MOHAMAD AMIRY ERFI BIN ABD AZIZ

B.ENG. (HONS) CHEMICAL ENGINEERING

THE EFFECT OF NON-NEWTONIAN PROPERTIES OF BLOOD FLOWING IN HUMAN ARETRY

MOHAMAD AMIRY ERFI BIN ABD AZIZ

CHEMICAL ENGINEERING

UNIVERSITI TEKNOLOGI PETRONAS

MAY 2013

The Effect of Non-Newtonian Properties of Blood Flowing in Human Artery

By

Mohamad Amiry Erfi bin Abd Aziz (12654)

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Chemical Engineering)

Supervisor: Dr. Anis Suhaila bt Shuib

MAY 2013

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

The Effect of Non-Newtonian Properties of Blood Flowing in Human Artery

By

Mohamad Amiry Erfi bin Abd Aziz (12654)

A project dissertation submitted to
Chemical Engineering Program
Universiti Teknologi PETRONAS
in partial fulfillment of the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

Approved by:

____

Dr. Anis Suhaila bt Shuib

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
AUGUST 2013

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mohamad Amiry Erfi bin Abd Aziz

ABSTRACT

This project is about the effect of non-Newtonian properties of blood flowing in the human artery. The human artery focused in this project is the brain artery and the disease under investigation is the cerebral aneurysm.

A cerebral aneurysm occurs as a result of the bulging of artery in human brain. A severed aneurysm will cause rupture and hence internal bleeding to the brain which to some extend will be fatal. The main contribution factor to the rupture is predicted to be caused by the Wall Shear Stress (WSS).

Computational Fluid Dynamics (CFD) is used to predict the WSS and the non-Newtonian properties of blood is studied by using Power law model, Herschel-Bulkley model, Carreau model and Cross model.

ACKNOWLEDGEMENT

First and foremost I would like to thank God for His blessing that helped me in completing this final year project. I would also like to express my gratitude to Dr. Anis Suhaila Shuib, Chemical Engineering Department, Universiti Teknologi PETRONAS for her supervision and guidance throughout the two semesters.

Not to forget our Final Year Project Coordinators, for their contributions in giving the students with guidance and assistance to complete their projects. They put high effort in ensuring that our projects are completed according to the schedule. Last but not least I would like to thank Mr. Yunus, a postgraduate student who have technically assisted me in the process of completing my final year project.

Again, I would like to thank all the Universiti Teknologi PETRONAS's lecturers, staffs and students for their kindness in helping students to make this final year project a success.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF GRAPHS

CHAPTER 1

PROJECT BACKGROUND

1.1 BACKGROUND STUDY

1.1.1 Cardiovascular Disease (CVD)

Cardiovascular disease (CVD) or also known as the heart disease is a category of diseases that involves the heart or the blood vessels (arteries, capillaries and veins). CVD is caused by the unhealthy lifestyles which include unhealthy diet, rare physical exercise and also comes from the intake of alcohol and tobacco. As quoted from World Health Organization (WHO), there are several types of CVD which are (WHO, 2012):

- Coronary heart diseases – disease of the blood vessel supplying to the heart muscle.
- Cerebrovascular disease – disease of the blood vessel supplying to the brain.
- Peripheral arterial disease – disease of the blood vessel supplying to the arms and legs.
- Rheumatic heart disease - damage to the heart muscle and heart valves from the rheumatic fever, caused by streptococcal disease.
- Congenital heart disease - malformation of the heart structure existing at birth.
- Deep vein thrombosis and pulmonary embolism – blood clots in the leg veins, which can dislodge and move to the heart and lungs.

1.1.2 Heart Attack/Stroke

The most common effects of acute CVD are heart attacks and strokes which to some extend can cause sudden death. Heart attacks occur due to blood clots that develop in one of the blood vessels that lead to the heart muscle (coronary arteries). If the clotting is big enough, it can stop the blood supply to the heart and eventually causes death. The symptoms of heart attacks are chest discomfort, mild pain; coughing; crushing chest pain; dizziness; shortness of breath; nausea; restlessness; vomiting (Christian, 2009).

On the other hand, strokes happen as a result of an obstruction in the blood flow and also the rupture of any arteries that goes to the brain. In other words, the brain dies because of lack of oxygen supply. Minor strokes will cause weakness in joints such as the arms and legs whereas the major strokes will cause paralysis or even death (Crosta, 2009).

1.1.3 Global Causes of All Deaths 2011

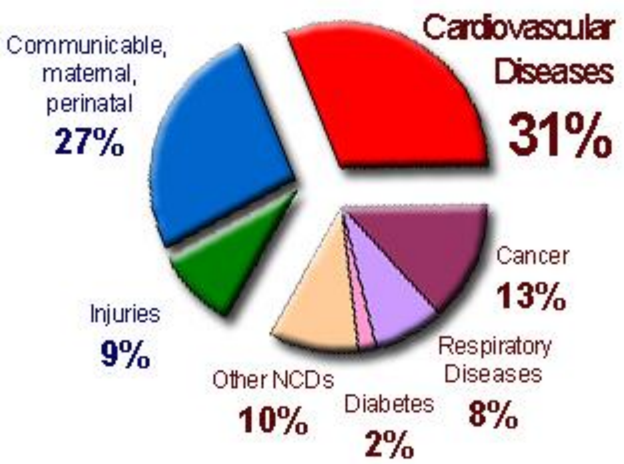


Figure 1.1: Statistics of Global Causes of All Deaths 2011

The Figure above shows the statistics of global causes of all deaths in 2011 (Heart News Link, 2011). This statistics was provided by the World Health Organization (WHO). From the Figure 1.1 above, it can be seen that CVD contributed to the highest amount of deaths worldwide compared to the other diseases.

According to the world death statistics, CVD weighs the highest cause of death caused by a disease compared to the other diseases. There were about 31% of people worldwide who died because of CVD. This is the highest rate of death cause globally.

It is expected that by 2030, almost 25 million people will die of CVD (WHO, 2012). All in all it can be said that the number of people who suffers from CVD will increase from time to time will which indirectly also triggers the death rate to increase as well. The main reason behind this is because people worldwide today live with unhealthy lifestyles and they take their body health for granted.

1.1.4 Cerebral Aneurysm

A cerebral aneurysm is a bulging, weak area in the wall of an artery that supplies blood to the brain. An artery is the blood vessel which functions to carry the oxygen-rich blood to the heart and also to the other parts of the body. An aneurysm is a weak area in the wall of a blood vessel that causes the blood vessel to bulge or balloon out. Cerebral aneurysm is present without any symptoms (Yale Medical Group, 2013).

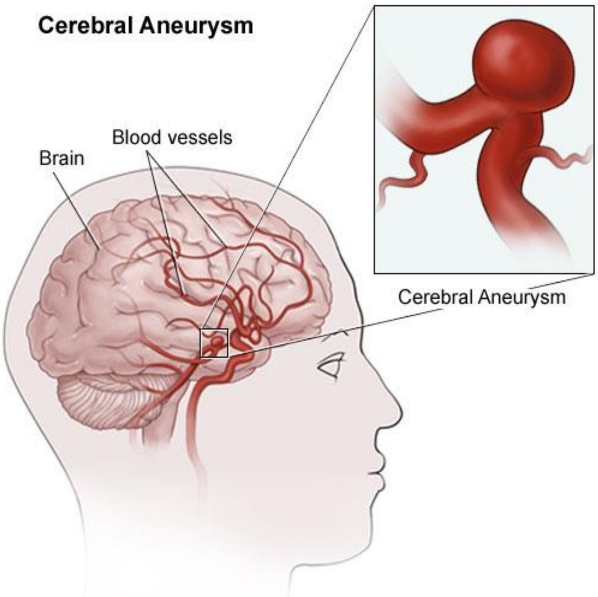


Figure 1.2: The Illustrated View of Cerebral Aneurysm

A normal artery wall is made up of three layers. However the aneurysm wall consists of only two layers due to the absence of the muscular layer of the artery wall which makes the wall thin compared to the normal artery wall. The most common type of cerebral aneurysm is called a berry aneurysm because it looks like a 'berry' with a narrow stem. The other two types of brain aneurysm are fusiform aneurysm and dissecting aneurysm. A fusiform aneurysm bulges out on all sides and forming a dilated artery. Fusiform aneurysms are often associated with atherosclerosis.

A dissecting aneurysm happens as a result from a tear along the length of the artery in the inner layer of the artery wall, which causes blood to leak in between the layers of the wall. This may cause a ballooning out on one side of the artery wall, and subsequently obstruct blood flow through the artery. Dissecting aneurysms usually occur from traumatic injury, but they can also happen spontaneously. The rupturing of the brain aneurysm will cause death. Brain aneurysm can be treated by two ways which are first, clipping whereby a tiny metal clip is clipped on the neck of the aneurysm to stop blood flow to it and the second method is coiling in which coils of wire is coiled up inside the aneurysm, disrupts the blood flow and causes blood to clot. Blood clotting will seal of the aneurysm from the artery (BNSHC, 2011).

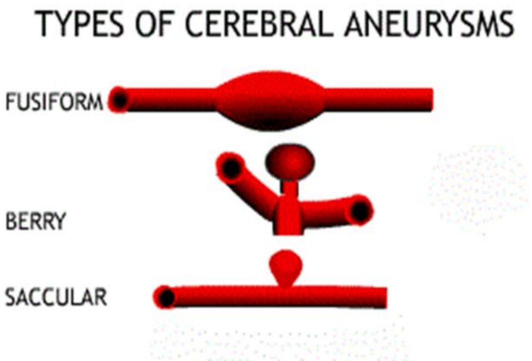


Figure 1.3: The Types of Cerebral Aneurysm

1.1.5 Wall Shear Stress (WSS) Effects on Cerebral Artery

Wall shear stress (WSS) is one of the main infective factors in the development of cerebral aneurysms. The rupturing of cerebral aneurysm occurs when the arteries wall tension exceeds the mechanical strength of the wall. In this case, the hemodynamic such as the blood pressure and WSS affects the rupture. High blood pressure and high WSS may directly influence wall rupture but low blood pressure and low WSS contributes to aneurysm wall weakening. A research to study a nonlinear bio mathematical model for study the intracranial aneurysms was carried out. The result shows that a sudden change in blood pressure and turbulent flow inside aneurysm affect the rupture of aneurysm (Poltem, 2012). The wall shear stress acts directly on the endothelium cell or a growth of mechanism of an aneurysm. Furthermore, high wall shear stress magnitude or temporal variation of wall shear stress might mechanically damage the inner wall artery (Crompton, 2008). A large blood pressure along a wall effects on wall shear stress in an aneurysm. Therefore, hypertension may affect the aneurysm rupture (Choong, Srinivas, 2011).

1.2 Problem Statement

Rheology is the study of the flow behavior of matter in fluid. The Newtonian properties and the Non-Newtonian properties of liquid is part of the rheological properties of any fluid. Blood is a type of fluid therefore blood exhibits both the characteristics of Newtonian and non-Newtonian properties depending on the diameter of the blood vessel and the shear rate.

According to the Navier-Stokes equation, viscosity place an important role in predicting fluid flow and the viscosity of a blood will affect the shear rate. If a patient is diagnoses to suffer from a bulging artery, it is very important to study the characteristics of the blood's behaviour through the artery and what is the shear stress acting on it. The Wall Shear Stress (WSS) has been investigated as a bio method for predicting artery rupture. Hence, the relation between the WSS and the rupture of artery is also in question. Since the WSS is a function of viscosity, it is important to consider the non-Newtonian properties of blood.

1.3 Objective

The objectives of this research are:

- To investigate on the effect of non-Newtonian properties of blood on artery wall shear stress.
- To compare the velocity profile of blood flow in healthy and aneurysmal artery.

1.4 Scope of Study

In this study, the main subjects under investigation is:

i. A Computational Fluid Dynamics (CFD) method using Ansys FLUENT will be used to study the flow behavior.

1.5 Feasibility of Project within the Scope and Time Frame

This project is feasible within the scope identified and the time allocated. The first half of this project is merely on reviewing literature reviews and getting the basic ideas for the proposed title. Next part would be the study on the method to solve the problem which is by using Computational Fluid Dynamics (CFD). The second half of the project is more likely to focus on getting the project running. The models will be tested in a software called ANSYS Fluent whereby the results are gathered and compared to each other.

In terms of scope of study, the project is feasible to be carried out in UTP as it only requires a simulation software and the software is available in the computer lab. The scope of study in this project are also quite similar to some other researches that have been carried out by other researchers. So, it is relevant and can be used to compare directly with other literature readings.

As such, this research project is feasible within the time frame and the scope of study. Strategic planning on the execution is very important in order for this research project to be completed on time and successfully.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Blood Flow Equation

The blood flow can be predicted using the Navier-Stokes equation. The Navier-Stokes equations are the basic governing equations for a viscous, heat conducting fluid. It is a vector equation obtained by applying Newton's Law of Motion to a fluid element and is also called the momentum equation. It is supplemented by the mass conservation equation, also called continuity equation and the energy equation (Wikipedia, 2013).

The derivation of the Navier–Stokes starts with the application of Newton's second law which is the conservation of momentum. The general equation is:

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \nabla \cdot \mathbf{T} + \mathbf{f}. \qquad (1)$$

Where v is the flow velocity, ρ is the fluid density, p is the pressure, $\mathbf{T}$ is the stress tensor, and f represents body forces (per unit volume) acting on the fluid.

Incompressible Flow of Newtonian Fluid

$$\overbrace{\rho\Big(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\text{Unsteady acceleration}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\text{Convective acceleration}}\Big)}^{\text{Inertia (per volume)}} = \overbrace{\underbrace{-\nabla p}_{\text{Pressure gradient}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}}}^{\text{Divergence of stress}} + \underbrace{\mathbf{f}}_{\text{Other body forces}}. \qquad (2)$$

In this case, f represents other body forces (forces per unit volume), such as gravity or centrifugal force. The shear stress term $\nabla \mathbf{T}$ becomes the useful quantity $\mu\nabla^2\mathbf{v}$ when the fluid is assumed incompressible, homogeneous and Newtonian, where μ is the constant dynamic viscosity. The convective acceleration is an acceleration caused by a possibly steady change in velocity over position, for example the speeding up of fluid entering a converging nozzle.

As for the non-Newtonian fluid, the parameter that varies is the μ where it is the dynamic viscosity because in non-Newtonian fluid, the viscosity is not constant. Therefore, the main parameter being investigated for non-Newtonian properties of blood is the viscosity.

2.2 The Human Blood

An average adult has about five litres of blood in his/her body. The blood flows in their vessels, providing the needed elements for the body and also removing any unwanted waste from it. A human will not survive without sufficient amount of blood supply (Franklin Institute, 2013).

Major Functions of Blood

The fact is blood is the fluid of life, without blood, human will not survive. Blood play major roles in human body which are transporting oxygen from the lungs to body tissue and carbon dioxide from body tissue to the lungs. Blood also transports nourishment from digestion and hormones from glands throughout the body. Besides that, blood transports disease fighting substances to the tissue and waste to the kidneys (Franklin Institute, 2013).

Compositions of Blood

Blood contains three formed elements and plasma. The three formed elements are the red blood cells, white blood cells and the platelets.

The red blood cell (RBC) or also known as Erythrocytes constitute 45% of blood by volume. The RBC is made up of haemoglobin which makes the blood red in colour. RBC is produced in the bone marrow and they have a life cycle of 100-120 days. Mature RBCs are biconcave and flexible, lacking cell nucleus and organelles. Its main function is to supply blood to the tissues.

The white blood cell (WBC) or also known as the leukocytes and make up of 1% from the total blood. Leukocytes are cells of the immune system that provide protection to the body from foreign particles and infectious diseases.

The platelets are also known as the thrombocytes. The main function of platelets is to promote blood clotting or blood coagulation. If a person has a low count of platelets, he/she will be hard to recover from any bleedings (Franklin Institute, 2013).

2.3 The Viscosity of Blood

Viscosity is used to describe the rheology of blood. It is the measure of resistance to flow exerted by the fluid. Blood viscosity is a measure of the resistance of blood to flow, which is being deformed by either shear or extensional strain. Viscosity is given by the ratio of the force exerted to move the fluid (shear stress) to the velocity gradient of the fluid.

$$\tau = -\mu \frac{\delta \nu}{\delta \gamma} = -\mu \gamma \qquad (3)$$

Where: τ is the shear stress

μ is the dynamic viscosity

$\frac{\delta \upsilon}{\delta \gamma}$ is the dynamic viscosity

2.4 Rheology of Blood

All fluid resist to a greater or lower extent which attempt to alter their shape and this resistance to flow is called the fluid's viscosity. As the layers of fluid move parallel to one another at different rates, a velocity gradient forms between these layers and is known as the shear rate. The force required to produce this velocity gradient is the shear stress and is measured in newton per square metre (Nm^2) (Stuart, Kenny, 1980).

Fluids such as plasma and most oils exhibit a linear relationship between shear stress and shear rate, hence showing Newtonian behaviour, and the viscosity remains constant. A Non-Newtonian fluid is one in which the viscosity depends on shear stress (Merrill, 1969). The human blood as a whole behaves as a non-Newtonian fluid in that viscosity increases exponentially at the low shear rates that characterize venous flow. This increase is due to the larger molecular weight plasma proteins which overcome the zeta potential between erythrocytes and form rouleaux whereby these large cellular aggregates cause a disproportionate increase in viscosity. Rouleaux formation increases the viscosity of blood. At near zero shear rates secondary aggregation of rouleaux occurs leading to the formation of a rouleaux network. At high shear rates these rouleaux segregate and RBC align with the flow. At even higher shear rate RBC deform and thus decreasing viscosity further (O'Callaghan, 2005).

Blood viscosity also depends on temperature, on the presence of platelets and on the presence of white blood cells (Johnston, 2004). Due to variation of viscosity, the definition of Reynolds Number is difficult and the shear thinning behaviour of blood is expected to lead to a lower viscosity near the wall boundaries. With increase in Re number, the local shear rates of the flow increase and subsequently leads to a decrease of viscosity (Bernsdof, 2009).

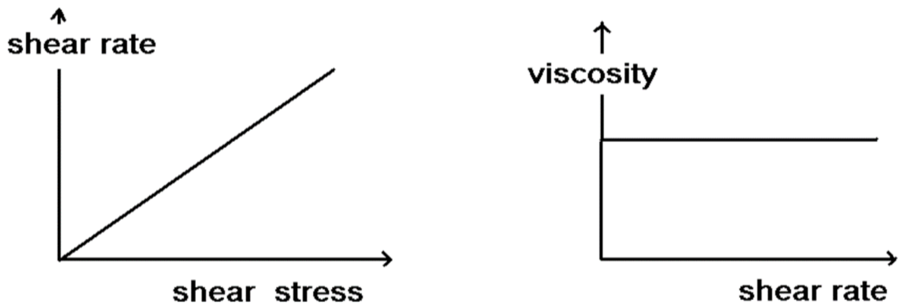


Figure 2.1: The Comparison Between Non-Newtonian Fluid (Left) and Newtonian Fluid (Right)

2.5 Models for Blood

Blood is characterised as an incompressible, viscoelastic, thixotropic fluid. Various researchers have proved that the elasticity of blood is undistinguished compared to the viscosity when considering velocity profiles and (WSS) distribution in arterial geometries. The viscosity of blood is not easily characterised and is dependent on many factors such as the haematocrit and the gender (O'Callaghan, 2005).

Based on various researches that have been carried out by numerous researchers, it can be said that blood cannot be treated as Newtonian/non-Newtonian fluid in general and under all circumstances. It is more meaningful to consider each case individually according to 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 (O'Callaghan, 2005). Figures below will show some comparisons of WSS and viscosity of blood based on non-Newtonian general models of blood.

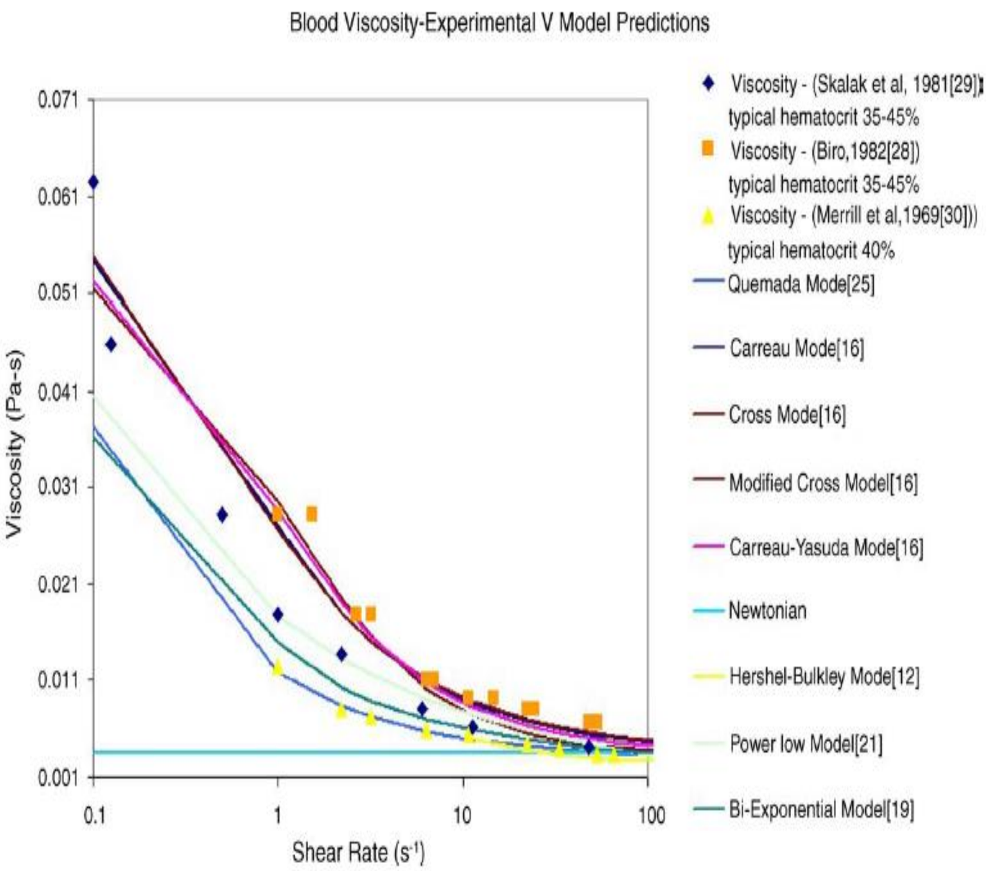


Figure 2.2: Blood Viscosity as a Function of Shear Rate

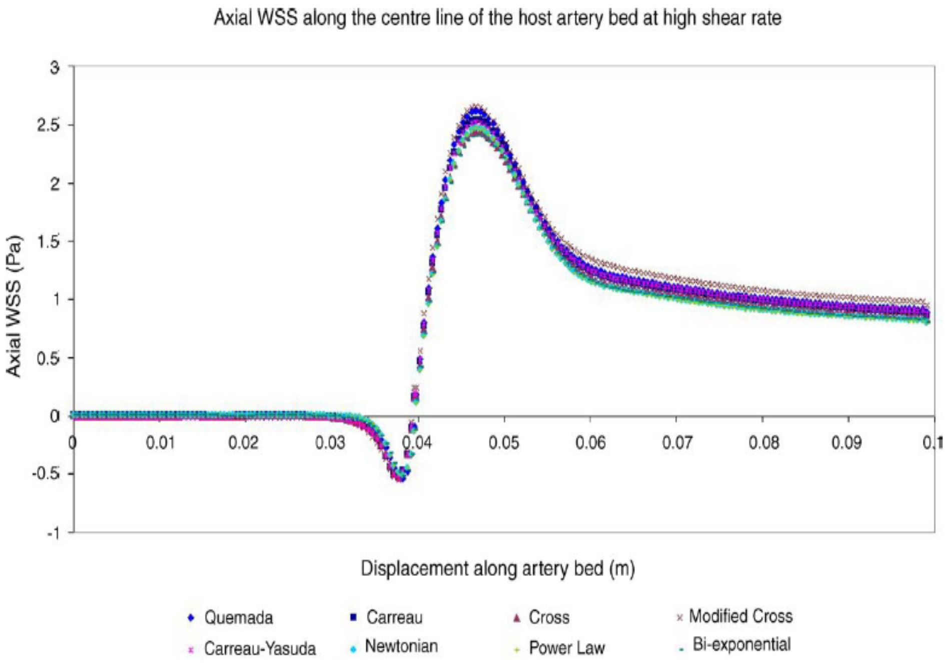


Figure 2.3: High Shear Rate WSS Distribution along the Centre Line of the Bed of the Host Artery

2.6 Non-Newtonian General Models

The Power Law Model for Non-Newtonian Viscosity

Non-Newtonian flow will be modelled according to the following power law for the non-Newtonian viscosity:

$$\eta = k\dot{\gamma}^{n-1}H(T) \quad (4)$$

Where k and n are the input parameters. k is a measure of the average viscosity of the fluid (the consistency index); n is a measure of the deviation of the fluid from Newtonian (the power-law index). The value of n determines the class of the fluid (FLUENT Inc., 2013):

$n = 1$; Newtonian fluid

$n > 1$; Shear-thickening (dilatant fluids)

$n < 1$; Shear-thinning (pseudo-plastics)

The disadvantage of the Power Law model are the high gradient and potentially infinite viscosity (Bernsdof, 2009).

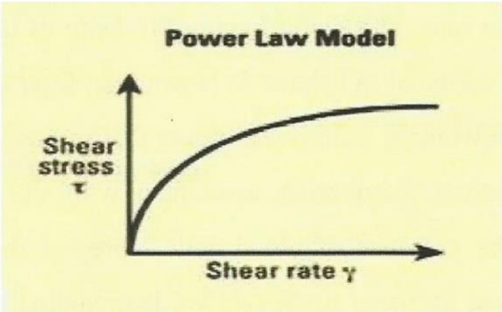


Figure 2.4: Shear Stress versus Shear Rate According to the Power Law Model

The Carreau Model

The Carreau model is used to describe a wide range of fluids by the establishment of a curve-fit to piece together functions for both Newtonian and shear thinning (n<1) Non-Newtonian laws. In this model, the viscosity is defined by (FLUENT Inc., 2013)

$$\eta = H(T)\left(\eta_\infty + (\eta_0 - \eta_\infty)\left[1 + \gamma^2\lambda^2\right]^{(n-1)/2}\right) \qquad (5)$$

The parameters n , λ , T_α , n_0 , and n_∞ are dependent upon the fluid.

λ = time constant

n =power-law index

n_0 = zero-shear viscosities

n_∞= infinite-shear viscosities

T_α = reference temperature

The Herschel-Bulkley Model

The Herschel–Bulkley fluid is one of the general models of a non-Newtonian fluid. According to this model, the strain experienced by the fluid is related to the stress in a complicated, non-linear way. The equation is given by (FLUENT Inc., 2013) :

$$\tau = \tau_0 + K\gamma^n \qquad (6)$$

Where τ is the shear stress, ϒ is the shear rate, τ_0 is the yield stress, and K and n are regarded as model factors.

If n = 1, τ_0 = 0 ;Newtonian fluid

If n > 1 ; shear-thinning

If n < 1 ; shear-thickening

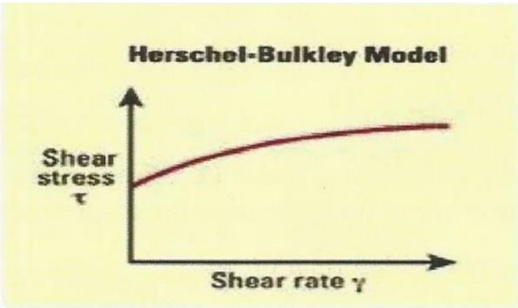


Figure 2.5: Shear Stress versus Shear Rate According to the Herschel Bulkley Model

The Herschel-Bulkley model is commonly used to describe materials such as concrete, mud, dough, and toothpaste, for which a constant viscosity after a critical shear stress is a reasonable assumption. In addition to the transition behavior between a flow and no-flow regime, the Herschel-Bulkley model can also exhibit a shear-thinning or shear-thickening behavior depending on the value of n.

The Cross Model

The Cross Model is commonly used when it is necessary to describe the low-shear rate behaviour of the viscosity (FLUENT Inc., 2013).

$$\eta = \frac{\eta_0}{1 + (\lambda\dot{\gamma})^{1-n}} \tag{7}$$

where n_0 = zero-shear-rate viscosity

λ = natural time (i.e., inverse of the shear rate at which the fluid changes from Newtonian to Power law behaviour)

n = power-law index

CHAPTER 3

METHODOLOGY

3.1 Research Methodology and Project Activities

The main methodology for conducting this project is by using Computational Fluid Dynamics (CFD) with the aid of software called FLUENT. The whole project is using only the simulation method. Before the simulation can be carried out, a detailed study is needed to find out information and details regarding the project.

3.2 Computational Fluid Dynamics (CFD)

CFD is the modern ways of replacing the Partial Differential Equation (PDE) which represent the conservation laws for mass, momentum and energy. In other words, CFD replaced the PDE system by using a set of algebraic equations which can be solved by digital computers. CFD is a combination of three disciplines that comprises of theoretical fluid dynamics, numerical mathematics and computer science. CFD enables scientist and engineers to use the computer to solve numerous mathematical equations for problems of fluid dynamics (Kunwar, 2009).

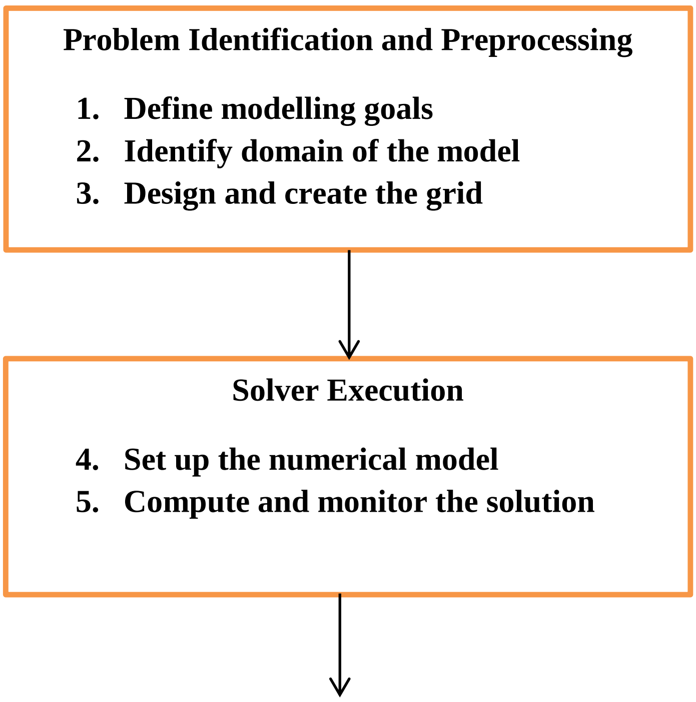
3.3 FLUENT

FLUENT is a computer software that functions to program for modelling fluid flow and heat transfer in complex geometries. FLUENT is used to stimulate all levels of complexity with much ease and can help engineers to reduce the total effort need in an experiment. It can be used to solve problems in 2D and 3D, compressible and incompressible, steady state and variety of material properties. Moreover, FLUENT uses a client or also known server architecture that allows it to run as separate simultaneous processes. There are a few packages in FLUENT which includes FLUENT (the solver), DesignModeler (the pre-processor for geometry modelling and mesh generation, T Grid (an additional pre-processor that can generate volume meshes from existing boundary meshes from existing boundary meshes) and Filters. FLUENT solvers usually based on the finite volume method (Kunwar, 2009).

There are a few steps involved to solve problems in FLUENT. First step is the discretion step. The domain is discretized into a finite set of control volumes or cells. Next step is the general conservation for mass, momentum, energy, species etc. whereby these equations are solved on this set of control volumes. The third step is the discretion of PDE into a system of algebraic equations before proceeding to the last step which all the algebraic equations are then solved numerically to render the solution field (Ansys, 2013).

3.4 FLUENT Modelling

There are three phases altogether to solve CFD problems. The first phase is the pre-processing phase where the geometry is created and done in Computer-Aided Design (CAD) tool named DesignModeler. The next phase is the solver execution where all the equations are solved using finite volume method. The last phase is post processing in which the visualization of a CFD's code are observed and further evaluated and revised (Kunwar, 2009).



Post-Processing

6. **Examine the results**
7. **Consider revisions to the model**

Figure 3.1: Steps in CFD

3.5 FLUENT Operating System

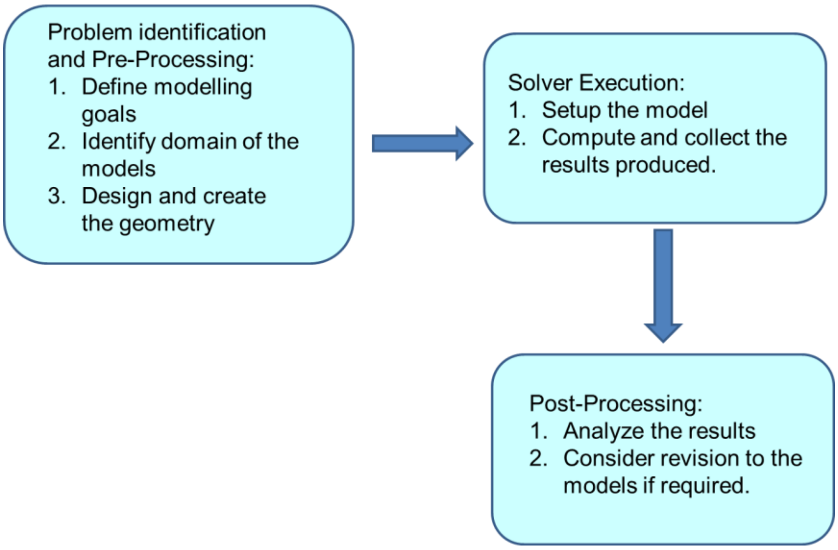


Figure 3.2: FLUENT Operating System

<u>Pre-Processing</u>

1. Generate geometry using DesignModeler.
2. The geometry is built according to the needs of the project by setting in necessary measurements and units.
3. Domain is discretized using finite volume method and is put into the mesh generator.
4. The domain is divided into a finite set of control volume.

<u>Solver</u>

1. The solver settings and pre-processing data are required in this solver part.
2. Transport equation and momentum equation are considered.

<u>Post-Processing</u>

1. Analyze the data and consider if revision is needed.

3.6 The Geometry

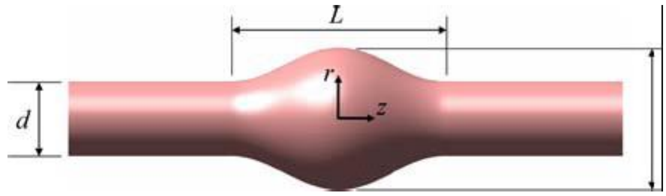


Figure 3.3: Schematic Idealized model under investigation, showing key dimensions and the cylindrical *(z-r)* coordinates. Fluid flows through the interior of the model

The above geometry model is constructed using Design Modeller in ANSYS 14.0 software. The model has a diameter(d) of 3mm. The length(L) and maximum diameter(D), are both 3 and 2 times the diameter respectively. Figure 3.1 shows this geometry. Relative to a cylindrical *(z-r)* coordinates system centered at the middle of the bulge, the bulge and tube wall are defined by the function (Sheard, 2009):

$$r'(z') = \begin{cases} 1/2 & \text{if} \quad |z'| > \mathrm{LR}/2 \\ \dfrac{DR+1}{4} + \dfrac{DR-1}{4}\cos\dfrac{2\pi z'}{LR} & \text{if} \quad |z'| \leq \mathrm{LR}/2\,, \end{cases} \tag{8}$$

where primes denote non-dimensionalisation by *d*, and a diameter ratio DR = *D/d* and length ratio LR = *L/d*.

Boundary Conditions

- Inlet flow
  - Pulse inlet flow
- Newtonian Viscosity
  - 0.0041 (kg/m-s)
- Density : 1080 (kg/m3)

Table 3.1: Boundary condition for Herschel Bulkley model (O'Callaghan, 2005)

Power law index (n)	Consistency index (kg-s ^n-2/m)	Yield stress (Pa)	Yielding viscosity (kg/m-s)
0.95	0.2073	0.00125	4

Table 3.2: Boundary condition for Power Law model (O'Callaghan, 2005)

Power law index (n)	Reference Temperature (K)	Minimum Viscosity limit (kg/m-s)
0.4851	310	0.00125

Table 3.3: Boundary condition for Cross model (O'Callaghan, 2005)

Power law index (n)	Zero shear viscosity (kg/m-s)	Time constant (s)
0.285	0.056	1.007

Table 3.4: Boundary condition for Carreau model (Moura, 2011)

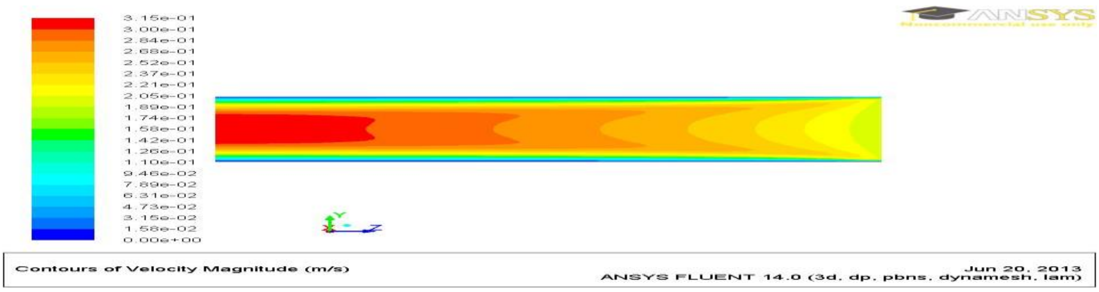
Power law index (n)	Zero shear viscosity (kg/m-s)	Infinite shear viscosity (kg/m-s)	Reference Temperature (K)	Time constant (s)
0.344	0.0456	0.0032	310.15	10.03

CHAPTER 4

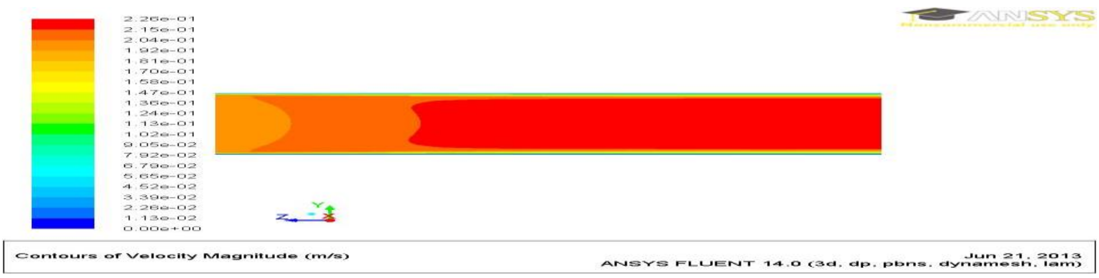
RESULTS AND DISCUSSION

4.1 Effect of Rheological Models on Velocity Magnitude of Blood Flow in Healthy Artery

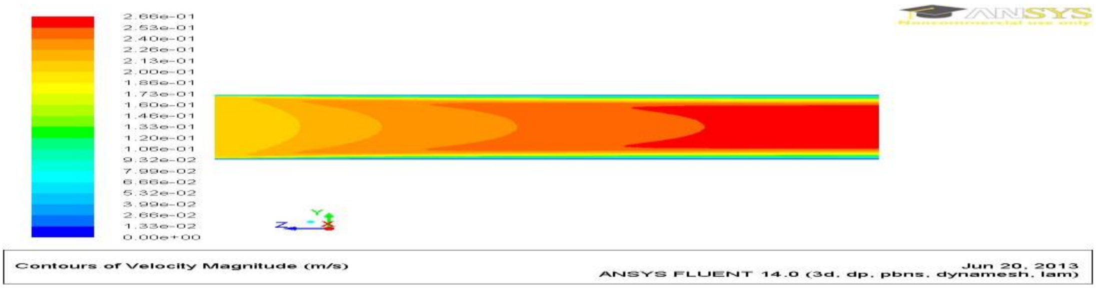
Contours



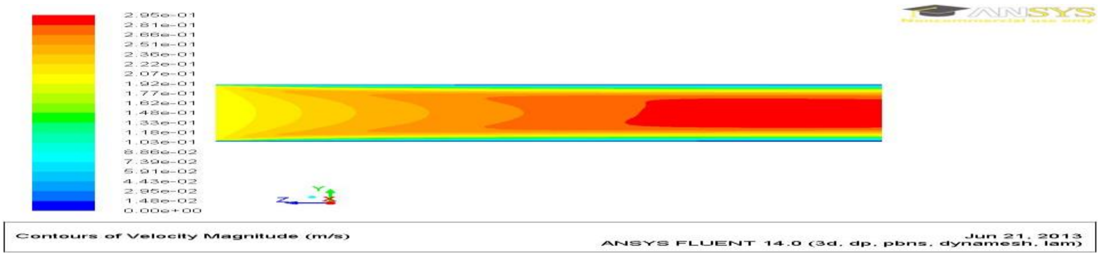
Newtonian Model



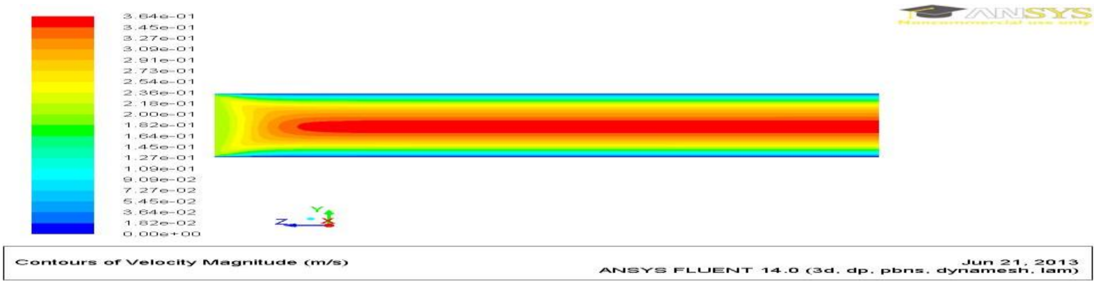
Cross Model



Power Law



Carreau Model



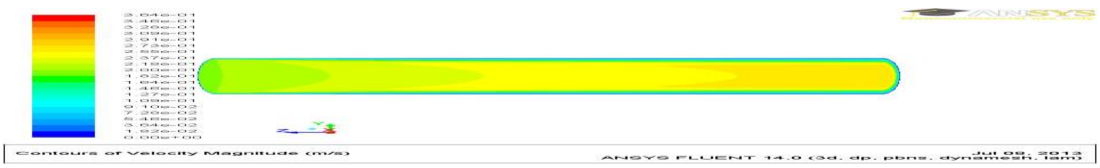
Herschel-Bulkley

Figure 4.1: Contours of Velocity Magnitude in Healthy Artery According to Rheological Models

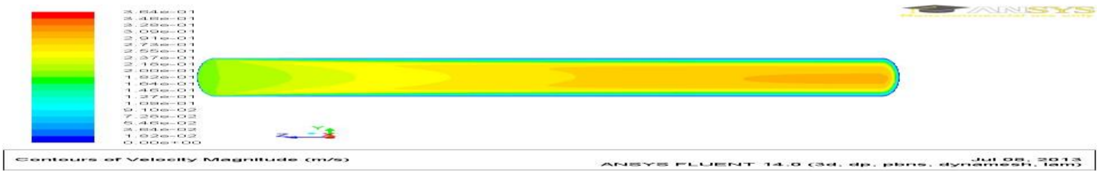
For a better comparison among the models, the following contours are presented with the same range of minimum and maximum values:

Newtonian

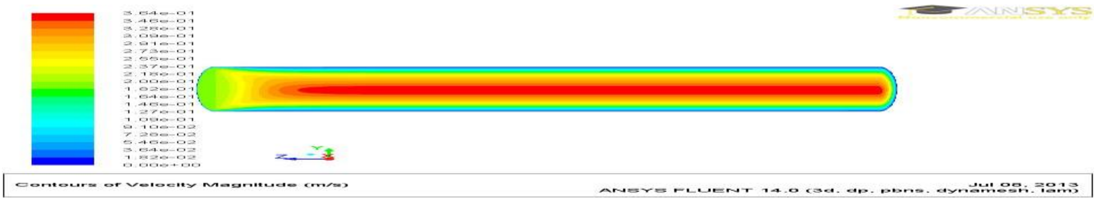
Cross



Power Law



Carreau



Herschel Bulkley

Figure 4.2: Standardized Scale of Velocity Magnitude in Healthy Artery According to Rheological Models

Discussion

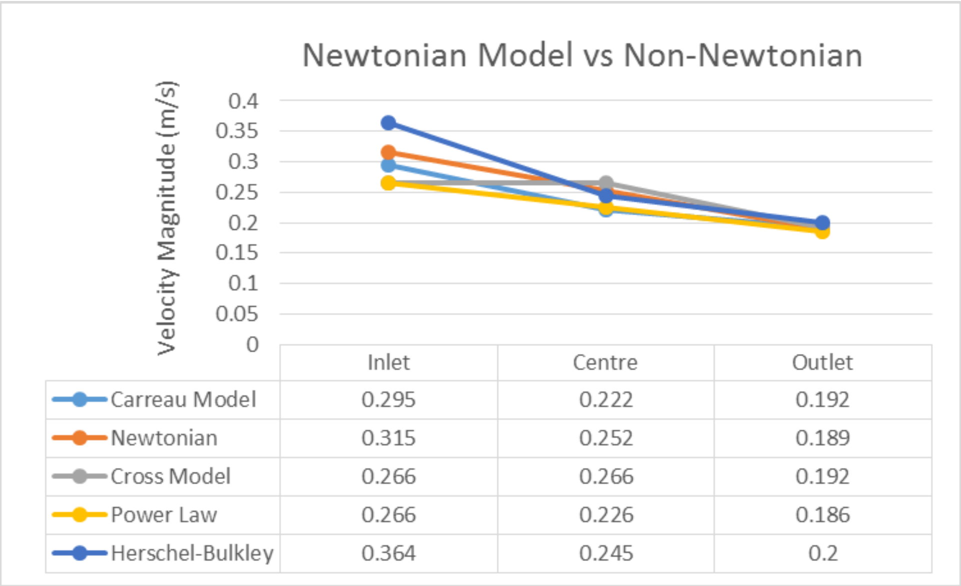
As can be observed from the above contour, the velocity magnitude of blood flow across the artery in the Newtonian model is almost uniform. At the starting point, the velocity achieved is approximately 0.315 m/s and the velocity decreases towards the end of the artery which is around 0.189 m/s at the outlet. In the Cross Model, the velocity magnitude is lower compared to the Newtonian model. However, the velocity across the artery from the inlet to the outlet is also uniform. The inlet velocity at point -10.5mm is recorded to be 0.266 m/s whereas the outlet at 10.5mm the velocity is 0.192 m/s. For Power Law model and Carreau model, the results obtained are almost similar whereby the initial velocity at point 10.5mm which is the inlet is high before it decreases uniformly towards the outlet.

In Herschel Bulkley on the other hand, records the highest velocity magnitude compared to the other non-Newtonian models. The velocity is high across the artery which is from the inlet moving towards the outlet. It is clearly observed that the velocity at the centre of the artery is higher which is 0.364 m/s compared to the velocity at the wall which is 0.245 m/s. The velocity of blood is dependent on the viscosity of blood. Therefore from the results, it can be concluded that in Newtonian model, the velocity magnitude of blood flow is higher than the other Non-Newtonian models. The velocity is only high at the inlet and decreases rapidly soon after which result in a more stable blood flow. The velocity magnitude for all the models is presented in the table below:

Table 4.1: Velocity Magnitude of Healthy Artery

Model	Inlet Velocity(m/s)	Centre Velocity (m/s)	Outlet Velocity (m/s)
Newtonian	0.315	0.252	0.189
Cross	0.266	0.266	0.192
Power Law	0.266	0.226	0.186
Carreau	0.295	0.222	0.192
Herschel Bulkley	0.364	0.245	0.20

Overall results shows that the Newtonian model achieved the highest velocity compared to the non-Newtonian models. The velocity of blood depends on the viscosity which explains the result. The biggest contrast can be seen if the comparison is made between the Newtonian model and the non-Newtonian model which is Carreau model. A graph of the above table is plotted to support the result.



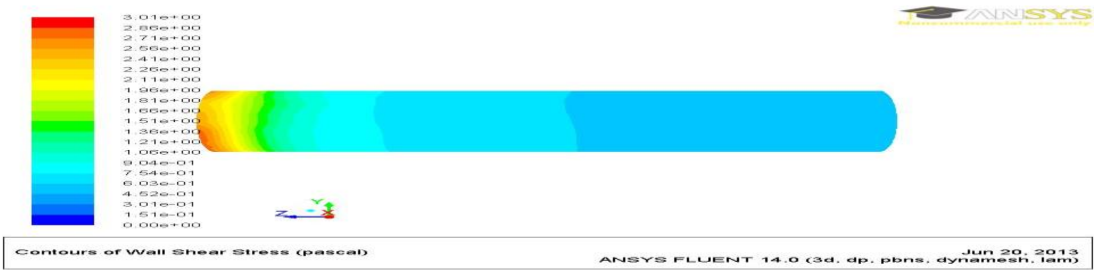
Graph 4.1: Healthy Artery Velocity Magnitude Comparison between Newtonian Model and Non-Newtonian Models

4.2 Effect of Rheological Models on the Wall Shear Stress (WSS) in Healthy Artery

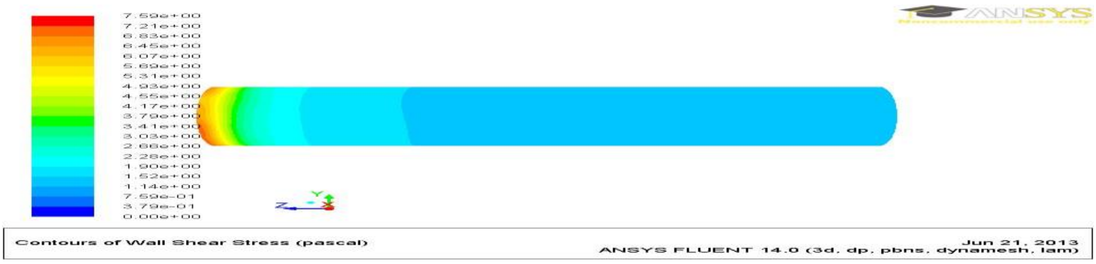
Contours

Newtonian Model

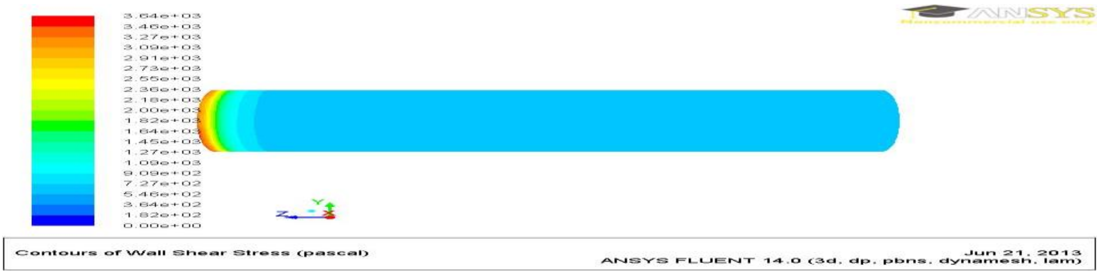
Cross Model



Power Law



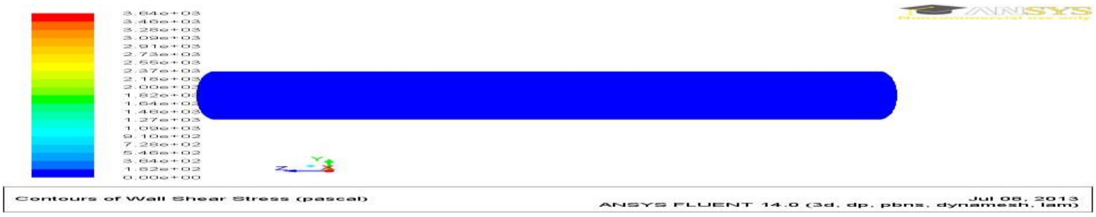
Carreau Model



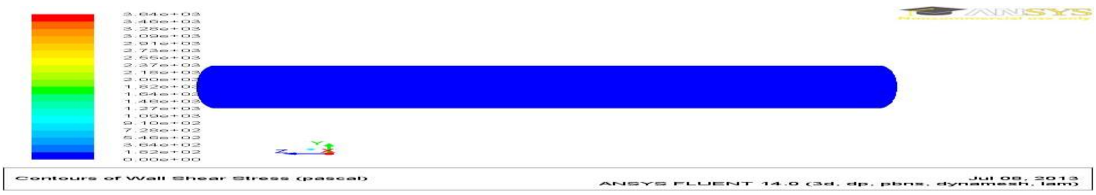
Herschel Bulkley

Figure 4.3 WSS in Healthy Artery According to Rheological Models

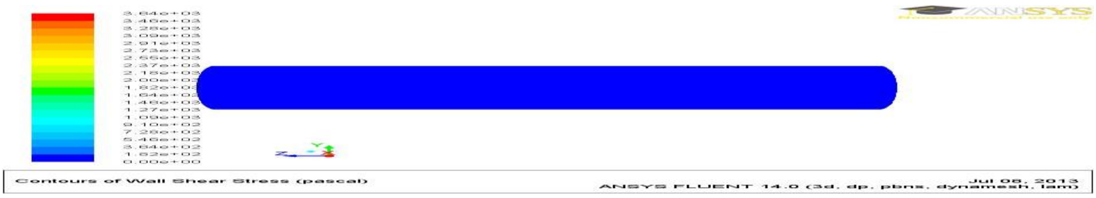
In order for a better comparison can be made, the following contours are simulated whereby the maximum and minimum value are standardized.



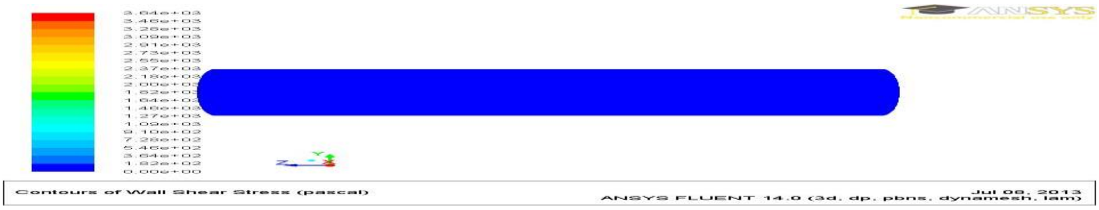
Newtonian Model



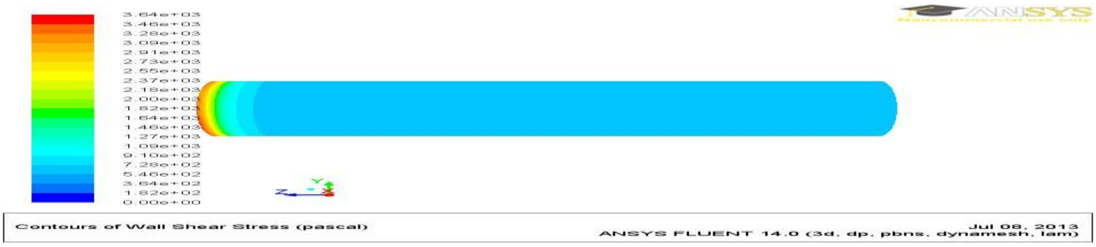
Cross Model



Power Law



Carreau Model



Herschel Bulkley

Figure 4.4: Standardized Scale of WSS in Healthy Artery According to Rheological Models

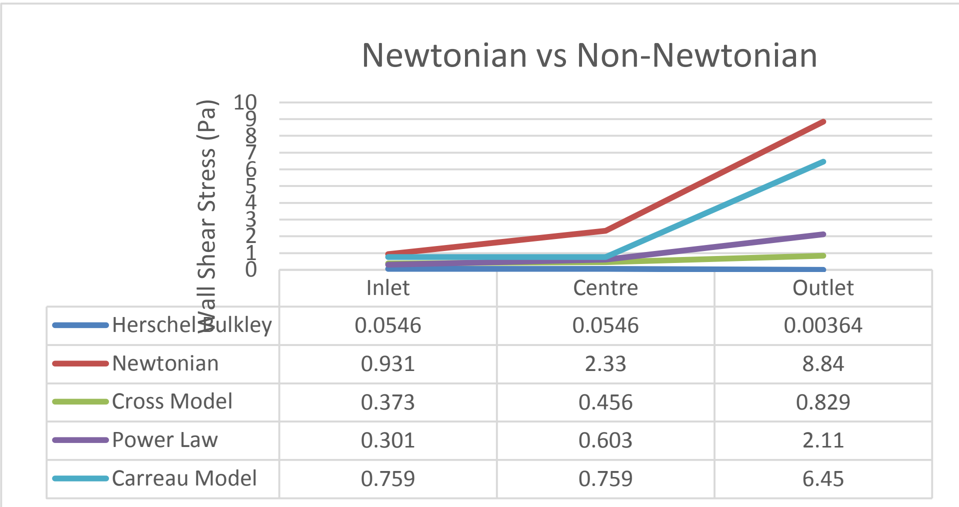
Discussion

In the Newtonian Model, the WSS at point -10.5mm is zero. However, the WSS increases across the artery. The highest recorded WSS is at pint 10.55mm whereby the WSS recorded is 8.84Pa. For the Cross Model, the WSS is lower compared to the Newtonian Model, where the WSS at the inlet is only 0.373Pa and at the outlet is 0.829Pa. In the Power law model, there is a big difference between the WSS at the inlet compared to the outlet where the WSS are 0.301Pa and 2.11Pa respectively. In the case of Carreau model, the WSS at the inlet and at the centre is the same with the value of 0.759Pa. However, the WSS is very much higher towards the outlet which is 6.45Pa. It is a different story for Herschel Bulkley since the outlet recorded a much lower WSS which is 0.00364Pa compared to the inlet and at the centre which is 0.0546Pa. The magnitude of WSS for all the models is tabulated as follows:

Table 4.2: WSS of Healthy Artery According to Rheological Models

Model	Inlet WSS(Pa)	Centre WSS (Pa)	Outlet WSS (Pa)
Newtonian	0.931	2.33	8.84
Cross	0.373	0.456	0.829
Power Law	0.301	0.603	2.11
Carreau	0.759	0.759	6.45
Herschel Bulkley	0.0546	0.0546	0.00364

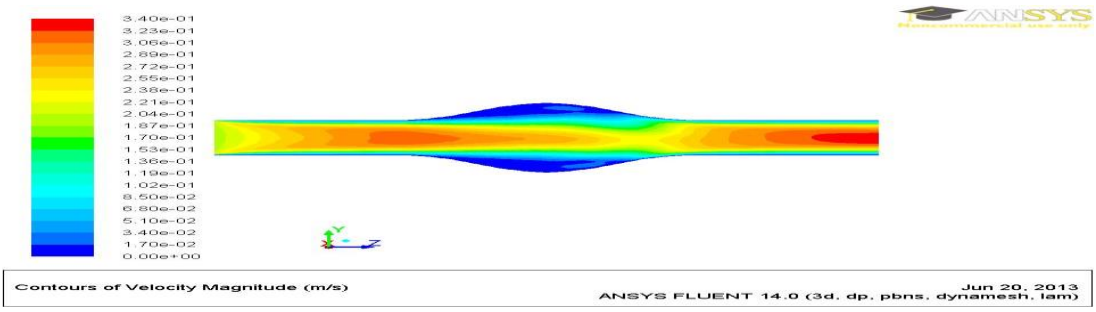
From the table above, it is observed that the Newtonian model has the highest WSS compared to the Non-Newtonian models. This is legit since the artery is in a straight shaped artery, therefore the WSS of each model is subjected to its own parameters according to the boundary conditions and as observed above, Herschel Bulkley has the lowest WSS among the non-Newtonian models. To get a better picture of the result, a comparison graph between the WSS in healthy artery of the Newtonian model and the non-Newtonian models is plotted.



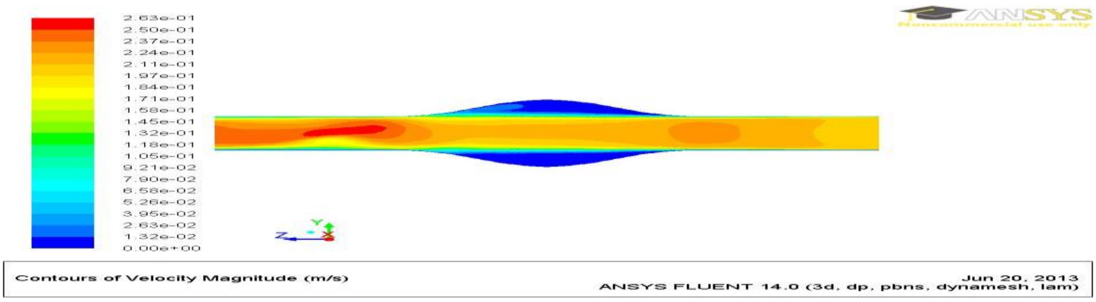
Graph 4.2: Healthy Artery WSS Comparison between Newtonian Model and Non-Newtonian Models

4.3 Effect of Rheological Models on the Velocity Magnitude in Aneurysmal Artery

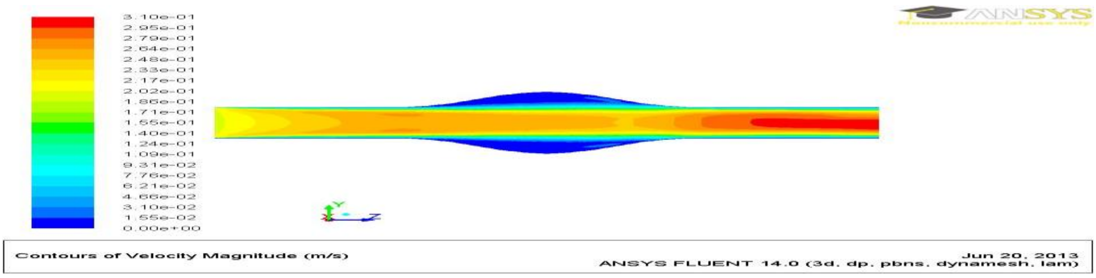
Contours



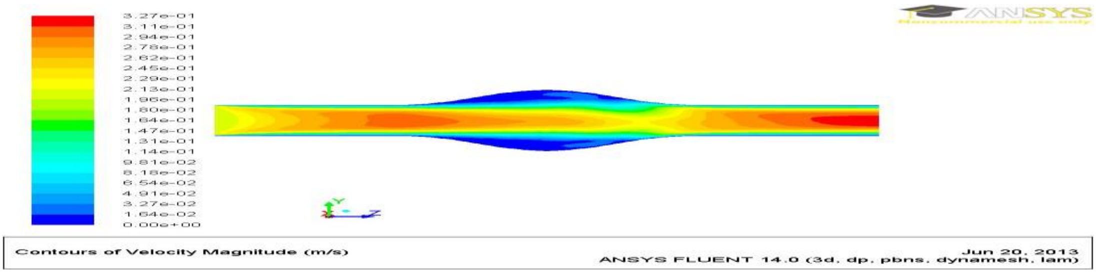
Newtonian Model



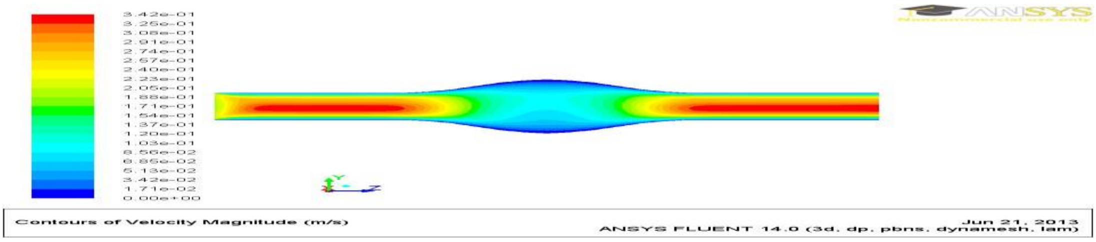
Cross Model



Power Law



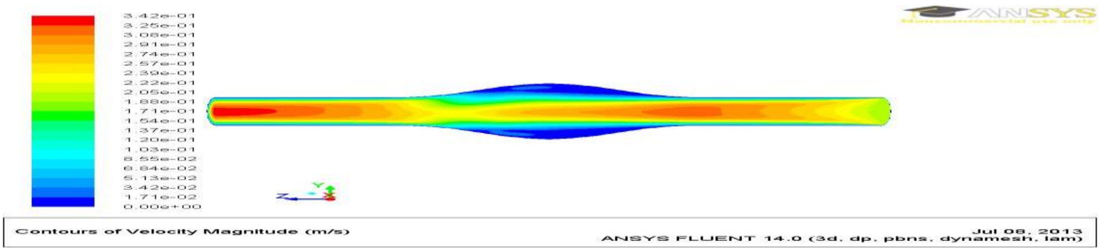
Carreau Model



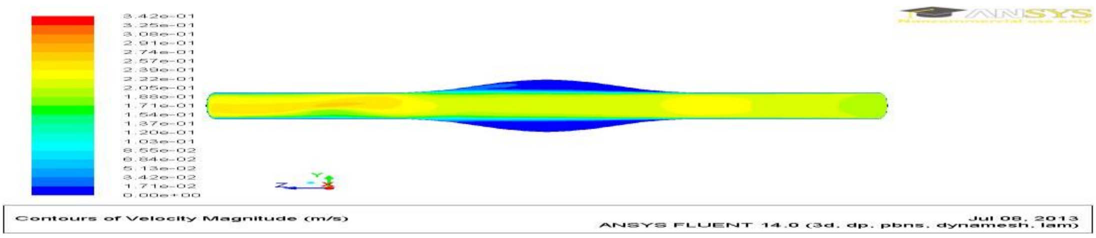
Herschel Bulkley

Figure 4.5: Velocity Magnitude in Aneurysmal Artery According to Rheological Models

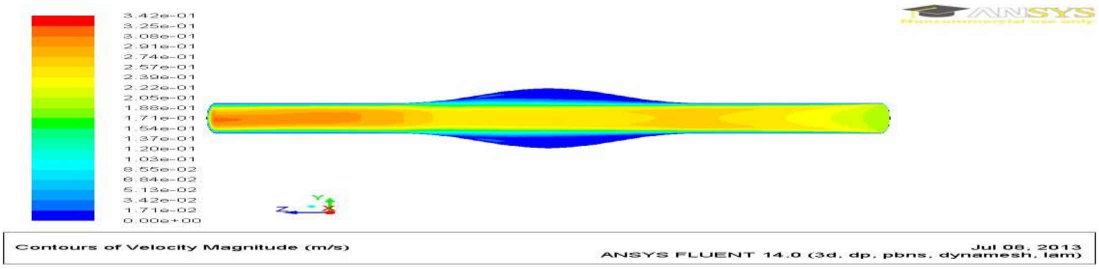
The following contours are constructed to distinguish a better comparison among the models by standardizing the minimum and maximum range:



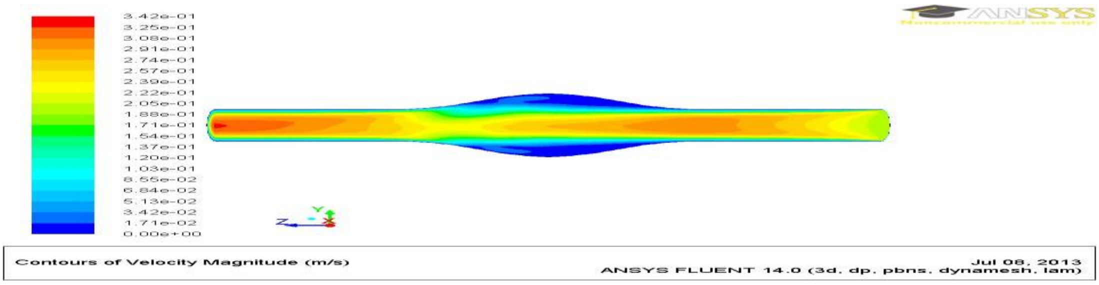
Newtonian Model



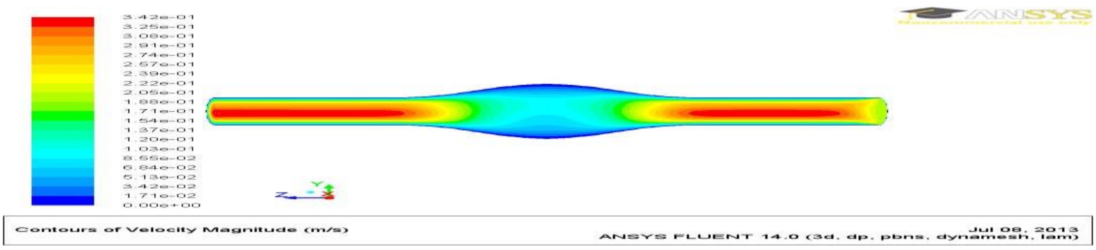
Cross Model



Power Law



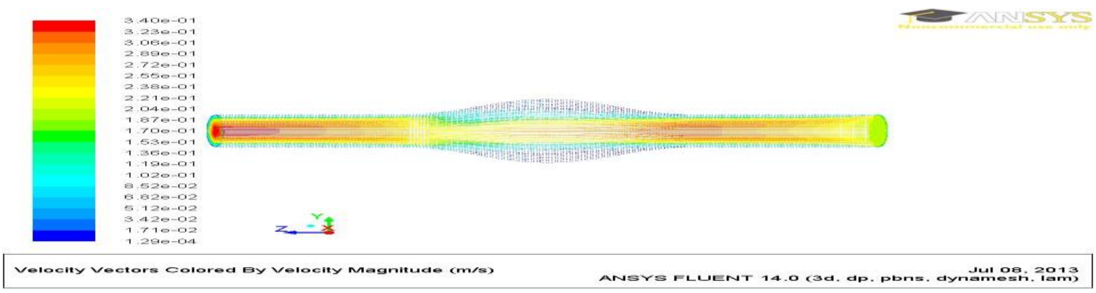
Carreau Model



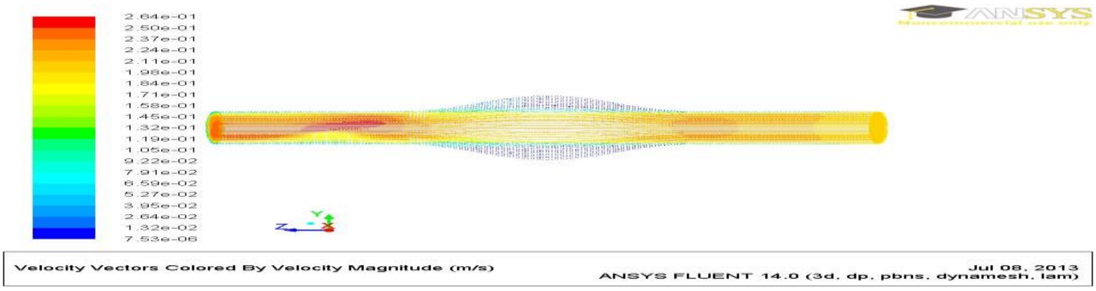
Herschel Bulkley

Figure 4.6: Standardized Scale of Velocity Magnitude in Aneurysmal Artery According to Rheological Models

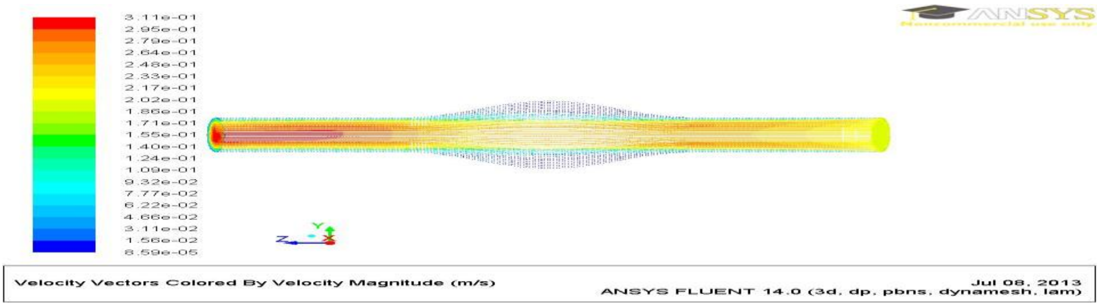
Vectors



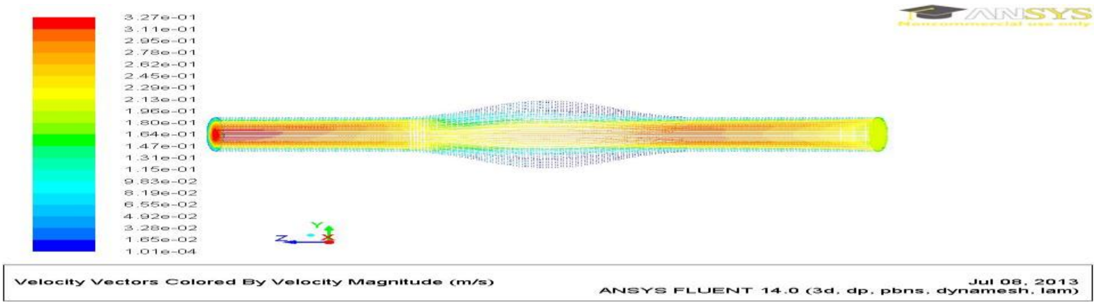
Newtonian Model



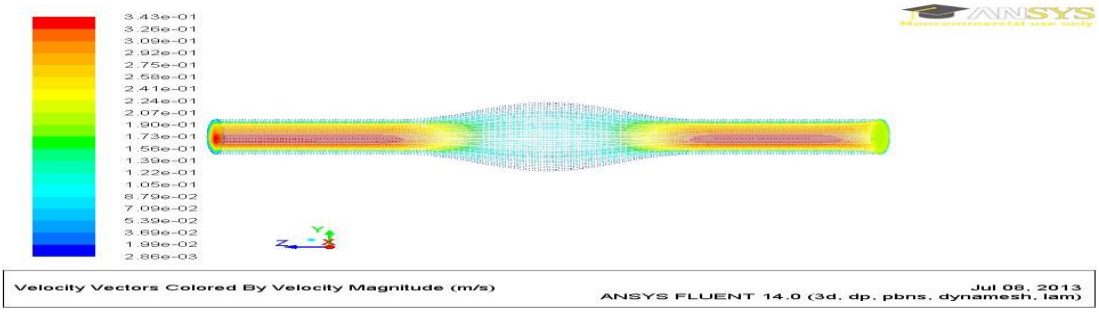
Cross Model



Power Law



Carreau Model



Herschel Bulkley

Figure 4.7: Velocity Vector of Velocity Magnitude in Aneurysmal Artery According to Rheological Models

Discussion

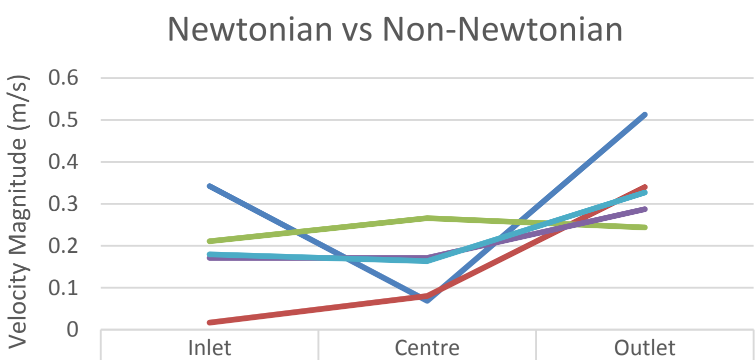
In the Newtonian model, the velocity magnitude can be concluded to be uniform across the artery where there is no significant change in the velocity throughout the artery. At the aneurysmal part of the artery, it is observed that the velocity at the wall is very small which is 0.017 m/s. For Cross model, the initial velocity at point -10.5mm is around 0.211 m/s and the velocity across the artery is of the same magnitude. However, there is a little increment towards the outlet whereby the velocity measured is approximately 0.2435 m/s. In the case of Power law model, the measured velocity at point -10.5mm is 0.171 m/s and this trend continue until the centre of artery. However, the velocity magnitude increases rapidly towards the end of the artery which the value recorded is 0.287 m/s. Looking at the Carreau model, the results obtained are almost similar to that of the Power law model. The pattern is also uniform across the artery and the inlet velocity is 0.18 m/s whereas at the outlet it is 0.327 m/s. At the aneurysmal part, the velocity magnitude is 0.164 m/s which can be said to be higher than the Newtonian model.

Lastly is the Herschel Bulkley model, where the pattern of the velocity magnitude differs completely compared to the other non-Newtonian models. The velocity magnitude at the inlet is 0.342 m/s. However, a sudden drop in velocity magnitude occurred at the bulging part where the velocity is only 0.0686 m/s before increasing again at the outlet to 0.513 m/s. The values obtained for the velocity magnitude are tabulated as below:

Table 4.3: Velocity Magnitude of Aneurysmal Artery According to Rheological

Model	**Inlet Velocity(m/s)**	**Centre Velocity (m/s)**	**Outlet Velocity (m/s)**
Newtonian	0.017	0.08	0.340
Cross	0.211	0.266	0.2435
Power Law	0.171	0.171	0.287
Carreau	0.180	0.164	0.327
Herschel Bulkley	0.342	0.0686	0.513

Comparing the velocity magnitude of the Newtonian model and the non-Newtonian models, it is obvious from the velocity vector that the flow of blood in Herschel Bulkley models undergoes a massive drop in velocity as compared to the Newtonian model whereby the velocity is higher across the bulging area. A graph to compare the velocity magnitude of the Newtonian model and the non-Newtonian models is plotted to display a better comparison:

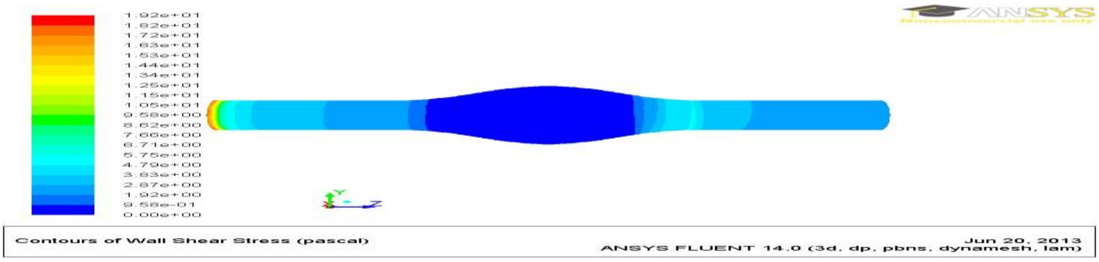


	Inlet	Centre	Outlet
Herschel Bulkley	0.342	0.0686	0.513
Newtonian	0.017	0.08	0.34
Cross Model	0.211	0.266	0.2435
Power Law	0.171	0.171	0.287
Carreau Model	0.18	0.164	0.327

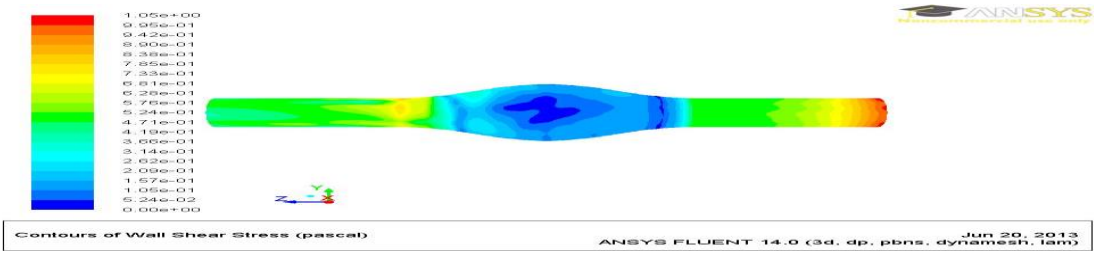
Graph 4.3: Aneurysmal Artery Velocity Magnitude Comparison between Newtonian Model and Non-Newtonian Model

4.4 Effect of Rheological Models on the Wall Shear Stress (WSS) in Aneurysmal Artery

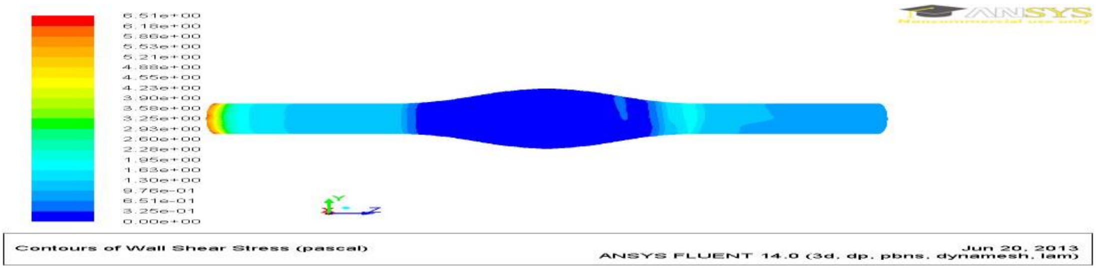
Contours



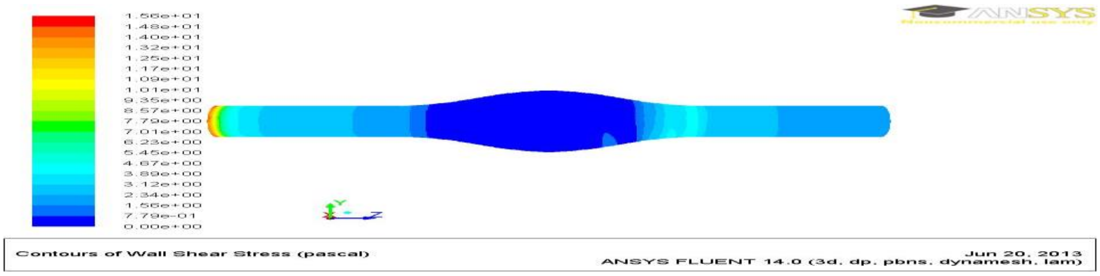
Newtonian Model



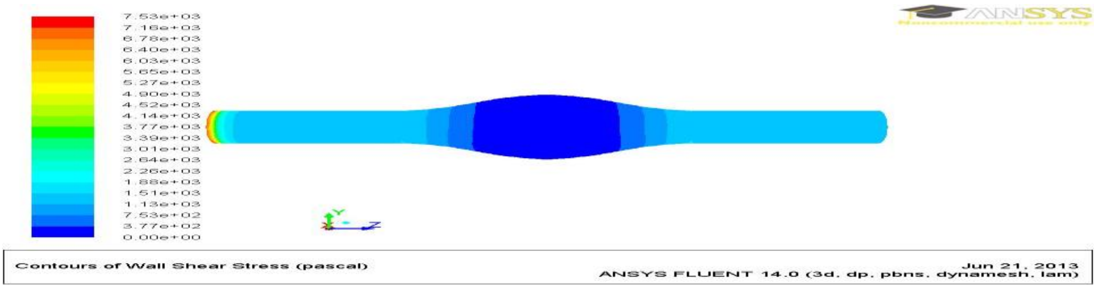
Cross Model



Power Law



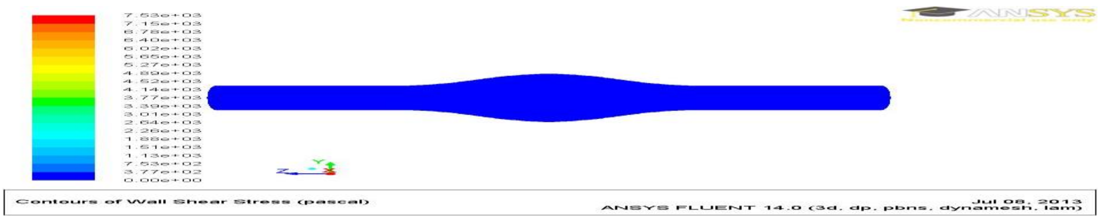
Carreau Model



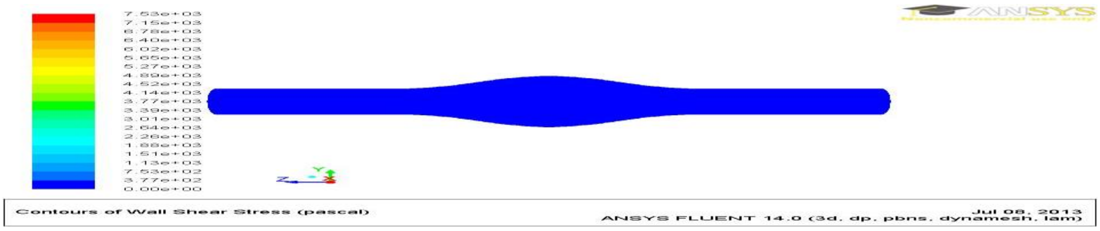
Herschel Bulkley

Figure 4.8: WSS in Aneurysmal Artery According to Rheological Models

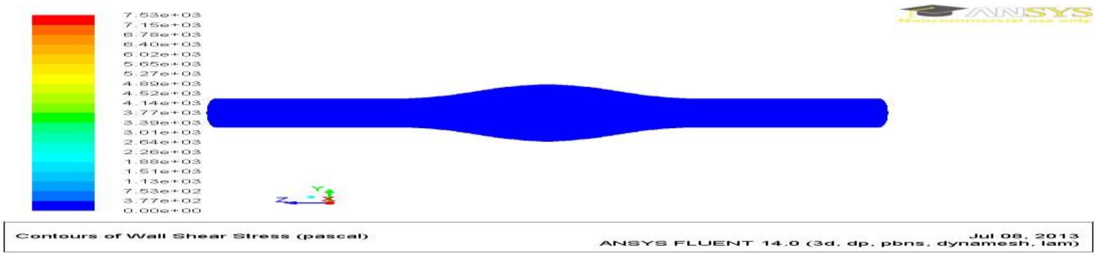
The contours below indicate a better comparison since the minimum and the maximum range of values have been standardized:



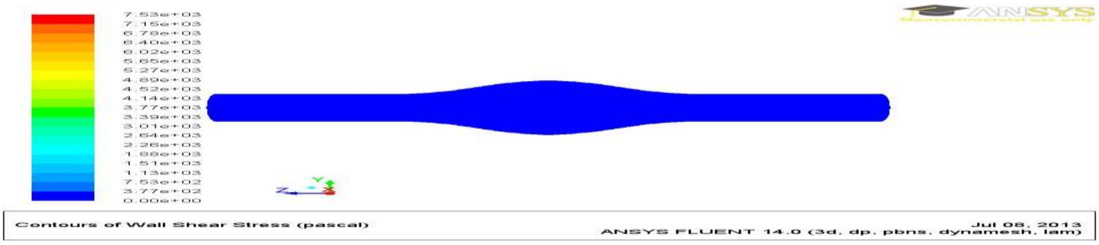
Newtonian Model



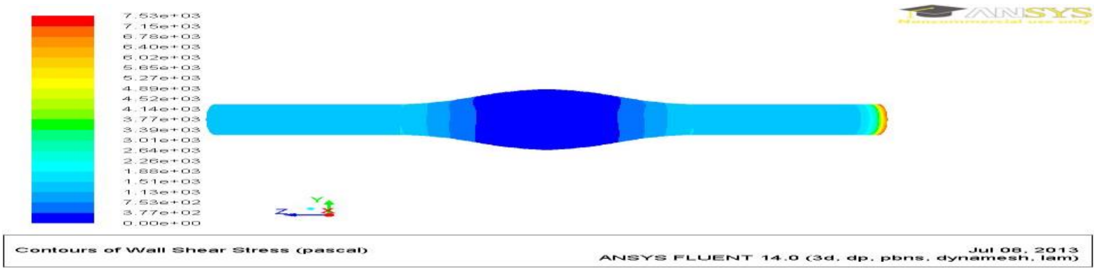
Cross Model



Power Law



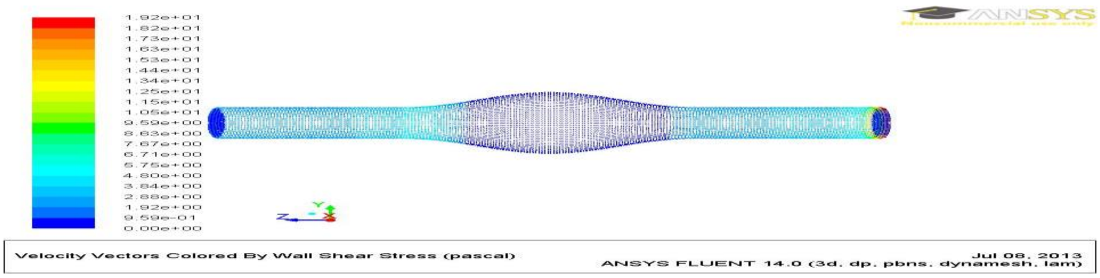
Carreau



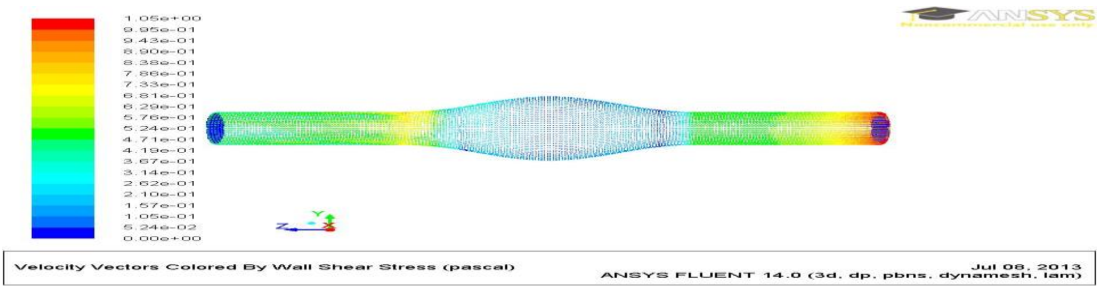
Herschel Bulkley

Figure 4.9: Standardized Scale of WSS in Aneurysmal Artery According to Rheological Models

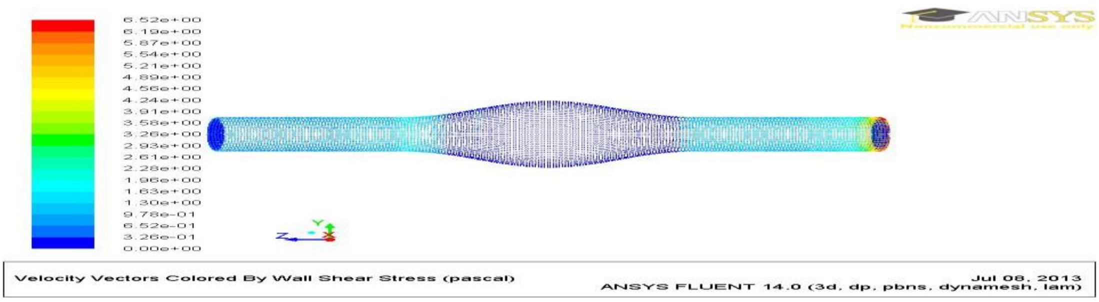
Vectors



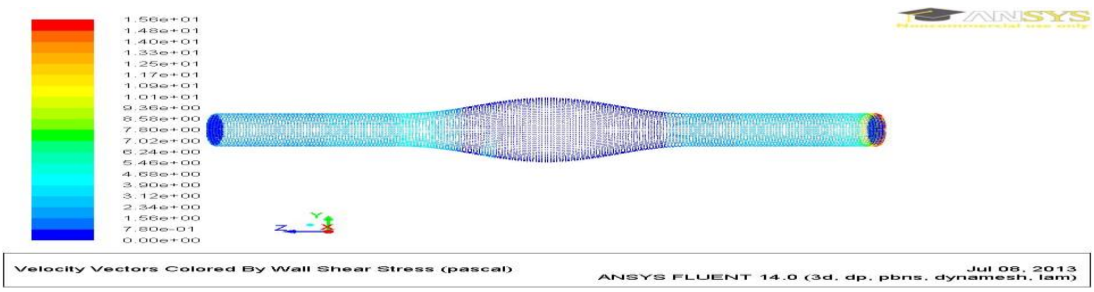
Newtonian Model



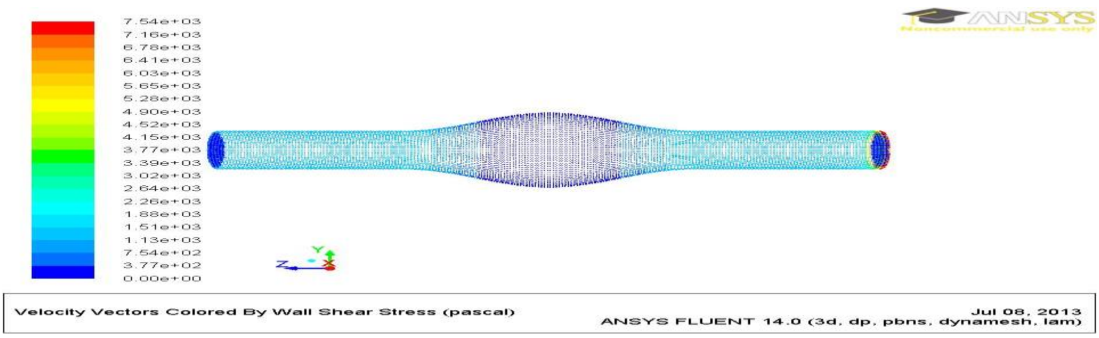
Cross Model



Power Law



Carreau Model



Herschel Bulkley

Figure 4.10: WSS Vector in Aneurysmal Artery According to Rheological Models

Discussion

The WSS is measured at the neck of the artery right before the bulging area. The WSS at this point is the area to measure WSS and thus a prediction of the expansion in the bulging size can be made. Referring to the vectors above, the pattern of WSS across the artery can be observed according to the different models. For the Newtonian model, the WSS at the outlet and at the inlet can be considered to be almost similar which is around 2.87 Pa at both ends. This can be the reference value of WSS as the neck since 2.87 Pa is the average value between the inlet and the neck. In the case for Cross model, the WSS at point -10.5 mm is between 0.524 Pa to 1.05 Pa and at the outlet is 0.524 Pa. At the centre area, WSS ranges between 0.0524 Pa to 0.366 Pa and this can be considered as high WSS compared to the other models.

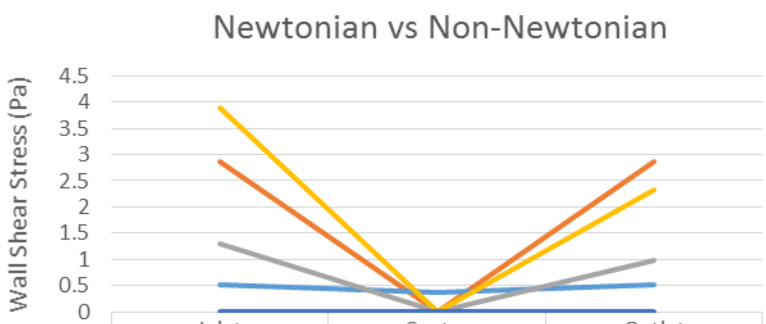
According to the results obtained in Power law, the inlet WSS is 1.3 Pa and at the outlet is 0.976 Pa. The centre of the artery reads a value of 0 which is the same compared to the Newtonian model.

On the other hand, the value of the inlet and outlet WSS in the Herschel Bulkley is observed to be completely the same with each other at 0.00151 Pa. Looking at the Carreau model, the outlet and the inlet WSS is very high whereby the value of WSS is 3.89 Pa and 2.34 Pa respectively. The value of 3.89 Pa can be taken as the value at the neck whereby it is also the average value of WSS from the inlet to the neck of before the bulging area, hence this is very high compared to the other non-Newtonian models and also the Newtonian model. The data for WSS is presented in the table below:

Table 4.4: WSS of Aneurysmal Artery According to Rheological Models

Model	Inlet WSS(Pa)	Centre WSS (Pa)	Outlet WSS (Pa)
Newtonian	2.87	0	2.87
Cross	0.524	0.366	0.524
Power Law	1.3	0	0.976
Carreau	3.89	0	2.34
Herschel Bulkley	0.00151	0	0.00151

For WSS, results obtained at the inlet is comparable for all the models except for Herschel Bulkley and Cross Model. The WSS for Newtonian model and the Carreau model has almost the same value of WSS. However, the Carreau model recorded the highest value of WSS of all. This indicates that the non-Newtonian properties of blood has caused the WSS to be higher compared to the Newtonian model and may contribute to the bulging of artery. Hence, a graph to show the comparison in WSS between the Newtonian Model and the non-Newtonian models is shown as below:



	Inlet	Centre	Outlet
Newtonian	2.87	0	2.87
Cross Model	0.524	0.366	0.524
Power Law	1.3	0	0.976
Carreau Model	3.89	0	2.34
Herschel-Bulkley	0.00151	0	0.00151

Graph 4.4: Aneurysmal Artery WSS Comparison in Aneurysmal Artery between Newtonian Model and Non-Newtonian Models

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

As a conclusion, this project aims to study on CVD or the cerebral aneurysm to be specific, by using the bio fluid mechanics approach to tackle the problem and hence providing the information and thus may prove the hypothesis. As being discussed earlier, cerebral aneurysm is a deadly disease whereby, depending on severity, may cause death. Hence, the characteristics of blood (non-Newtonian properties) in the diseased bulging artery are studied to figure out whether does the non-Newtonian properties of blood effects the wall shear stress and subsequently causing the artery to rupture. This is very important since the information gathered can be used as a decision making indicator to treat the patient. Therefore, the general models for non-Newtonian properties of blood is expected to result in difference in WSS and hence becoming the main parameter to evaluate the condition of the artery based on the comparison of WSS. In the case of the velocity magnitude in healthy artery, the Newtonian model has a higher velocity by average throughout the artery compared to the non-Newtonian models except for Herschel-Bulkley. The percentage difference is approximately between 4% to 7%. For WSS in healthy artery, the values obtained in Newtonian model and Cross model is almost similar where the difference only account for 1% but with the other non-Newtonian models the difference is big which is around 75% to 97%. In determining velocity magnitude in aneurysmal artery, the velocity can be concluded to be comparable for Cross model, Carreau model and Power law model. Major difference can be seen between Newtonian model and Herschel-Bulkley where average difference accounts for 30%. In aneurysmal artery, the average WSS between the inlet and the neck is the highest in Carreau model. For comparison, the difference in WSS between Carreau model and Herchel-Bulkley is 99%. However, difference between Carreau model and Newtonian model is 26%. This conclude that Carreau model has the highest WSS recorded compared to other models.

5.2 Recommendation

The application of bio-fluid mechanics should be widened in the medical field. The purpose is to assist doctors and medical expertise in giving predictions with regards to the condition of the patient's diseases by using simulator software such as Ansys FLUENT. More research should be carried out in order to ensure that more diseases can be predicted by using software applications.

The results obtained can be further validated with a real physical model of human artery and human blood sample running through the model. By doing this, a more precise result can be produced and a better comparison between physical model and the simulation model can be done.

REFERENCES

A

Ansys. (2013). Ansys Fluent. [Online]. Available: http://www.ansys.com/Products/Simulation

B

Brain and Nervous System Health Centre. (2011, January 7). Brain Aneurysm – Topic Overview. *WebMD.* [Online]. Available: http://www.webmd.com/brain/tc/brain-aneurysm-topic-overview

Blood (2013). The Human Heart.*The Franklin Institute*.[Online]. Available: http://www.fi.edu/learn/heart/blood/blood.html

Bernsdof, J., Wang, D.,(2009). Non-Newtonian Blood Flow Simulation in Cerebral Aneurysm. Computers and Mathematics with Applications. *Elsevier.*

C

Christian, N. (2009, May 27). What is a heart attack? What Causes a Heart Attack?. *Medical News Today*. [Online]. Available: http://www.medicalnewstoday.com/articles/151444.php

Crosta, P. (2009, August 17). What is a Stroke? What Causes a Stroke?. *Medical News Today*. [Online].Available: http://www.medicalnewstoday.com/articles/7624.php

Crompton, M.R., (2008). The Pathogenesis of Cerebral Aneurysm. *Oxford Journal*, 89, pp.797-814.

Choong, L.C., Srinivas, K., (2011). Wall Shear Stress Divergence as Rupture Indicator of Cerebral Aneurysm. *The University of Sydney.* [Online]. Available: http://sydney.edu.au/engineering/engineeringsydney/.../07-ChoongL.pdf

F

FLUENT Incorporated. Viscosity for Non-Newtonian Fluids. [Online]. Available: http://combust.hit.edu.cn:8080/fluent/Fluent60_help/html/ug/node285.htm

H

Heart News Link. (2011). Statistics of Global Causes of All Deaths 2011 [Online]. Available:
http://www.heartnewslinks.com/editors-blog

J

Johnston, B.M., Johnston, P.R.,(2004). Non-Newtonian Blood Flow in Human Coronary Right Arteries: Transient Simulations. *University of Tasmania*.[Online]. Available:
http://www.ncbi.nlm.nih.gov/pubmed/16549100

K

Kunwar, A., (2009). Computational Fluid Dynamics: An Introduction. *E-Vision*.

M

Merrill, E.W., (1969). Rheology of blood. *Physiological Reviews*, 49,pp.4

Moura, J.P., (2011).Analysis and Simulation of Blood Flow in Portal Vein with Uncertainty Quantification. Instituto Superior Tecnico. [Online]. Available: https://dspace.ist.utl.pt/bitstream/2295/1051326/1/Tese_.pdf

O

O' Callaghan, S., Walsh, M., McGloughlin, T., (2005). Numerical modelling of Newtonian and non- Newtonian representation of blood in a distal end-to-side vascular bypass graft anastomosis. *Science Direct Elsevier*. **28**: p. 70-74.

P

Poltem, D., (2012). A Review: Hemodynamics of Cerebral Aneurysm with Mathematical Modeling. *International Mathematical Forum*, 54, pp. 2687-2693

S

Stuart, J., Kenny, M.W., (1980). Blood Rheology, 33, 417-429.[Online]. Available: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1146104/

Sheard, G. J., Flow Dynamics and Wall Shear Stress Variation in a Fusiform Aneurysm. Journal Eng Math (2009). 64. p: 379-390.

W

WHO. (2012, September). Cardiovascular Diseases (CVD) [Online]. Available: http://www.who.int/mediacentre/factsheets/fs317/en/index.html

Wikipedia.(2013). Navier Stokes Equation.[Online]. Available: http://en.wikipedia.org/wiki/Navier%E2%80%93Stokes_equations

Y

Yale Medical Group. (2013). Cerebral Aneurysm: What is a Cerebral Aneurysm?. Yale School of Medicine. [Online]. Available: http://www.yalemedicalgroup.org/stw/Page.asp?PageID=STW025719

APPENDICES

Project Management

Problem Statement and Objective of the project

Identifying the purpose of this research project

Literature Review

Gathering as much information as possible from various sources such as journals and websites

Simulation Process

Identifying the subjects that need to be investigated and the procedures to conduct the simulation using FLUENT

Data Analysis and Interpretation

The findings obtained are analyzed and interpreted. A comparison with other literature are carried out to look for differences.

Documentation and Reporting

The whole research project will be documented and reported in detail. Recommendations for further improvement in the future will also be discussed.

Milestones

FYP I

Week	Milestone
7	Submission of Extended Proposal
11	Completion of Geometry
12	Completion of Meshing
13	Submission of Interim Draft Report
14	Submission of Interim Final Report

FYP II

Week	Milestone
2	Completion of Newtonian Model
2	Completion of Power Law Model
3	Completion of Carreau Model
4	Completion of Herschel-Bulkley Model
5	Completion of Cross Model
6	Completion of Carreau-Yasuda Model
7	Submission of Progress Report
10	Pre-SEDEX
11	Submission of Draft Report
12	Submission of Dissertation (soft bound)
12	Submission of Technical Paper
13	Oral Presentation
15	Submission of Project Dissertation (hard bound)

Gantt Chart For FYP I

NO	DETAIL WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Title															
2	Literature Review on Blood Properties and Wall Shear Stress (WSS)								M I							
3	Submission of Extended Proposal Defence							●	D							
4	Preparation for Oral Proposal Defence								-							
5	Oral Proposal Defence Presentation								S							
6	Detailed Literature Review on Blood Properties and WSS								E							
7	Preparation of Interim Report								M							
8	Submission of Interim Draft Report														●	
9	Submission of Interim Final Report															●

● Suggested milestone

Process

Gantt Chart For FYP II

NO	DETAIL / WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Simulation Process on The Project Continues								M								
2	Submission of Progress Report								I	●							
3	Simulation Work on The Project Continues								D								
4	Pre-SEDEX								-			●					
5	Submission of Draft Report								S				●				
6	Submission of Dissertation (soft bound)								E					●			
7	Submission of Technical Paper								M					●			
8	Oral Presentation														●		
9	Submission of Project Dissertation (hard bound)																●

● Suggested milestone

Process