconsciousness are the other symptoms can be observed.

1.1.2 WHO Statistics

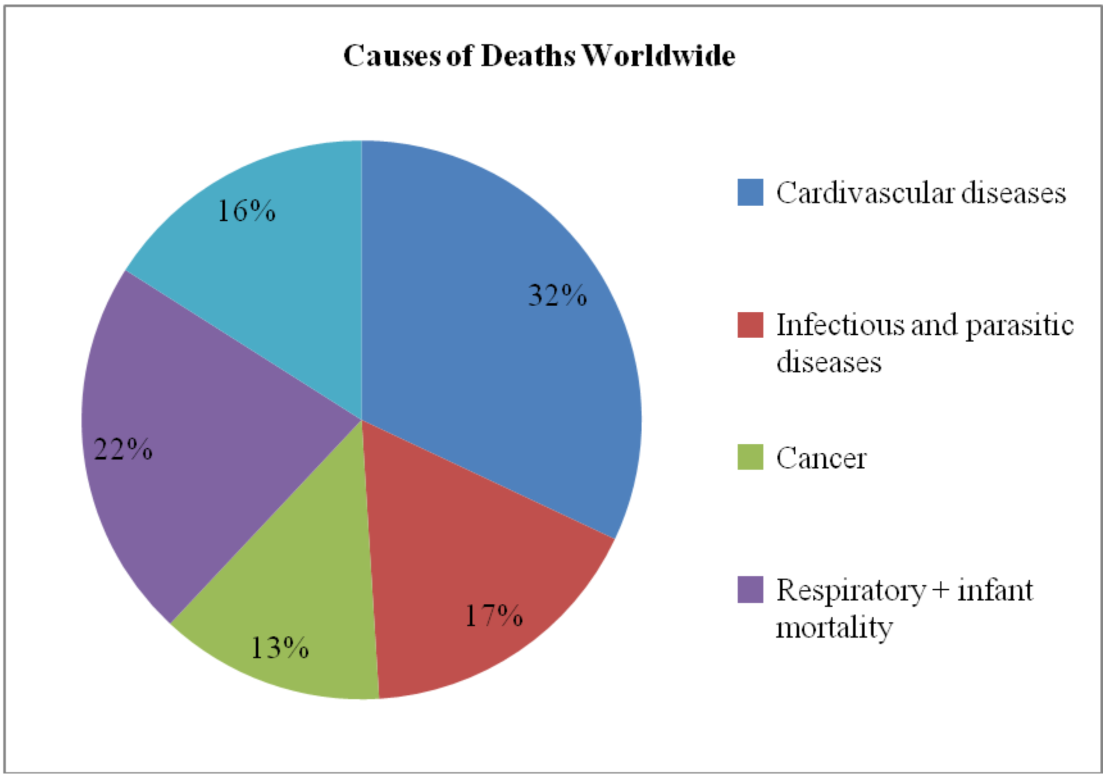

Figure 1.1 : Causes of deaths worldwide

Figure 1.1 above shows the pie chart of death causes worldwide[3].Cardiovascular diseases (CVDs) is placed as the number one cause of death with the percentage of 32%.The number is estimated to be increasing through this year as CVDs is expected to be the leading cause of death in 2010[2].In 2004, an estimated 17.1 million people died from CVDs , representing 29% of all global deaths. Of these deaths, an estimated 7.2 million were due to coronary heart disease and 5.7 million were due to stroke .Based on these trends ,it is predicted that by 2030, almost 23.6 million people will die from CVDs, mainly from heart disease and stroke. It is projected to remain the single leading causes of death. The largest increment will occur in the Eastern Mediterranean Region and the largest increment in number of deaths will occur in the South-East Asia Region.

1.1.3 Blood as Fluid

The average adults have about five liters of blood living inside of their body ,coursing through their vessels .Blood function in delivering essential elements, and removing harmful wastes .Hence ,without blood ,the human body would stop working[4].

Blood is said to be the fluid of life ,the fluid of growth and the fluid of health .Blood is the fluid of life because it transports oxygen from the lungs to body tissue and carbon dioxide from body tissue to the lungs .Blood is the fluid of growth where blood transports nourishment from digestion and hormones from glands throughout the body. Blood is the fluid of health where blood transports disease fighting substances to the tissue and waste to the kidneys[4].

Blood Compositions

Blood consists of formed elements and plasma .Formed elements consists of red blood cells (RBCs) or erhythrocytes (99.9%),white blood cells (WBCs) or leukocytes and platelets where combination of these two resulting in the remaining 0.1% of formed elements .Plasma consists of water (92%),plasma proteins (7%) and other solutes (1%). Hematocrit (H) is the percentage of whole blood occupied by cellular elements[5].

The main components of blood are plasma with 54% of blood volume ,red blood cells with 45% of blood volume and white blood cells with 1% of blood volume[5]. The whole blood is found that to exhibit non-Newtonian behaviour which can be described by the power law rheological model[6].

Functions of blood

Blood acts as a transportation medium .Besides that ,it also has a role in temperature regulation ,fluid and electrolyte balance, pH regulation, prevention of fluid loss ,nourishment and disease prevention[7]. These can be divided into:

1) Supply of oxygen to tissues (bound to hemoglobin, which is carried in red cells).
2) Supply of nutrients such as glucose, amino acids, and fatty acids (dissolved in the blood or bound to plasma proteins).
3) Removal of waste such as carbon dioxide, urea, and lactic acid.
4) Immunological functions, including circulation of white blood cells, and detection of foreign material by antibodies.
5) Coagulation, which is one part of the body's self-repair mechanism (the act of blood clotting when you get cut to stop the bleeding).

6) Messenger functions, including the transport of hormones and the signalling of tissue damage.
7) Regulation of body pH (the normal pH of blood is in the range of 7.35–7.45) (covering only 0.1 pH unit).
8) Regulation of core body temperature.
9) Hydraulic functions.

1.1.4 Atherosclerosis

Atherosclerosis is a disease where the plaque is build up in the arteries. Arteries are the blood vessels which are functioning in carrying oxygen-rich blood to the heart and other parts of body. Atherosclerosis means hardening (sclerosis) of the arteries in which the wall of an artery becomes thicker and less elastic [7].

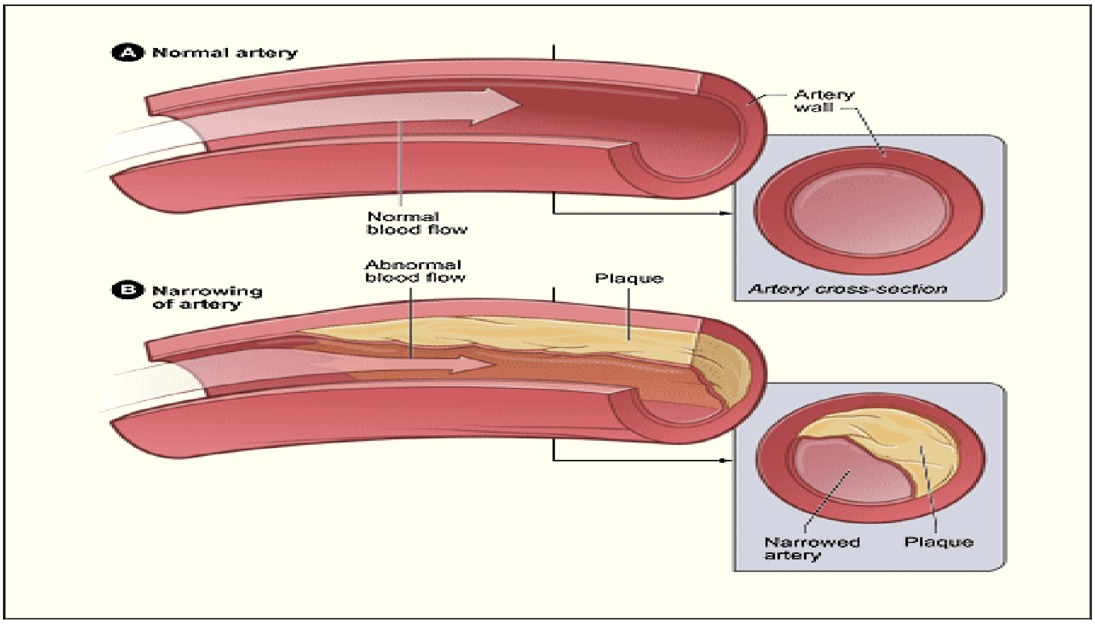

Figure 1.2 : A shows a normal artery with normal blood flow and B shows an artery with plaque build up.

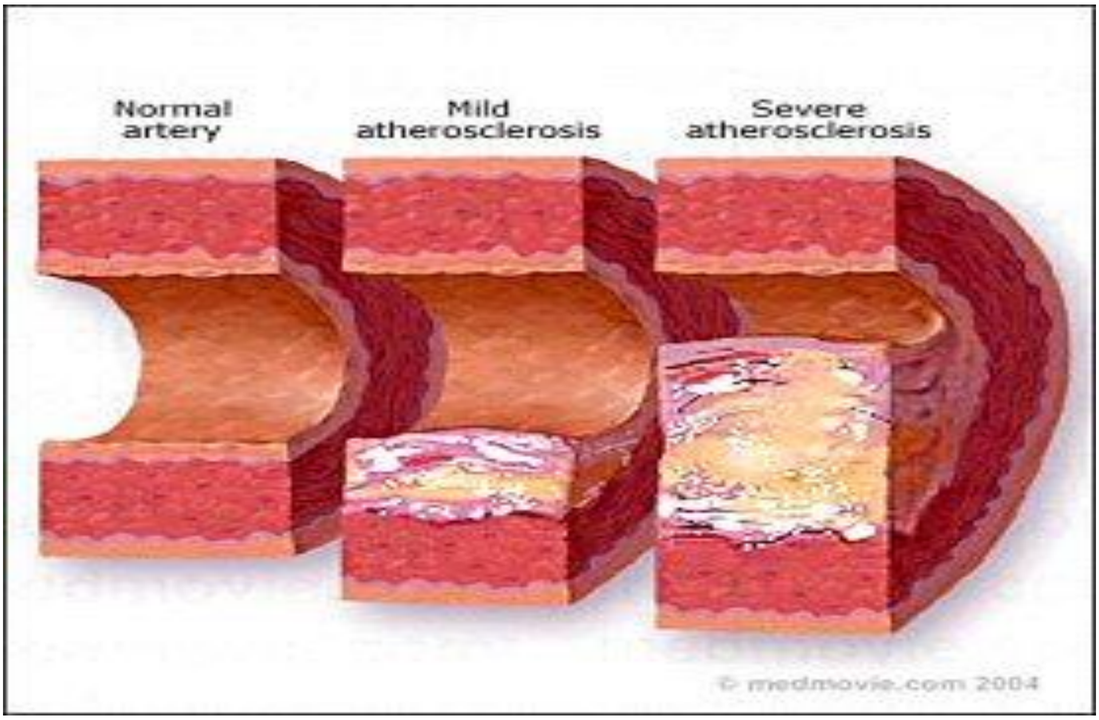

Figure 1.3 : The development of atherosclerosis.

Based on the Figure 1.3 [10],this kind of condition happens when the fatty substances ,cholesterol ,cellular waste products and other substances build up in the inner lining of an artery .The build up is called plaque .When ,the plaque became severe ,it will blocked the blood vessels and caused the atherosclerosis became severe[10].

Atherosclerosis is the common initiator of CVD where it narrows an artery and caused the tissues may not receive enough blood and oxygen .The first symptom of narrowing artery is pain or cramps which is caused by the flow of blood cannot keep up with the tissues need for oxygen[9].

Atherosclerosis also can caused artery hardening in which arteries are originally flexible to allow vascular responses upon blood flow. For instance ,when the wall of artery senses the higher stress (increase in blood flow) ,the artery will dilate and remodel with larger diameter and vice versa.

1.1.5 Image Guided Modelling

In image-guided modelling ,the estimation of velocity components at every point within a volume is used as the basis in which it is referred as the “flow field’ ,in a time-resolved manner[25].It is only possible in highly simplified geometries in which it means that it is not possible in the more complex geometries of arteries and for that ,CFD is used to provide an estimation of the time-varying flow field[25].The steps in the processing chain for image-guided modelling can be simplified in Figure 1.4.

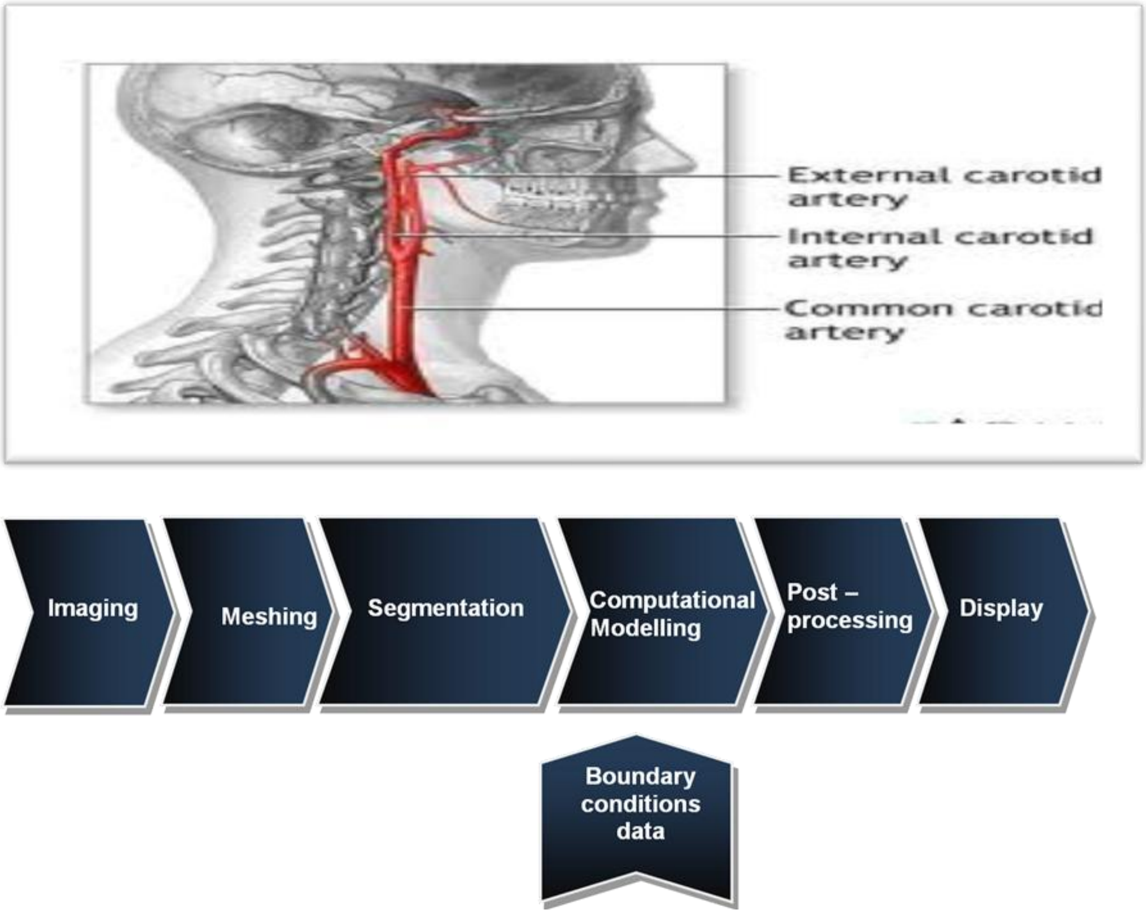

Figure 1.4:The steps in the processing for image-guided modelling.

Based on the Figure 1.4 [25], the image of patient’s artery is acquired .Then , the image is meshed and segmented where the governing equation was solved. In the CFD ,the boundary conditions from the real data were specified. Then , the result undergone the post-processing where the result is displayed .

1.2 PROBLEM STATEMENT

The understanding of blood hydrodynamic is important since blood can behave as Newtonian and non-Newtonian fluid according to flow changes . However , in CFD blood is usually simplified as Newtonian fluid .According to Navier-Stokes equation ,the viscosity of fluid can change the flow behaviour. Therefore , the assumption of blood as Newtonian fluid has to be further verified.

When a patient is diagnosed to have narrowed artery ,it is important to measure the flow behaviour of the blood through the artery .The information will assist the clinical decision of the type of suitable treatment in which either to have dietry changes ,oral medication or surgery .Therefore ,it is appropriate to compare flow of a different artery and healthy artery to gauge the abnormal flow behaviour.

The understanding of blood behaviour is also important since in human circulation ,blood flows from artery to capillary and experience changes in diameter .Blood flows experience changes in size since the artery has wide range of diameter. A large artery measure up to 8mm and small artery (capillary) is within 1mm.

1.3 OBJECTIVES OF THE STUDY

The objectives if this study are :

1) To investigate the effect of blood rheology on flow behavior by simulating the flow with a Newtonian and non-Newtonian model.
2) To compare the flow behaviour in healthy artery with diseased artery.
3) To investigate the flow behavior of blood in artery and capillary by simulating the flow at different vessel sizes.

1.4 SCOPE OF STUDY

In this study ,the Navier-Stokes equation will be employed for multi component system .Then ,the flow behavior of blood in diseased blood vessel will be looked into .The flow behavior of the blood is modeled as Newtonian fluid and non-Newtonian fluid in which three models of non-Newtonian models are used (Cross Model ,Power Law Model & Herschel-bulkley Model).A Computational Fluid Dynamics (CFD) method using FLUENT will be employed to examine the flow behavior .The computational is based on the applications of the Navier-Stokes equation to an idealized model of an artery.

CHAPTER 2

2.0 THEORY AND LITERATURE REVIEW

2.1 THEORY

2.1.1 Navier-Stokes Equation

In physics ,the Navier-Stokes equation is named after Claude-Louis Navier and George Gabriel Stokes in which it describes the motion of fluid substance .These equations arise from applying Newton's second law to fluid motion ,together with the assumption that the fluid stress is the sum of diffusing viscous term (proportional to the gradient of velocity) ,plus a pressure term. In this project , Navier-Stokes equation is used as the governing equations for the blood flow. The equations are set of nonlinear partial differential equations which are time-dependent and consist of a continuity equation for conservation of mass ,three conservation of momentum equations and a conservation of energy equation[13].

Conservation of Mass

The principle is applied to fixed volumes, known as control volumes (or surfaces), like that in the figure below:

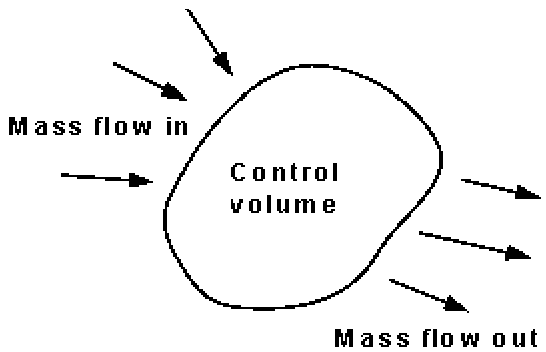

Figure 2.1: An arbitrarily shaped control volume.

For any control volume the principle of *conservation of mass* given by:

Mass entering per unit time = Mass leaving per unit time + Increase of mass in the control volume per unit time

For steady flow :

Mass entering per unit time = Mass leaving per unit time

This can be applied to a stream tube such as that shown below. No fluid flows across the boundary made by the streamlines so mass only enters and leaves through the two ends of this stream tube section.

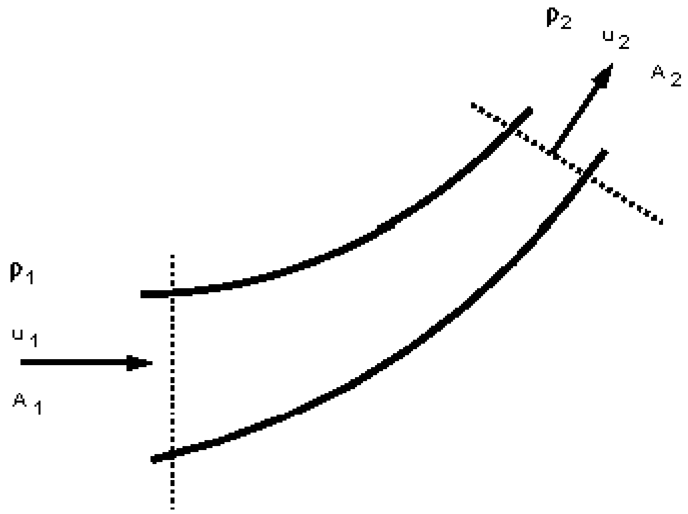

Figure 2.2 :A stream tube

In which;

$$\text{mass entering per unit time at end 1} = \text{mass leaving per unit time at end 2} \qquad (1)$$

$$\rho_1 \delta A_1 u_1 = \rho_2 \delta A_2 u_2$$

Or for steady flow,

$$\rho_1 \delta A_1 u_1 = \rho_2 \delta A_2 u_2 = \text{ Constant } = \dot{m} \tag{2}$$

This is the equation of continuity.

The flow of fluid through a real pipe (or any other vessel) will vary due to the presence of a wall .Then, the *mean* velocity is used and given by;

$$\rho_1 A_1 u_{m1} = \rho_2 A_2 u_{m2} = \text{ Constant } = \dot{m} \tag{3}$$

When the fluid can be considered incompressible, i.e. the density does not change, $r_1 = r_2 = r$ so (dropping the *m* subscript)

$$A_1 u_1 = A_2 u_2 = Q \tag{4}$$

Conservation of Macroscopic Momentum Equation

According to Newton's second law, the rate of change of the momentum of a particle is proportional to the resultant force ,F acting on the particle and is in the direction of that force. The derivation of force from momentum is given below, however because mass is constant the second term of the derivative is 0 so it is ignored.

$$\sum \mathbf{F} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} + v\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = m\mathbf{a} \tag{5}$$

The conservation of Momentum law :

$$p_1 + \frac{\rho}{2}v_1^2 + \rho g z_1 = \rho \int_{s_1}^{s_2} \frac{\partial v(s,t)}{\partial t} ds + p_2 + \frac{\rho}{2}v_2^2 + \rho g z_2 \tag{6}$$

This the Bernoulli’s Equation of unsteady state flow ,then for steady state flow is given by

$$\frac{p}{\rho}+\frac{1}{2}v^2+gz=const\ \ [N\cdot m/kg] \tag{7}$$

The balances of mass (incompressible fluid) and momentum (inviscid flow) are called macroscopic or integral balances .Thus ,deriving more general forms of these equations is needed where a microscopic and differential approach are used .This derivation leads to continuity and the Navier-Stokes Equation.

Navier-Stokes Equation

The equation is derived fron the law of momentum conservation :

$$\underbrace{\rho\frac{\partial \bar{\mathbf{v}}}{\partial t}}_{\text{Local Acceleration}}+\underbrace{\rho\,\bar{\mathbf{v}}.\nabla\,\bar{\mathbf{v}}}_{\text{Convective Acceleration}}=\underbrace{-\nabla p}_{\text{Pressure Force per Unit Volume}}+\underbrace{\rho g}_{\text{Body Force per Unit Volume}}+\underbrace{\mu\nabla^2\,\bar{\mathbf{v}}}_{\text{Viscous Force per Unit Volume}} \tag{8}$$

2.1.2.Fluid Mechanics in Straight Tube

When the fluid behaves as if it were flowing in a concentric nest of thin cylinders one inside another ,it is said to be laminar flow. Due to fluid’s viscosity, the cylinder next to the wall is stationary, while the one in the centre of the pipe is moving with the highest velocity. Besides that ,in the laminar flow there is no mixing between the layers of fluid and velocity does not pulsate . Meanwhile ,in the turbulent flow, there is random mixing between the layers of fluid. Thus ,the velocity distribution is much more uniform across the pipe cross section[23].

Normal blood flow would normally be laminar flow because normally ,the laminar flow is well organized and very efficient compared to turbulent flow in which is more complicated and not very organized. In this case, artery is assumed to be horizontally placed with the gravitational force is neglected.

For the fluid flows in straight tube ,the flowrate is given by :

$$Q = \frac{\pi R^2 \Delta P}{8\mu L}$$

In which: (9)

Q is the flowrate

R is the radius of the tube

ΔP is pressure drop along the tube

μ is dynamic viscosity

Then ,solving for the pressure drop lead to the poiseulle equation :

$$\Delta P = \frac{128\mu L Q}{\pi d^4}$$

(10)

2.1.3.Flow Through Constriction

With the aid of Figure 2.3 ,it shows as the fluid flow through a constriction ,the fluid will experience pressure reduction since the fluid flows from higher diameter to lower diameter .Thus ,the fluid velocity will increase in order to satisfy the equation of continuity . Meanwhile ,the conservation of energy and the gain of energy in the fluid is balanced by the pressure drop in accordance to the pressure reduction.

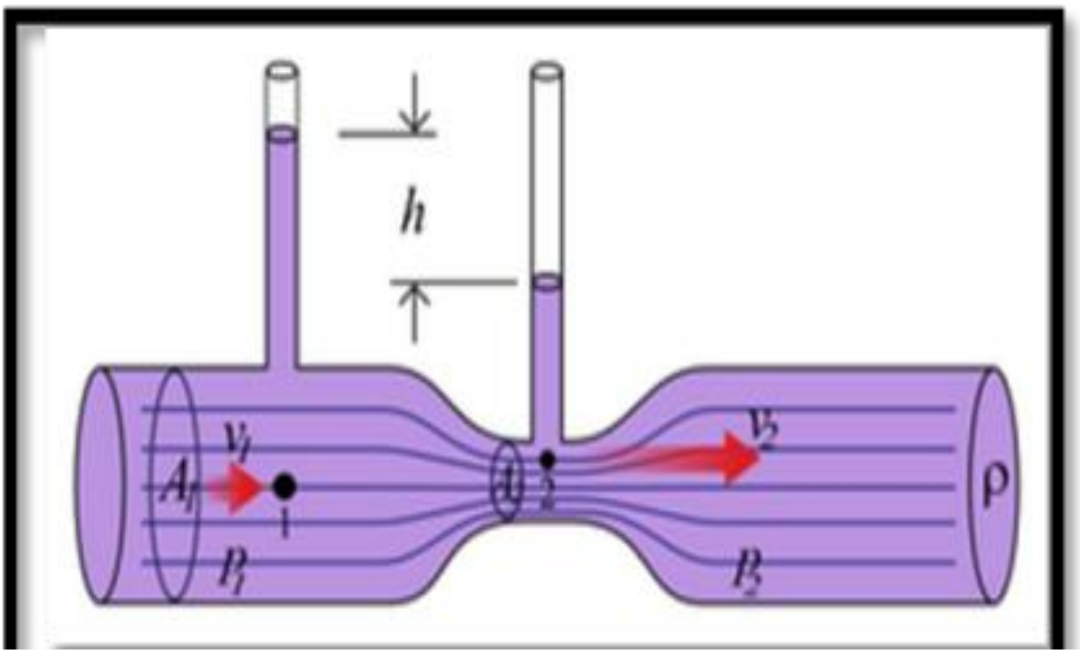

Figure 2.3: The venturi flow

There are two main equations to this venturi concept .The first one is Bernoulli equation :

$$\left(\frac{P}{\gamma}+z+\frac{v^2}{2g}\right)_1 = \left(\frac{P}{\gamma}+z+\frac{v^2}{2g}\right)_2 \tag{11}$$

Then ,the continuity equation states that the total normal flow must be constant :

$$Q = vA$$

Since, Q1 = Q2

So,

$$\begin{cases} Q = v_1 A_1 = v_2 A_2 \\ p_1 - p_2 = \frac{\rho}{2}\left(v_2^2 - v_1^2\right) \end{cases}$$

Solving this equation,lead to :

$$Q = A_1\sqrt{\frac{2\left(p_1 - p_2\right)}{\rho\left(\left(\frac{A_1}{A_2}\right)^2 - 1\right)}} = A_2\sqrt{\frac{2\left(p_1 - p_2\right)}{\rho\left(1 - \left(\frac{A_2}{A_1}\right)^2\right)}} \tag{12}$$

2.2 LITERATURE REVIEW

2.2.1 Blood Flow Behaviour

Basically ,viscosity is used to describe the rheology of the blood .Viscosity is a measure of the resistance to flow exerted by the fluid [12].Viscosity is given by the ratio of the force exerted to move the fluid (shear stress) to the velocity gradient of the fluid.

$$\tau = -\mu\frac{\delta v}{\delta y} = -\mu\gamma \tag{13}$$

Where :

τ is the shear stress

μ is the dynamic viscosity

$\partial v/\partial y$ is the velocity gradient

Blood is describe as Newtonian fluid as the blood have constant viscosity regardless of velocity but blood also is describe as non-Newtonian fluid as the formed elements in blood behave as non-Newtonian fluid in which its viscosity varies depending on velocity.

2.2.2 Blood Rheology

Blood consists of formed elements and plasma. Plasma is classified as Newtonian fluid .Combination of both results in the whole blood behave as non-Newtonian fluid .Newtonian fluids are fluids having constant viscosity regardless of velocity while ,non-Newtonian fluids are fluids varying in viscosity depending on velocity of the fluid .Generally, the blood, being a suspension of cells, behaves as a non-Newtonian fluid at low shear rate .The blood having viscosity of 0.00345 Pa.s and high shear rate (>200 s^{-1}) is assumed to behave as Newtonian fluid .When ,blood is modelled to behave as non-Newtonian fluid ,it is known that the non-Newtonian effects weaken the wall shear stress distribution associated with the stenosis .The variation of viscosity and the presence of blood cells represent the importance of two-phase nature of the blood .In these studies ,blood is modelled as power law (diameter less than 0.2 mm and at less than 20 sec^{-1} shear rate) ,cross model and Herschel-bulkley model [14,15].

2.2.3 Newtonian and non-Newtonian General Models

There are four types of common rheological models of fluid[22].They are Newtonian model and three non-Newtonian models which are Power law ,Cross and Herschel-bulkley model. Power law model ,Cross model and Herschel-bulkley model describe the behaviour of fluid having varying in viscosity depending on the velocity of the fluid where it is called as non-Newtonian fluid. The Newtonian model describe the behaviour of fluid having constant viscosity regardless of velocity. Based on the figure 8,the shear stress is proportional to shear rate for the Newtonian model[22].

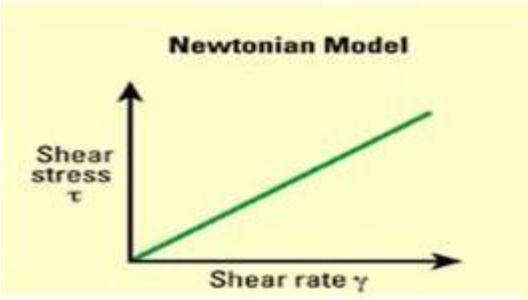

Figure 2.4 : The graph of Shear stress vs Shear rate of Newtonian model.

Power Law Model

It is known as the model which predict shear-thinning .The value of n determines the class of fluid ; i) n = 1 (Newtonian fluid),n > 1 (shear-tickening – dilatant fluids), n<1 (shear-thinning – pseudo plastics)[21].

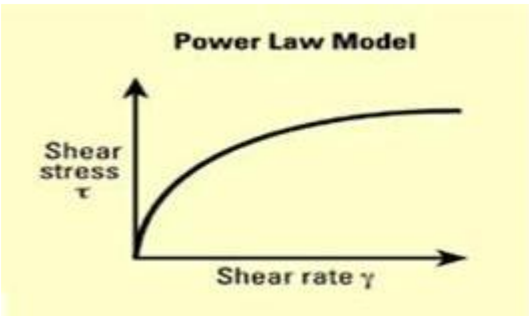

Figure 2.5 : The graph of Shear stress vs Shear rate of Power Law model.

The Power Law predicts that the effective viscosity would decrease as shear rate increases indefinitely, requiring a fluid with infinite viscosity at rest and as the shear rate approaches infinity the viscosity became zero, but a real fluid has both a minimum and a maximum effective viscosity[21].

The non-Newtonian viscosity is given by :

$$\eta = \kappa\gamma^{n-1} e^{\,To/T}$$

(14)

Where ;

η is viscosity

κ consistency index

n is power law index

T is reference temperature

Herschel-Bulkley Model

The Herschel-Bulkley indicates that the stress experienced by the fluid is related to the strain in a non-linear way .For the Herschel-bulkley model ,the viscous stress tensor is given by the viscosity multiplied by the rate-of-strain tensor .Herschel-Bulkley model requires a certain minimum of stress to initiate flow ,but less stress with increasing shear[20].

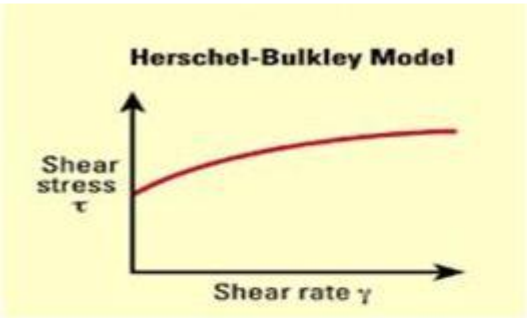

Figure 2.6 : The graph of Shear stress vs Shear rate of Herschel-bulkley model.

In Herschel-bulkley model, the stress experienced by the fluid is related to the strain in a complicated, non-linear way. It is described by the relationship of the consistency *k*, the flow index *n*, and the yield shear stress τ_0. The consistency is a simple constant of proportionality, while the flow index measures the degree to which the fluid is shear-thinning or shear-thickening .Finally, the yield stress quantifies the amount of stress that the fluid may experience before it yields and begins to flow.

Herschel-bulkley model can be described as:

$$\tau = \tau o + k(\gamma)^n$$

Where: (15)

τ = shear stress

τ_0 = yield stress

k = consistency

γ = shear rate

n = power law exponent

Cross Model

In the present study, Cross model is used to simulate the shear thinning behaviour of blood where it is also one of the non-Newtonian general model [24].Cross model can be described as :

$$\eta = \eta_\infty + \frac{\eta_0 - \eta_\infty}{1 + (C\dot{\gamma})^m}$$

Where : (16)

η_0 is the zero shear viscosity

η_∞ is the infinite shear viscosity

m is the (cross) rate constant

C is the cross time constant (or sometimes the consistency)

$\dot{\gamma}$ is the symmetric rate of deformation tensor

With the aid of Figure 2.7,it shows that all four parameters of Cross model can predict well the shear thinning behaviour of blood[24].It also shows that viscosity is indirectly proportional to the shear rate.

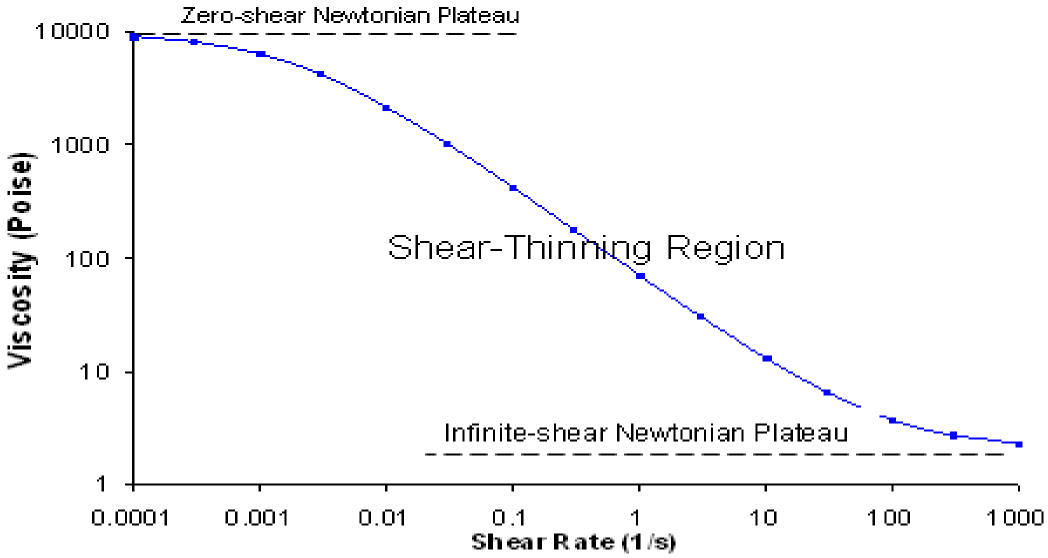

Figure 2.7 : The graph of viscosity of blood and Cross model versus different values of shear rate.

2.2.4 Review of Blood Rheology Research

Blood is characterised as an incompressible , viscoelastic , thixotropic fluid .In the current study ,various researchers have shown that the elasticity of blood is insignificant compared to viscosity when considering velocity profiles in arterial geometries[15].This has attributed to the difference in model of predictions at the lower shear rate range where at the high shear rate ,the various viscosity models lead to similar wall shear stress distribution. For steady flow simulations of blood flow, the shear thinning non-Newtonian nature of blood flow has to be considered .Tu and Deville completed a similar study based on flow through an arterial stenosis [27]. From this study, it was found that rheological properties of blood can significantly affect the flow phenomena .For the steady state case, the results indicated that the non-Newtonian effects weaken the wall shear stress distribution associated with the stenosis. As the conclusion ,it can be conclude that blood cannot be treated as a Newtonian or non-Newtonian fluid in general and under all circumstances .It is more meaningful to consider each case individually e.g. flow rate, steady/unsteady, and geometry under investigation. A constitutive equation is still not available which adequately describes the viscous properties of blood under all circumstances.

CHAPTER 3

3.0 METHODOLOGY

3.1 COMPUTATIONAL FLUID DYNAMICS (CFD)

Computational Fluid Dynamics is the science of predicting the unknown value by solving the numerically the set of governing equation .It is also the art of replacing such partial differential systems (conservation laws of mass ,momentum and energy) by a set of algebraic equations which can be solved using digital computers .CFD is the combination three disciplines which are theoretical fluid dynamics ,numerical mathematics and computer science .It uses a computer to solve the mathematical equations (Navier-Stokes equations and others allied equations)for problem of fluid dynamics[18].

3.2 FLUENT

FLUENT is a computer program for modeling fluid flow and heat transfer in complex geometries .It is used in engineering to stimulate all levels of complexity with relative ease .It has broad physical capabilities such as flow problems in 2D and 3D,compressible and incompressible ,steady state and time dependent ,variety of material properties and others .FLUENT can reduce the total effort required in the experiment .In addition ,FLUENT uses a client or server architecture ,which allows it to run as separate simultaneous processes .FLUENT package includes FLUENT(the solver),GAMBIT(the preprocessor for geometry modeling and mesh generation ,T Grid (an additional preprocessor that can generate volume meshes from existing boundary meshes)and Filters .FLUENT solvers usually based on the finite volume method[19].

3.3 HOW DOES CFD WORK?

FLUENT solvers are based on the finite volume method .There are few steps taken in solving the problem , firstly ,the domain is discretized onto a finite set of control volumes (or cells). Then ,the general conservation (transport) equations for mass, momentum, energy ,species, etc. are solved on this set of control volumes .After that, the partial differential equations are discretized into a system of algebraic equations . Finally ,all algebraic equations are then solved numerically to render the solution field.

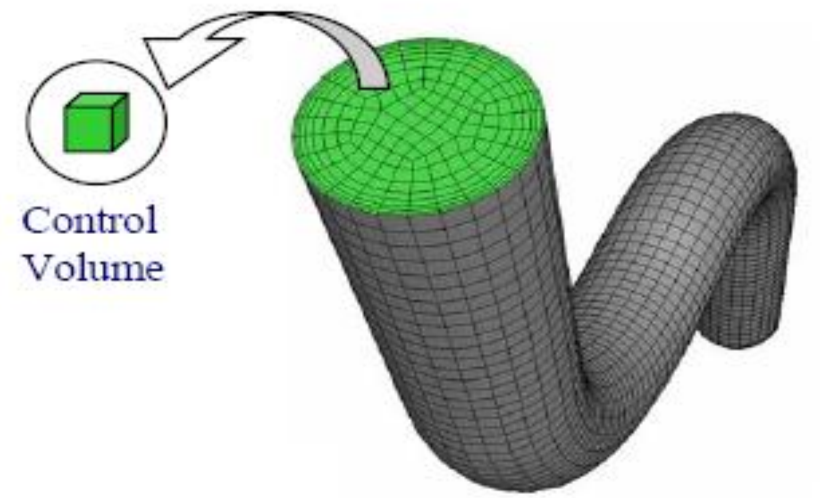

Figure 3.1: A region of pipe flow is discretized into a finite set of control volume (mesh)

3.4 FLUENT MODELING OVERVIEW

There are three phases to CFD problems .The first phase is preprocessing which is the creation of geometry and done in CAD tool named GAMBIT .The second phase is the solver execution where all the equations are solved using finite volume method .The final phase is post processing which the visualization of a CFD's code can be observed and further evaluate or revise .The basic step and the overview of CFD modeling is summarized below as shown in Figure 3.2.

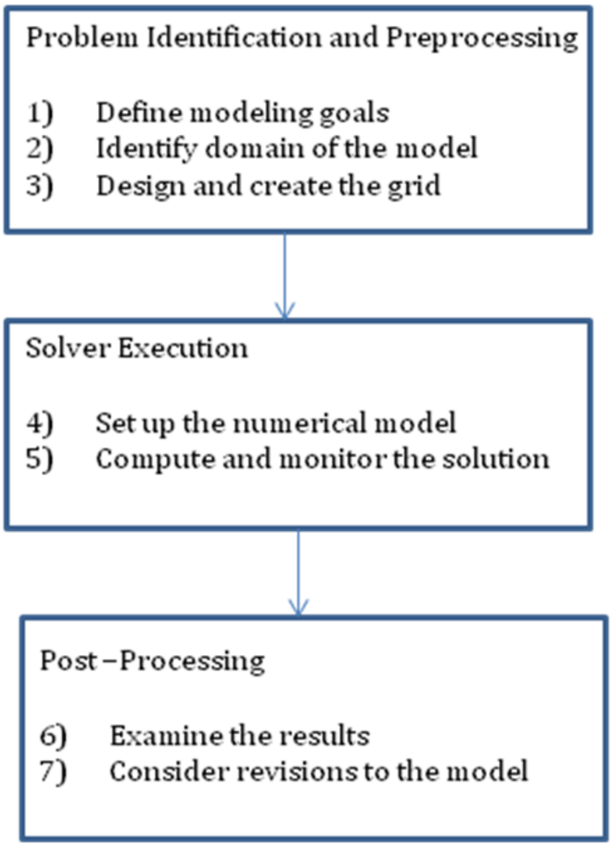

Figure 3.2 : Basic steps of CFD.

Further explanation of CFD modelling of FLUENT software is shown in Figure 3.3 where the main part consist of pre-processing and solver .In pre-processing ,a solid geometry is generated by a software called GAMBIT. Then ,the domain is modelled before it is put into a mesh generation step to generate and divide the domain into a finite set of control volume.

Then ,the selection of solver setting is required for setting up the numerical model .Here ,the solver setting and pre-processing data are required as an input to the solver.

After that ,the solver will continue by taking into consideration of transport equations and momentum equations .The characteristics of the domain in specified in this equation solver such as material properties ,boundary conditions ,initial conditions and the condition of the physical model .In this study ,the laminar model will be applied.

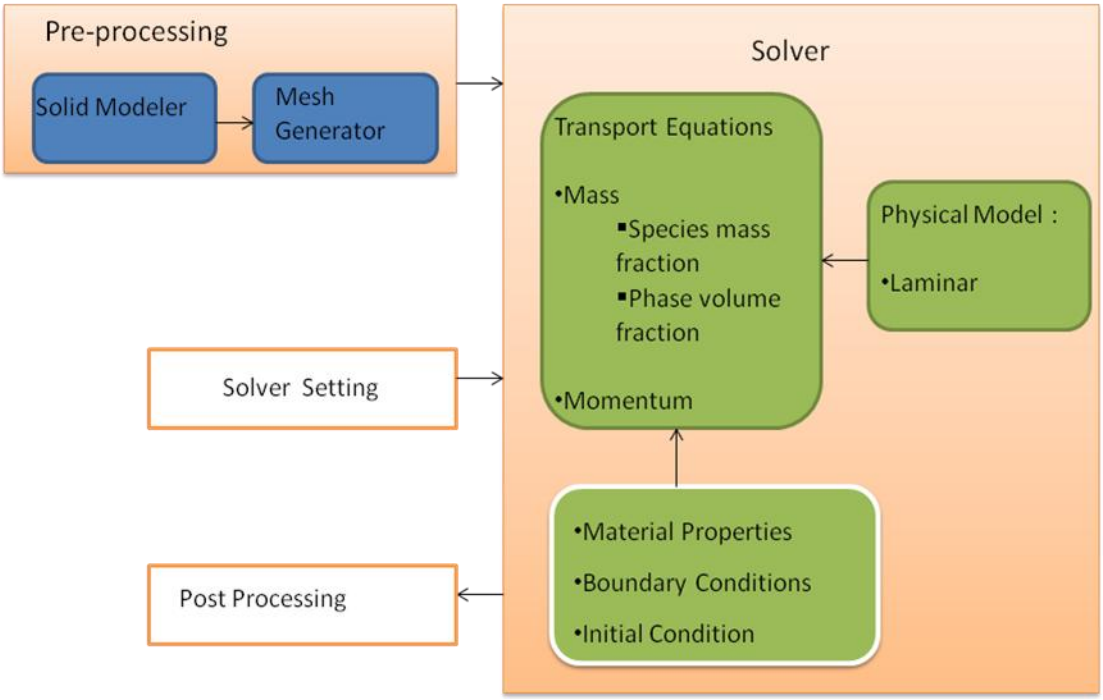

Figure 3.3 :FLUENT operation system

3.5 PRE-PROCESSING

In the pre-processing ,a solid geometry is modelled .In this study, geometry of straight tube and stenosis tube are created in GAMBIT(software) as shown in Figure 3.4 and Figure 3.5.For the Newtonian model and non-Newtonian model of Power Law ,Cross model and Herschel-bulkley model ,the straight tube is modelled to represent an idealized geometry of artery having diameter of 8mm and 6mm with the length of 700 mm .As for the stenosis tube ,it is modelled to represent an idealized geometry of artery having 30% area reduction with the diameter of 8mm with the length of 400mm and 6mm with the length of 201mm

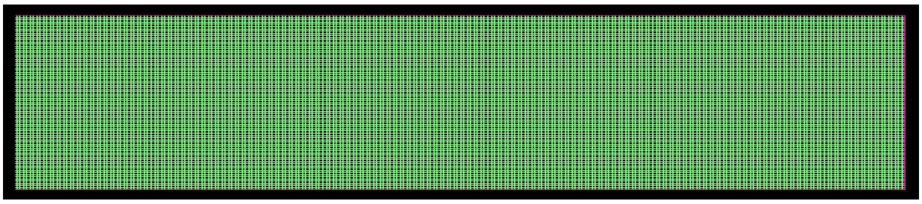

Figure 3.4 : Geometry of straight tube

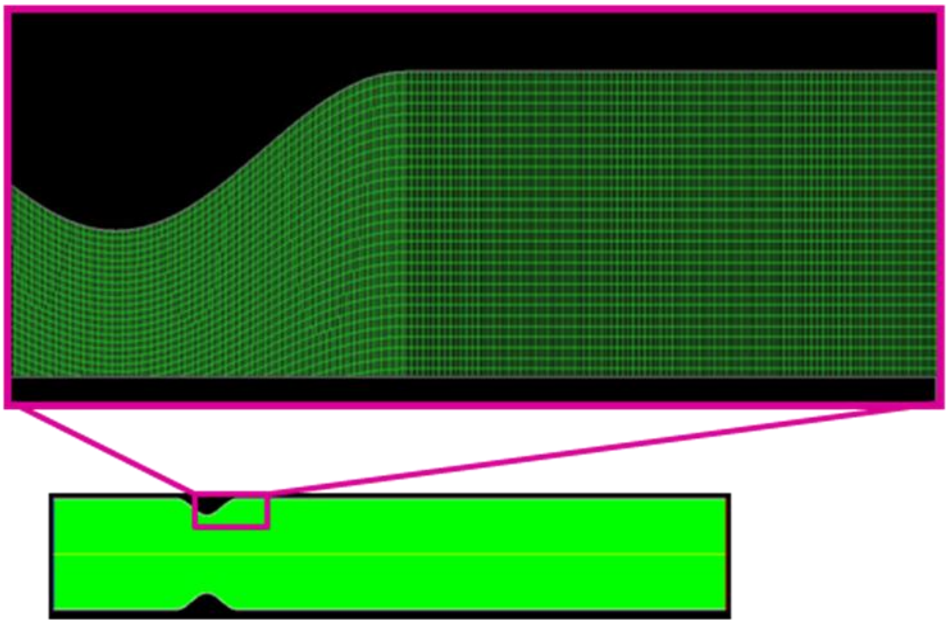

Figure 3.5 : Geometry of stenosis tube with 30% area reduction.

3.5.1 Simulation Validation

The stenosis tube is modelled as having diameter of 8mm with the length of 400mm and diameter of 6mm with the length of 201mm.It is calculated by using:

$$\frac{L}{D} = 0.06\ Re$$

Where: (17)

L= Entrance length ,mm

D = Diameter ,mm

Re = Reynolds number, $\frac{\rho D v}{\mu}$

In calculating the entrance length ,the Reynolds have to be determine first and after that ,the value is substituted in the equation (18) to obtain the value of entrance length.

3.6 SOLVER EXECUTION

In solver execution the inlet data will be executed .In this phase ,the mesh file is read and scale and then the material properties ,operating conditions and boundary conditions are defined .After that ,the convergence monitors is set up and finally ,wait for the software to compute and monitor the solution.

FLUENT needs the user to set up the numerical model .In this case ,the physical model used is laminar. Another important step is to define the material and their physical properties .In this study ,the energy equation is negligible.

Transport equation for laminar is given by :

Q = dV/dT

Solving this ,lead to :

$$Q = \frac{\Delta p\, d^2}{32 \mu L} \frac{\pi d^2}{4} = \frac{\Delta p}{L} \frac{\pi d^2}{128 \mu}$$

Then ,the viscous model used for Newtonian flow is given by :

$$\tau = \mu \frac{du}{dy}$$

In which :

τ is the shear stress exerted by the fluid ("drag") [Pa]

μ is the fluid viscosity - a constant of proportionality [Pa·s]

is the velocity gradient perpendicular to the direction of shear [s^{-1}]

At the current research state ,there is no single blood viscous model suit every flow condition .So ,several models has been proposed and three of them are investigated in this study which are Cross model[24],Power Law model[21], and Herschel-bulkley model[20].Cross model is used to simulate the shear thinning behaviour of blood Cross model is given by :

$$\eta = \eta_\infty + \frac{\eta_0 - \eta_\infty}{1+(C\dot{\gamma})^m}$$

Where :

η_0 is the zero shear viscosity.

η_∞ is the infinite shear viscosity.

m is the (cross) rate constant.

C is the cross time constant (or sometimes the consistency).

$\dot{\gamma}$ is the symmetric rate of deformation tensor.

Power law is used to describe the fluid behaviour across the range of shear rates in which the coefficients were fitted .Power law is given by :

$$\boldsymbol{\eta = \kappa\gamma^{n-1} e^{To/T}}$$

Where ;

η is viscosity.

κ consistency index.

,n is power law index.

T is reference temperature.

Then, Herschel-Bulkley model can be described as:

$$\boldsymbol{\tau = \tau o + k(\gamma)^n}$$

Where:

τ = shear stress.

$\tau_{0\,=}$ yield stress.

k = consistency.

γ = shear rate.

n = power law exponent.

The operating conditions used in this case are given in the table below.

1) Newtonian

Velocity (m/s)	**Density (kg/m^3)**	**Visocity (kg/m-s)**	**Gravity (m/s^2)**
0.11	1080	0.004	-9.81
0.25	1080	0.004	-9.81
0.32	1080	0.004	-9.81

Table 3.1 : Operating conditions of Newtonian fluid

2) non-Newtonian(Cross Model)

Velocity (m/s)	**Density (kg/m^3)**	**Gravity (m/s^2)**	**Power law index (n)**	**Zero shear viscosity (kg/m-s)**	**Time constant (s)**
0.11	1080	-9.81	0.285	0.056	1.007
0.25	1080	-9.81	0.285	0.056	1.007
0.32	1080	-9.81	0.285	0.056	1.007

Table 3.2 : Operating conditions of non-Newtonian fluid (Cross Model).

3) Non-Newtonian (Power Law)

Velocity (m/s)	**Density (kg/m^3)**	**Gravity (m/s^2)**	**Power law index (n)**	**Reference Temperature (K)**	**Minimum Viscosity limit (kg/m-s)**
0.11	1080	-9.81	0.4851	310	0.00125
0.25	1080	-9.81	0.4851	310	0.00125
0.32	1080	-9.81	0.4851	310	0.00125

Table 3.3 : Operating conditions of non-Newtonian fluid (Power Law).

4) Non-Newtonian (Herschel-Bulkley)

Velocity (m/s)	**Density (kg/m^3)**	**Gravity (m/s^2)**	**Power law index (n)**	**Consistency index (kg-s ^n-2/m)**	**Yield stress (Pa)**	**Yielding viscosity (kg/m-s)**
0.11	1080	-9.81	0.95	0.2073	0.00125	4
0.25	1080	-9.81	0.95	0.2073	0.00125	4
0.32	1080	-9.81	0.95	0.2073	0.00125	4

Table 3. 4 : Operating conditions of non-Newtonian fluid (Herschel-bulkley).

After setting up the solver settings and the numerical model, the computation of the model is executed by iterations .The discrete domain in which the grid is solved by the conservation equations until a converged solution is reached .A solution is said to be convergence when the overall mass, momentum, energy, and scalar balances are achieved ,the residual values have reached the specified tolerance and the overall mass ,heat ,species conservation is satisfied.

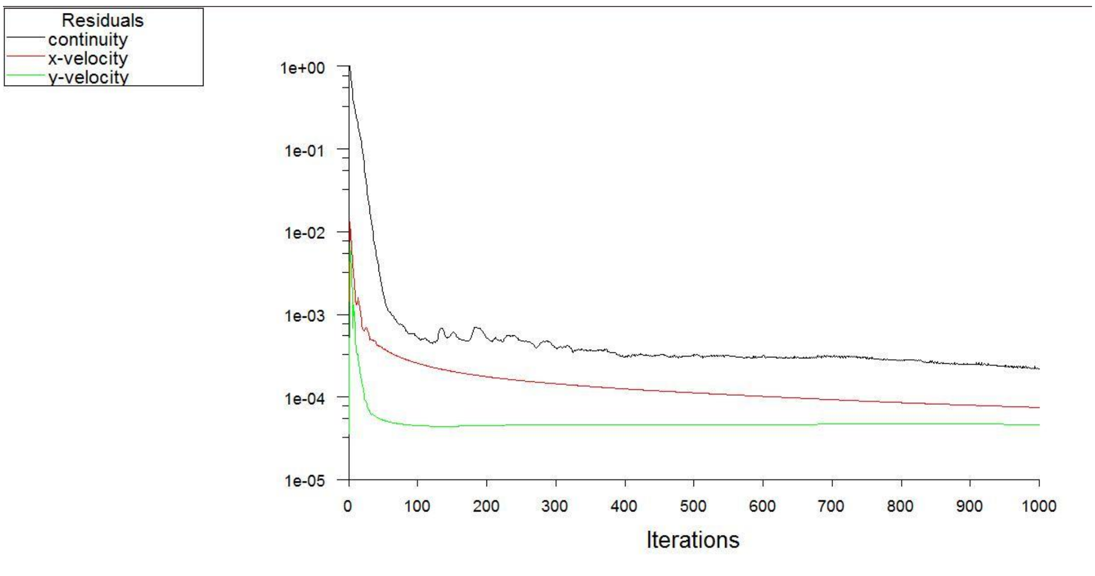

Figure 3.6 : Scaled residuals

A solution is converged when the changes in the solution variables from iteration to the next iterations are negligible .Residual as in Figure 15 provide a mechanism to monitor this trend.

3.4 GANTT CHART

The flow of project work is presented in Gantt chart below:

No	Detail/Week	1	2	3	4	5	6	7	Mid Semester Break	8	9	10	11	12	13	14
1	Project Work Continue															
2	FYP II Briefing															
3	Lab Briefing															
4	Submission of Progress Report 1															
5	Project Work Continue															
6	Professional Writing															
7	Technical Writing															
8	Submission of Progress Report 2															
9	Seminar															
10	Project Works continue															
11	Poster Exhibition															
12	Submission of Dissertation (Soft Bound)															
13	Oral Presentation															
14	Submission of Dissertation (Hard Bound)															

Suggested Milestone

Work Progress

CHAPTER 4

4.0 RESULTS AND DISCUSSIONS

4.1 EFFECT OF RHEOLOGICAL MODELS ON BLOOD FLOW IN HEALTHY ARTERY

The diagram below shows the effect of rheological models on blood flow in healthy artery .The results are presented in velocity vectors.

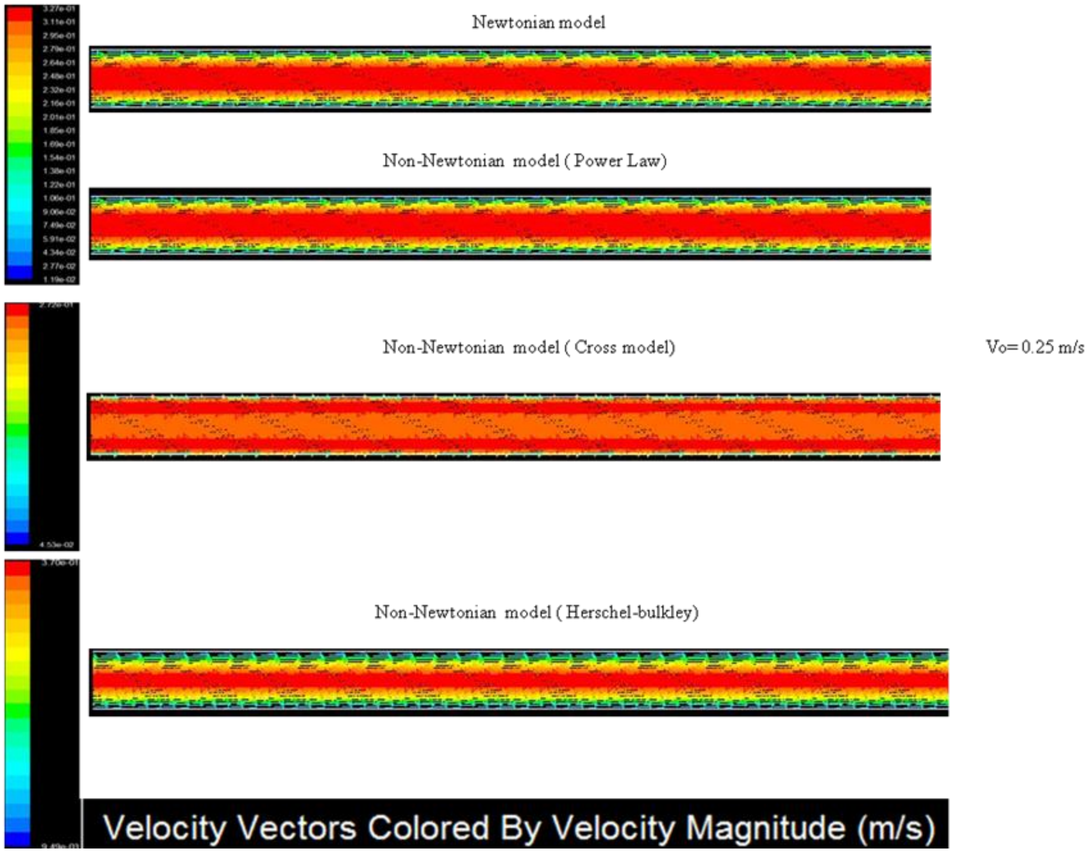

Figure 4.1 :Velocity Magnitude of blood

As the starting point,the flow of blood in healthy artery (straight tube) for all models are observed at the same initial velocity of 0.25 m/s at point 200mm to. 350mm.Based on the Figure 4.1,for the newtonian model,the blood moving with highest velocity as it is moving towards the end and the flow is also fully developed.Besides that,in the laminar flow there is no mixing between the layers of blood and velocity does not pulsate.Hence,resulting in fully developed flow.Meanwhile ,as for the non-Newtonian models, the blood achieved fully developed flow earlier compared to Newtonian model .This is due to the blood viscosity varying depending on the velocity of the blood.

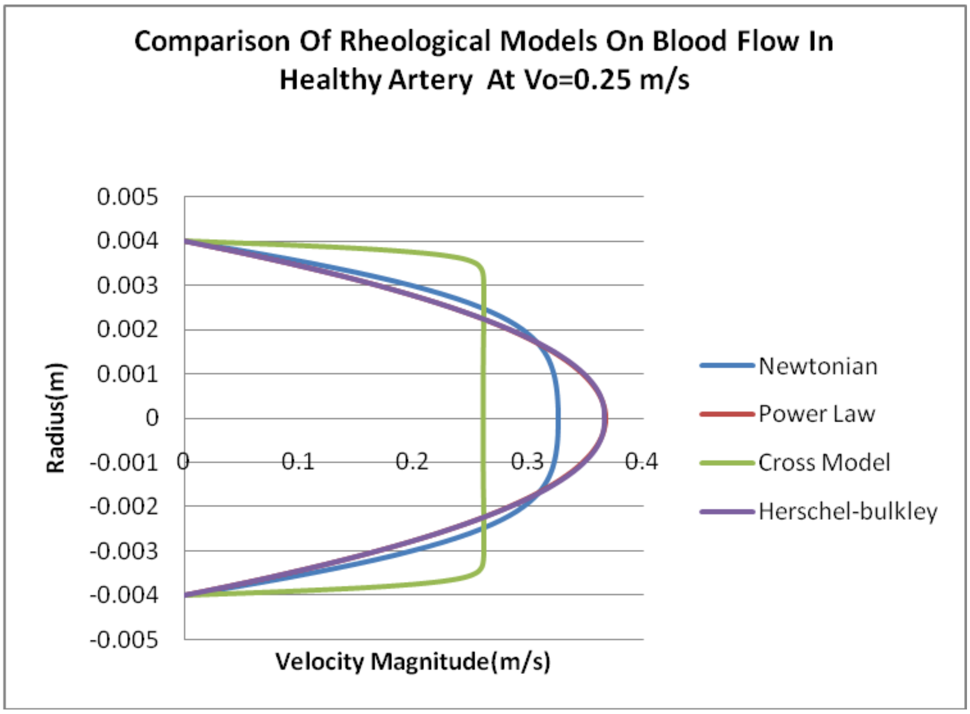

Figure 4.2 : Comparison Of Rheological Models On Blood Flow In Healthy Artery At Vo=0.25 m/s

The graph above describes the comparison between the Newtonian model with three models of non-Newtonian models .Based on the graph ,at the point of 350 mm ,non-Newtonian models (Power law and Herschel-bulkley) have higher velocity magnitude (0.37 m/s) compared to Newtonian model(0.33m/s).Besides that ,the non-Newtonian models achieves fully developed flow earlier compared to Newtonian model .When blood behaves as non-Newtonian fluid ,the results indicates that the non-Newtonian effect weaken the wall shear stress distribution.

4.2 EFFECT OF RHEOLOGICAL MODELS ON BLOOD FLOW IN DIESEASED ARTERY

The diagram below shows the effect of rheological models on blood flow in diseased artery .The results are presented in velocity vectors.

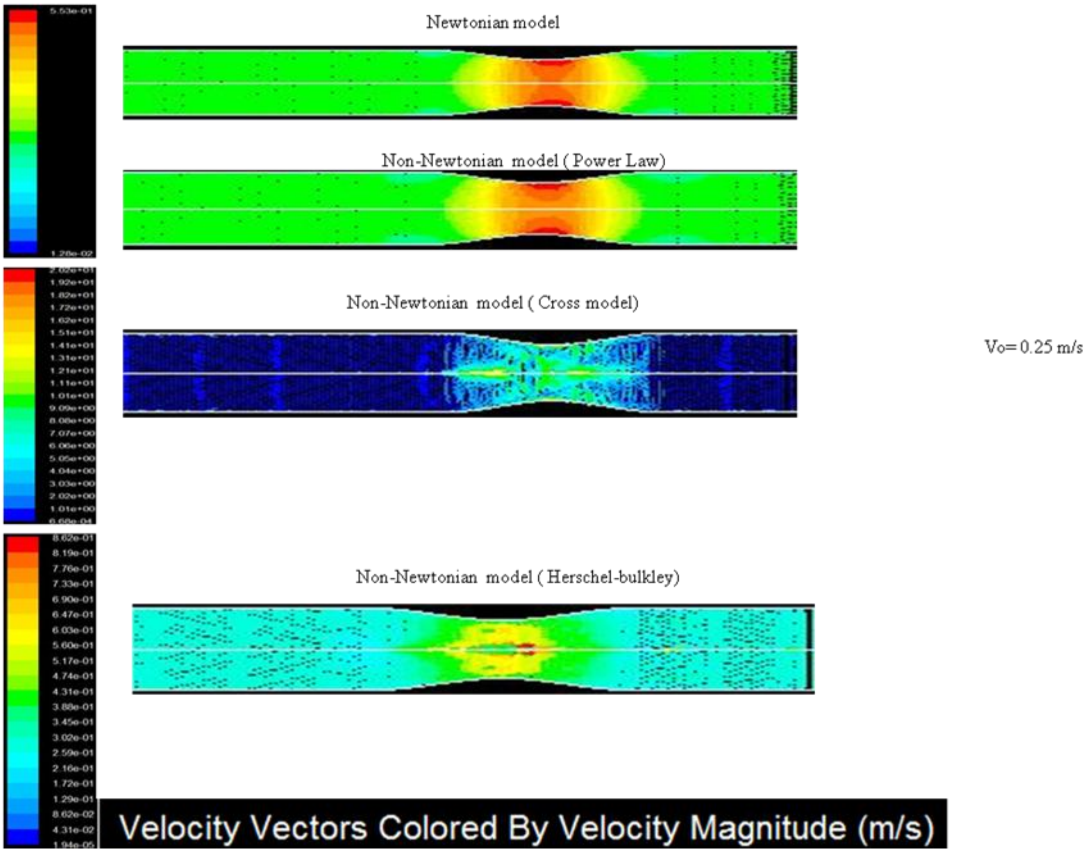

Figure 4.3 :Velocity Magnitude of blood

Figure 4.3 shows the velocity magnitude of blood flow in diseased artery (stenosis tube) at initial velocity of 0.25 m/s at point -8mm to 16 mm.Based on the figure 20 ,for the blood modelled as Newtonian fluid,the blood was at its maximum velocity as it passed through the throat since the blood experiences pressure reduction as the blood flows from higher diameter to lower diameter Thus ,the blood velocity will increase in order to satisfy the equation of continuity .Besides that, the blood also experiences recirculation region and the flow is more stable for the Newtonian model .For the blood is modelled as non-Newtonian fluid ,it is observed that the blood experiences more recirculation region but smaller in size. Besides that ,slower flow is observed since the flow is not well organized.

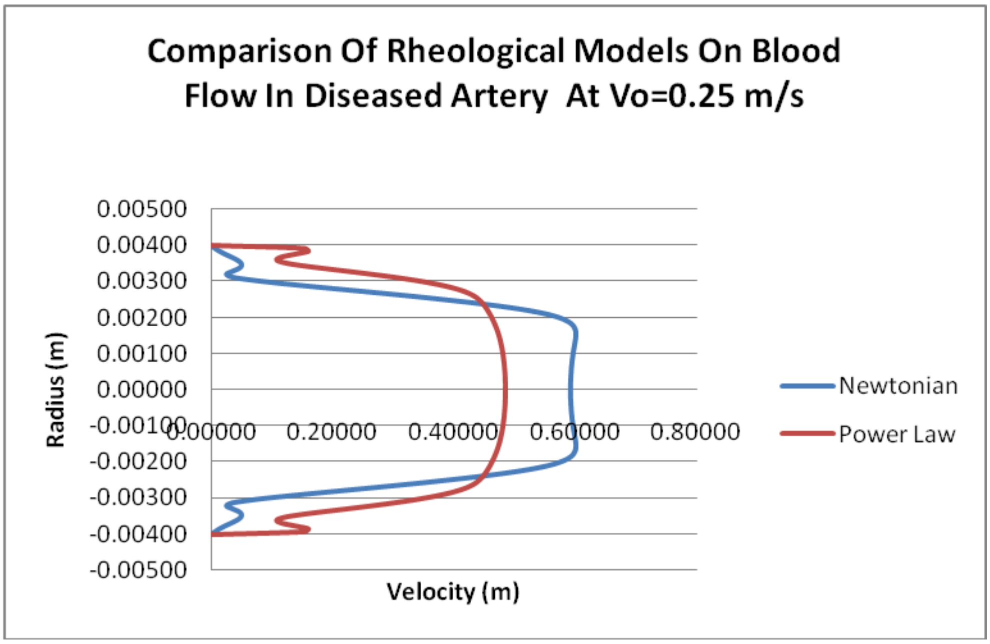

Figure 4.4 : Comparison Of Rheological Models On Blood Flow In Diseased Artery At Vo=0.25 m/s

The graph above describe the comparison between the Newtonian model with non-Newtonian model of power law at initial velocity of 0.25 m/s at point of 8mm to 16 mm. Based ,on the graph as the blood modelled as Newtonian model ,the blood have higher velocity(0.6m/s) compared to the blood modelled as non-Newtonian model (0.5m/s) but the flow still does not fully developed compared to non-Newtonian where the flow is fully developed flow .So ,it can be concluded that blood achieved fully developed earlier when it is modelled as non-Newtonian model .The graph also shows the recirculation region where as the blood is modelled as the non-Newtonian model ,blood experiences more recirculation region compared to Newtonian model but smaller in size.

4.3 COMPARISON OF BLOOD FLOW IN HEALTHY ARTERY AND DISEASED ARTERY.

4.3.1 Newtonian Model

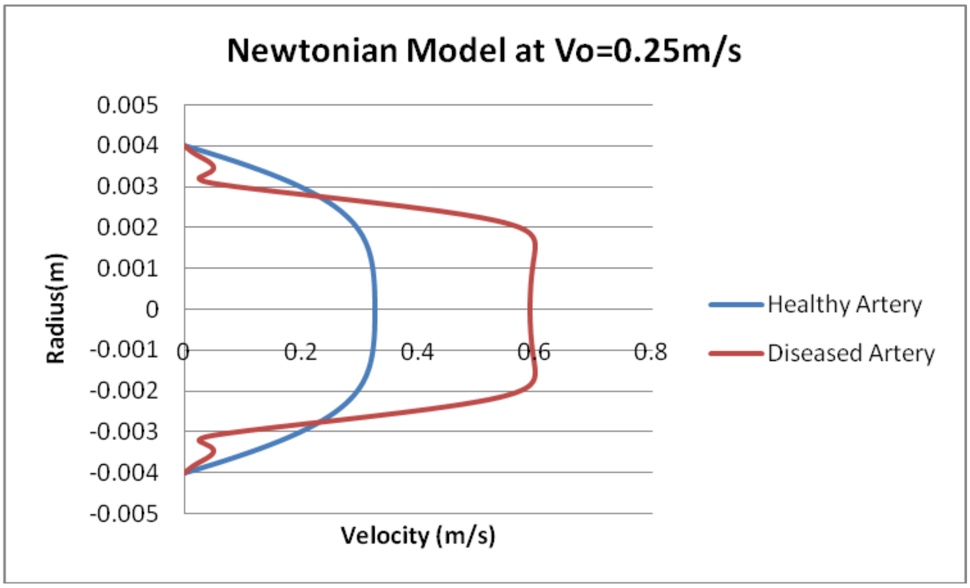

Figure 4.5: Comparison Of Blood Flow In Healthy and Diseased Artery Of Newtonian Model At Vo=0.25 m/s

The graph shows the comparison of blood flow behaviour in healthy artery (point 200 mm to 350mm) and diseased artery (point -8mm to 16 mm) where the blood is modelled as Newtonian fluid. Based on the graph above ,blood have higher velocity(0.6m/s) as it flows through diseased artery since blood experiences pressure reduction as the blood flows from higher diameter (normal artery) to lower diameter(diseased artery).Meanwhile ,for blood flows through healthy artery blood experiences highest velocity(0.33m/s) at the centre of the artery and velocity distribution is much more uniform across the artery .Based on the graph ,there is recirculation region as blood flows through the diseased artery since blood experiences diameter reduction where the artery size became narrower.

4.3.2 Non-newtonian Model (Power Law)

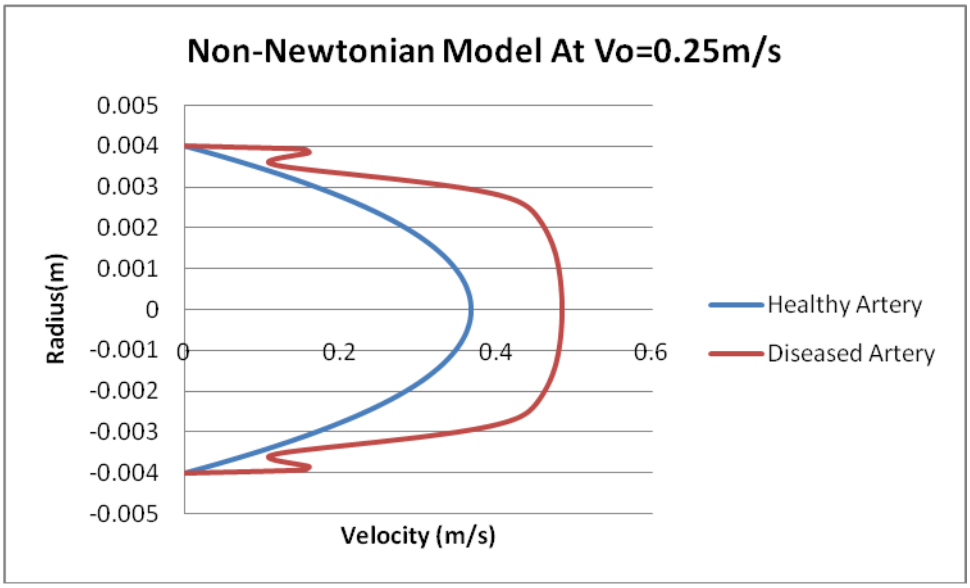

Figure 4.6 : Comparison Of Blood Flow In Healthy and Diseased Artery Of non-Newtonian Model At Vo=0.25 m/s

The graph shows the comparison of blood flow in healthy artery(at point 200mm to 350mm) and diseased artery(at point -8mm to 16mm) as blood is modelled as non-Newtonian fluid. Based on the graph ,as blood flows through the diseased artery ,blood experiences higher velocity (0.5m/s) since its experience pressure reduction as blood flows from higher diameter (normal) to lower diameter (diseased) and the flow of blood is also not fully developed .Besides that ,as the blood flows through the diseased artery blood also experiences more recirculation region but smaller in size. Meanwhile ,as blood flows through healthy artery ,blood experiences lower velocity (0.38m/s) compared to diseased artery .As blood flows through healthy artery ,fully developed flow also can be observed.

4.4 EFFECT OF VELOCITY ON BLOOD FLOW IN DISEASED ARTERY

The diagrams below show the effect of velocity on blood flow in diseased artery when blood is modelled as Newtonian model and non-Newtonian model of Power Law.

4.4.1 Newtonian Model

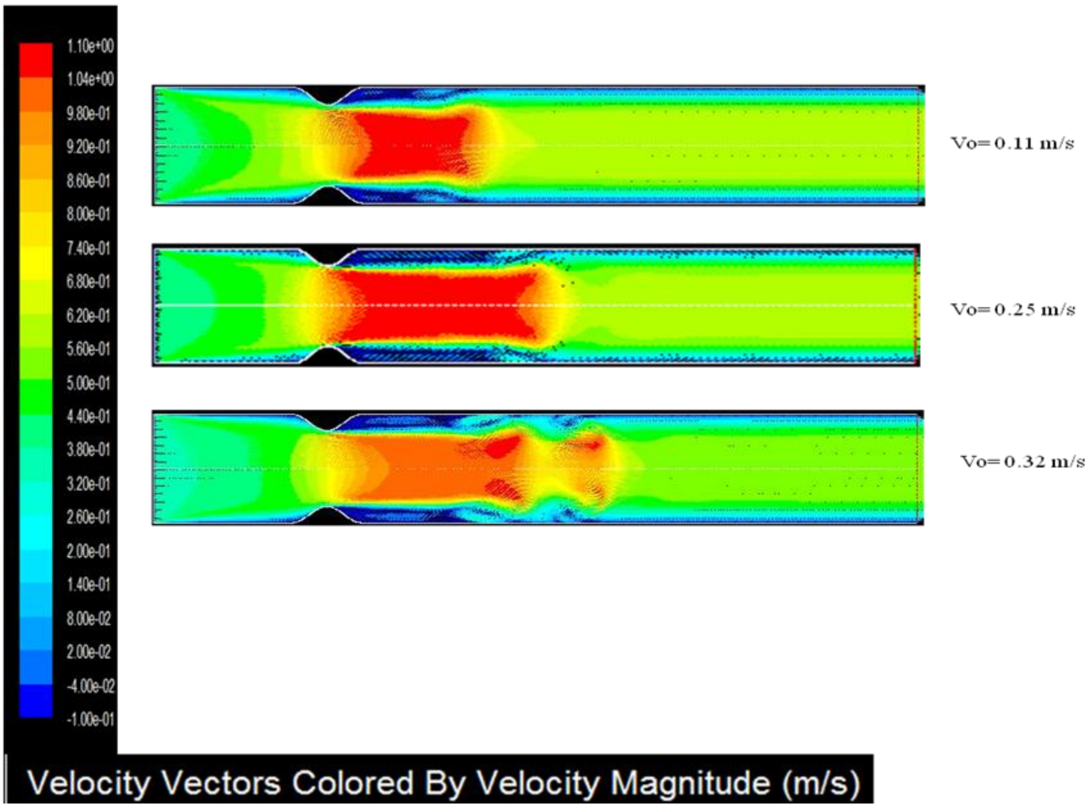

Figure 4.7(a) :Effect Velocity On Blood Flow In Diseased Artery Of Newtonian Model(Vector Plot)

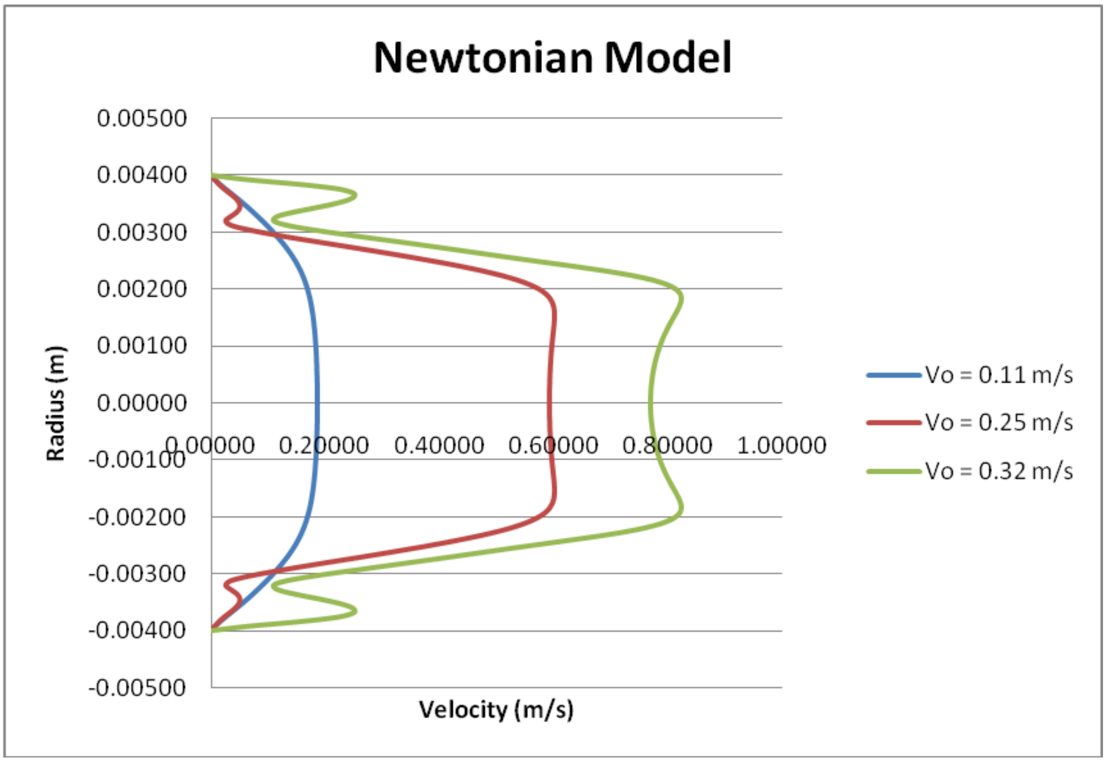

Figure 4.7(b) :Effect Velocity On Blood Flow In Diseased Artery Of Newtonian Model(graph)

The figures show the effect of velocity on blood flow in diseased artery as blood modelled as Newtonian fluid at point -8mm to 16 mm .Based on figures above, regardless of initial velocity the blood still experience highest velocity at the throat due to pressure reduction as it flows from larger diameter to lower diameter but as the initial velocity increases ,the velocity of the blood also increases .From the figures above ,it is observed that the blood with velocity initial of 0.32 m/s have the highest velocity magnitude(0.8m/s) compared to all but the flow is not fully developed. Whereas, as the blood with initial velocity of 0.11 m/s (lowest) have the lowest velocity (0.2m.s) magnitude but the flow is fully developed .It cab also be observed that ,there is more recirculation region as the initial velocity increases.

4.4.1 Non – Newtonian Model (Power Law)

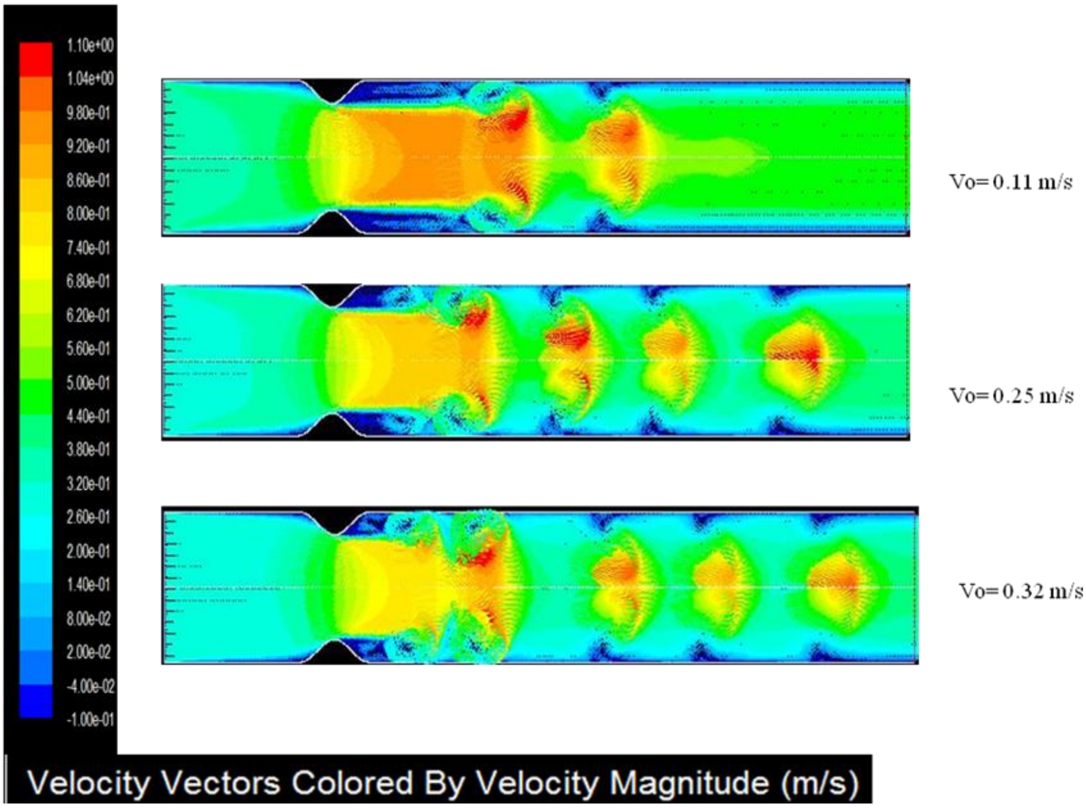

Figure 4.8(a) :Effect Velocity On Blood Flow In Diseased Artery Of non-Newtonian Model(Vector plot)

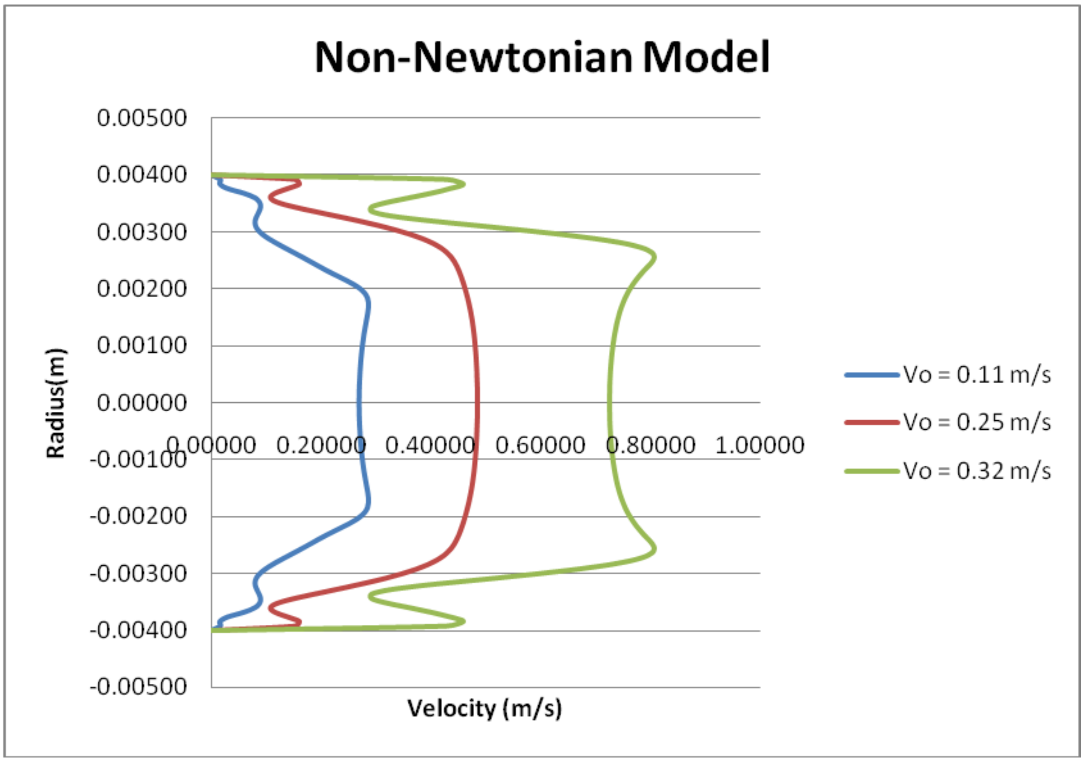

Figure 4.8(b) :Effect Velocity On Blood Flow In Diseased Artery Of non-Newtonian Model(graph)

The figures show the effect of velocity on blood flow behaviour in diseased artery (at point -8mm to 16mm) when blood is modelled as non-Newtonian fluid. Based on figures above ,regardless of initial velocity the blood still experience highest velocity at the throat due to pressure reduction as it flows from larger diameter to lower diameter but as the initial velocity increases ,the velocity of the blood also increases .From the figures above it is observed that the blood with velocity initial of 0.32 m/s have the highest velocity compared to all but the flow is not fully developed whereas (0.8m/s),the blood with initial velocity of 0.11 m/s (lowest) have the lowest velocity(0.3m/s).Based on the figures above ,it is also observed that as the initial velocity increases the recirculation region also increases but smaller in size since blood behaves as non-Newtonian fluid .Besides that, slower flow is observed as the initial velocity increases as the flow is not fully developed.

4.5 EFFECT OF ARTERY SIZE ON BLOOD FLOW IN DISEASED ARTERY

The diagrams below show the effect of artery size on blood flow in diseased artery when blood is modelled as Newtonian and non-Newtonian models (Power Law ,Cross model and Herschel-bulkley).

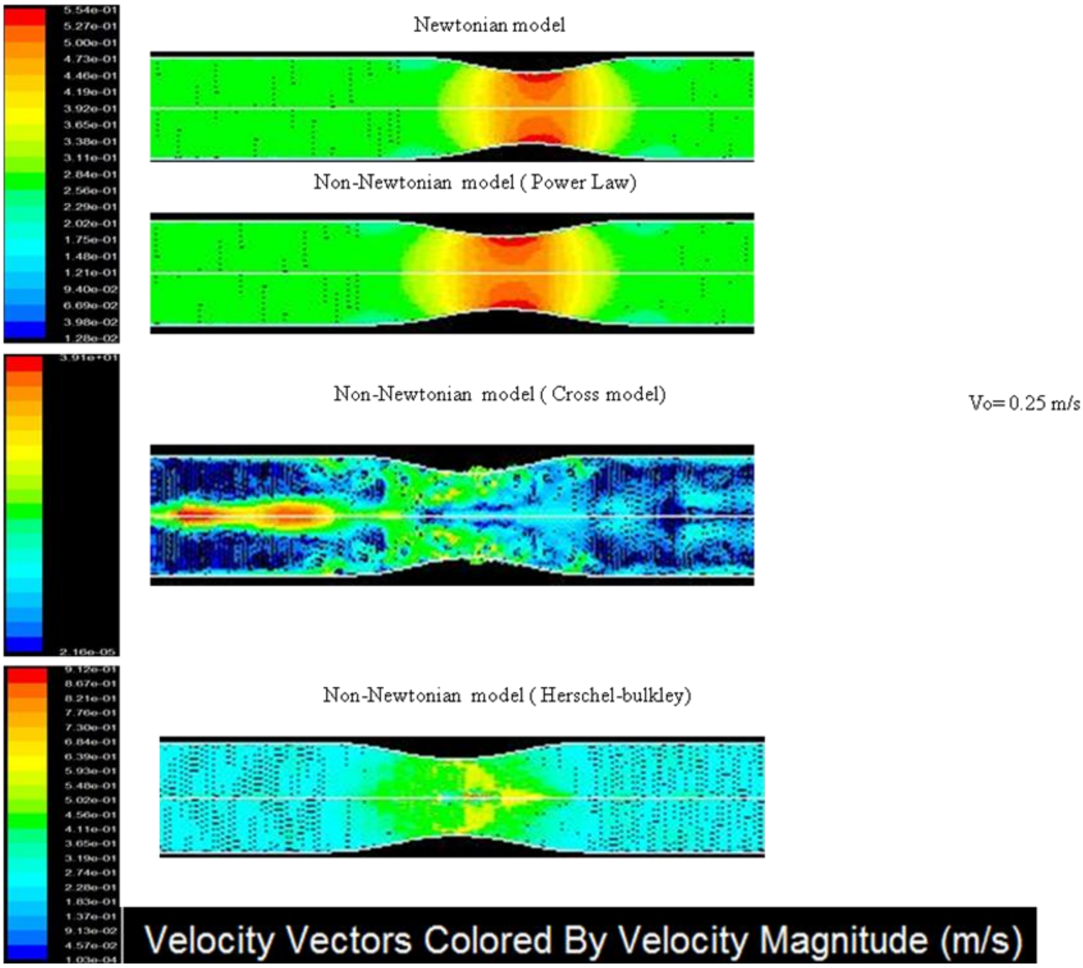

Figure 4.9(a) :Effect of Artery Size On Blood Flow In Diseased Artery (Vector plot)

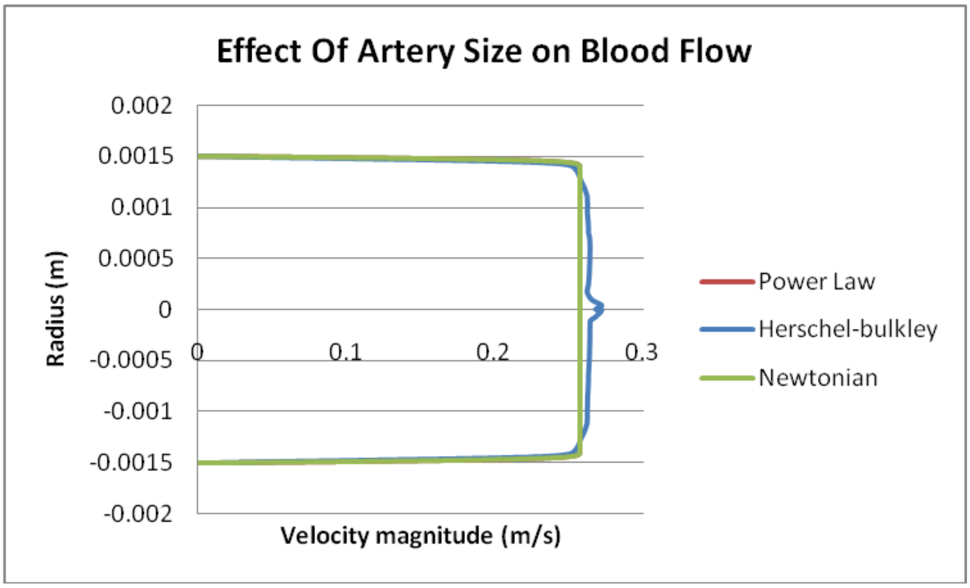

Figure 4.9(b) :Effect of Artery Size On Blood Flow In Diseased Artery (graph plot)

The figures show the effect of artery size on blood flow in diseased artery .Based on the both figures, as the blood flow through larger diameter(8mm) of artery to smaller diameter of artery (3mm),blood experiences increase in velocity as the blood experiences pressure reduction .As blood flows from larger diameter to smaller diameter ,blood also experiences recirculation region where more in quantity but smaller in size.

CHAPTER 5

5.0 CONCLUSION

As the conclusion, the flow behaviour in diseased artery is not the same as in the healthy artery in which at the throat, the diseased artery is having the maximum velocity. Besides that, slower flow is observed in non-Newtonian since the flow is not stabilized and there is more recirculating region but smaller in size. As the initial velocity increases, it is observed there is more recirculating region but the size is different for Newtonian model and non-Newtonian model in which non-Newtonian experiences smaller size since the flow is not fully developed. Besides that ,as the initial velocity increases, the velocity magnitude also increases.Then,considerations of non-Newtonian is important in image-guided modelling to model the blood flow behavior.From the results obtained, it can also be concluded that as the blood flows from larger artery to smaller artery, blood experiences changes in velocity and pressure in which the velocity increases as the blood flows through the smaller artery and the pressure decreases as blood flows through it

5.1 RECOMMENDATION

There is still further improvement of the project work that can be done in order to obtain more accurate results.For this simulation ,the simulation is already completed but the result is a bit deviate from what it is expected to be. In order to achieved more accurate results, it can be done by refining the geometry created since the geometry maybe a bit coarse. Other improvement that can be done is by changing the diameter of artery and then, comparing the larger diameter with the smaller one.

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