ANALYSIS OF STEADY FLOW FOR VARIOUS CEREBRAL ANEURYSM SIZE

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BORANG PENGESAHAN STATUS TESIS♦

JUDUL: **ANALYSIS OF STEADY FLOW FOR VARIOUS CEREBRAL ANEURYSM SIZE**

SESI PENGAJIAN: **2009/2010**

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ANALYIS OF STEADY FLOW FOR VARIOUS CEREBRAL ANEURYSM SIZE

MOHD ZAMRI DERAMAN

Thesis submitted in fulfillment of the requirements
For the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

NOVEMBER 2009

APPROVAL DOCUMENT

UNIVERSITI MALAYSIA PAHANG
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We certify that the project entitled “Analysis of steady flow for various cerebral aneurysm sizes“is written by Mohd Zamri Deraman. We have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award of the degree of Bachelor of Engineering. We herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering.

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SUPERVISOR'S DECLARATION

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

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STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Thank God, my dearest father, mother, brother and sisters for their love and care….as well as my friend and foes….the joy we had….the pain we shared….always on my mind…

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ABSTRACT

Investigation on the changes of flow patterns in a blood vessel with a fixed fusiform aneurysm resulting from placement of a different size of aneurysm. The velocity profile and pressure distribution had been analysis from different size of aneurysm. Three different modeling of aneurysm had been analysis which is small, large, and giant. The diameter of small aneurysm is less 12mm. For the large aneurysm is between 12mm to 25mm of diameter. The giant sizes are about more 25mm in diametr. To identify the changes in local hemodynamics due to stent implantation, a stented and non stented aneurysm model was taken into considerations. The simulation of the model was studied under incompressible, Non-Newtonian, viscous, non pulsatile condition in which we investigated computationally in a three-dimensional configuration using a fluid dynamics program. Hence, the different size of aneurysm produces the different results of flow field in aneurysm. The velocity gets with different analysis from different size of diameter aneurysm. Different pressure distribution is feature from aneurysm that have different diameter. Aneurism that have big diameter will show changes in the pressure distribution graph. However, aneurysm that have small diameter can be detected using special device. Research and analysis parameter or other factor that influence flow in the aneurysm must be consider in future research.

ABSTRAK

Kajian mengenai perubahan bentuk aliran didalam salur darah telah dibuat ke atas aneursm simetri dengan diameter ukuran aneurism yang berbeza. Profil halaju dan taburan tekanan diperolehi hasil dari struktur ukuran diameter yang berbeza. Tiga rekabentuk model aneurism yang dikaji iaitu kecil, besar dan sangat besar. Diameter size aneurism kecil ialah kurang dari 12mm. Untuk aneurism size besar diantara 12mm hingga 25mm. Diameter size aneurism sangat besar ialah lebih dari 25mm. Aneurism tanpa implant stent dan aneurism dengan implant stent diambil kira dalam kajian untuk menentukan perubahan hemodinamik darah. Simulasi model dikaji dengan parameter aliran mampat, bukan Newtonian, bendalir likat dan keadaan tiada denyut menggunakan program dinamik bendalir tiga dimensi. Perbezaan struktur ukuran telah menghasilkan bentuk aliran yang berbeza disekitar aneurism. Halaju yang berbeza diperolehi daripada aneurism yang mempunyai ukuran yang berbeza. Taburan tekanan juga berbeza dikaji daripada aneurism yang mempunyai ukuran diameter yang berbeza. Hanya aneurism yang mempuyai diameter yang besar sahaja yang menunjukkan perubahan dalam graf taburan tekanan. Walaubagaimanapun, aneurism yang mempunyai diameter kecil dapat dikesan menggunakan alat khas. Kajian dan analisis parameter atau factor lain yang mempengaruhi aliran didalam aneurism perlu diambil kira untuk kajian masa akan datang.

TABLE OF CONTENTS

CHAPTER 2 LITERATURE REVIEW

CHAPTER 3 METHODOLOGY

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

u_i	velocity in the i-th direction
P	pressure
f_i	body force
ρ	density
μ_i	viscosity
δ_{ij}	Kronocker delta
A	area
a	acceleration vector
B	body force vector per unit volume
E	total energy
f	friction factor
g	local acceleration of gravity
K	thermal conductivity of working fliud
L	length
m	mass
Re	Reynolds number
P	pressure
Q	volume flow rate
T	temperature

t	time
U	internal energy for system
V	velocity
$\mathcal{T}$	Shear stress
ω	vorticity vector
Φ	dissipation function
Ψ	stream function

LIST OF ABBREVIATIONS

WSS	Wall Shear Stresss
FVM	Navier-Stokes Finite-Volume
GDCs	Guglielmi Detachable Coils
CFD	Computational Fluid Dynamics
GTA	Computer tomographic angiography
MRA	Magnetic resonance angiography

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

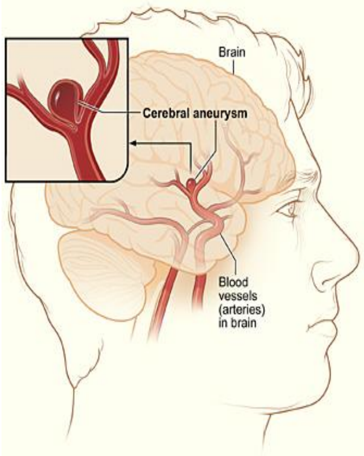
An aneurysm is a balloon-like in an artery. Aneurysm is very dangerous for now day because an aneurysm that bleeds into the brain can be to stroke or death. This happens due to when an aneurysm grows and become giant enough can burst, causing dangerous and bleeding inside the body. This is because the blood cannot flow liberally and the aortic walls rupture. Aneurysms occur in arteries in the brain, heart, intestine, neck, spleen, back of the knees and tight. For example if the aneurysm in the brain bursts, it causes a stroke. In United States, about 15 000 people die each year because ruptured aortic aneurysms (David C, 1999).

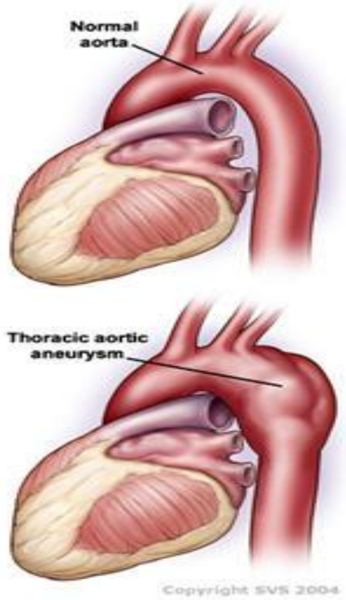
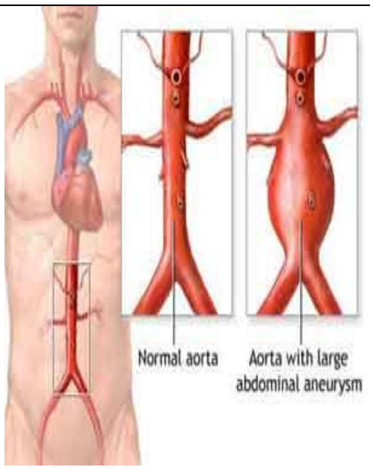
In this project, I consider the first part of the project the modeling and simulation of different size aneurysm has been investigated using a methodology which is Solid Work and Cosmos Flow. In the second part the focus has been placed on the blood flow dynamics in branching geometries approaching the microvessels. A computational model has been usedto study of the bifurcation influence on the blood flow distribution. In the flow analysis, the time-dependent, three-dimensional, incompressible Navier–Stokes equations for Non-Newtonian fluid have been applied.Movement of blood flow has been simulated using the volume of fluid method. In the third part of this project modeling and simulation of flow behavior of cerebral aneurysm with different diameter and differant neck' s aneueysm. To predict the behavior of blood flow, velocity, static preesure and real wall was applied at the system. The simulation results have been evaluated by comparing them with published preview in terms of different size of cerebral aneurysm.

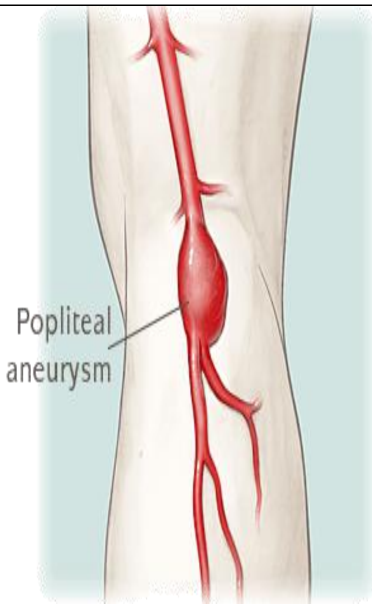
1.1 TYPE OF ANEURYSM

Four main type of aneurysm which are cerebral aneurysm, thoracic aortic aneurysm (TAA), abdominal aortic aneurysm (AAAs)**,** Peripheral Aneurysm (Popliteal) have explained in table 1.1

Table 1.1: Type of Aneurysm

No	Type	Explanation	Figure
1.	**Cerebral aneurysm**	-At the brain are called cerebral aneurysms which develop at the point a blood vessel branches. -Sometimes we called berry aneurysms because that size like a small berry. -Mainly cerebral aneurysms make no symptoms until they become large and burst, begin to leak blood, or rupture.	 Cerebral aneurysm Source:www.daviddarling.info

2.	**Thoracic aortic aneurysm(TAA)**	-At the aorta through the thorax. -Size like a balloon(Fusiform and saccular). -Internal bleeding and to shock or death.	 Thoracic aortic aneurysm Source:www.vascularweb.org
3.	**Abdominal Aortic Aneurysm(AAAs)**	-At the aorta through the abdomen. -Size grow very large about >5.5 cm in diameter. -Also internal bleeding and shock or death	 Abdominal Aortic Aneurysm Source:www.bailey-law.com

4.	**Peripheral Aneurysm(Popliteal)**	-In the popliteal artery which lower thigh and knee. -Size very larger about an inch in diameter. -Do not rupture but it block flow to limbs or brain	 Peripheral Aneurysm Source:www.vasculardoc.net

1.2 SYMPTOMS

Symptoms is depends location of aneurysm and type of aneurysm. This aneurysm can show symptoms until their very large or rupture. When this happen blood flow cannot flow correctly and that it can show signs. Aneurysm to grow large takes for years to showing any symptom. Many aneurysms are present without symptoms and are discovered by feeling or on x-ray films during a routine examination. When symptoms occur, they include a pulsing sensation and there may be pain if the aneurysm is pressing on internal organs. In some cases, the aneurysm may leak blood, causing pain without the rapid deterioration characteristic of a rupture. Also, clots often form in the aneurysm, creating danger of embolisms in distant organs. Another cases, aneurysm may dissect into the wall of an artery, blocking some of the branches. In this situation, people can feel symptoms of aneurysm.

1.2.1 Cerebral aneurysm

At this location the people may have warning signs, including blurred or double vision, sensitivity to light (photophobia), loss of sensation, and a droopy eyelid, pain above or behind the eye, a dilated pupil, and weakness in area of body, cranial nerve palsy, headaches, pain in neck and face and lastly difficulty speaking.

1.2.2 Thoracic aortic aneurysm

This thoracic aortic aneurysm is not show any symptoms if the aneurysm not to leak or grow. Possible warning sign include pain in the mouth, neck and upper back, chest or back pain, coughing, hoarseness and trouble breathing.

1.3.3 Abdominal aortic aneurysm

Abdominal aortic aneurysm (AAAs) has no signs or symptoms until they rupture. When sign are there, we can include, pain in the back or the side of the abdomen, coldness, numbness, or tingling in the feet due to blocked blood flow in the legs, a pulsing feeling in abdomen and heartbeat, on rare occasions, feet may develop pain, discoloration, or sores on the toes or feet, abdominal pain, pain in the lower back that may give off to the buttocks, groin or legs, paleness, dry mouth/skin and excessive thirst, nausea and vomiting and lastly symptoms of shock, such as shaking, dizziness, fainting, sweating, rapid heartbeat and sudden weakness.

1.3.4 Peripheral aneurysm

Signs and symptoms of peripheral aneurysm while it is small may include a pulse that can be felt in your neck, arm, or leg, pain at leg or arm pain, or cramping with exercise, hurting sores on toes or fingers and tissue death which blocked blood flow in the limbs.

1.4 DIAGNOSIS OF ANEURYSM

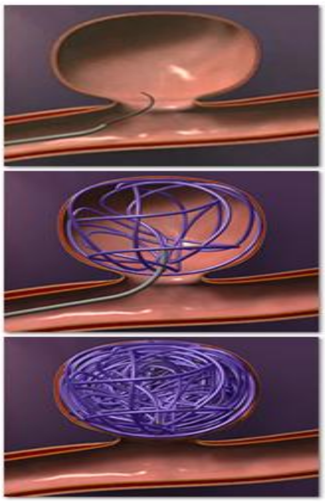
To detect and estimate an aneurysm, one or more test and procedures may be perform;

1. Chest X-ray. A chest X-ray can show a picture of the organs and structures inside the body, including the heart, lungs, and blood vessels. So, an aneurysm can be detected from these producers.
2. Computed tomography (CT scan). A CT scan is a computer-generated and X-ray images of the internal organs. This test to suspects a TAA or AAA. The CT scan images can show size and shape of an abdominal aneurysm. This is more perfectly than an ultrasound
3. Magnetic resonance imaging (MRI). MRI uses strong magnetic and radio waves to produce image of an aneurysm. This is very precise in detecting location of an aneurysms and can show the size and shape
4. Angiography. Special dye injected into the blood stream to show up on X-ray pictures. An angiogram can calculated the amount of damage and block flow in blood vessels
5. Aortography. This is angiography uses to aorta. It is displays the location and size of an aortic aneurysm

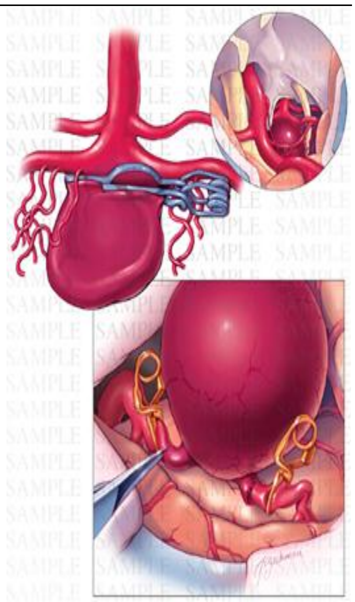
1.5 TREAMENT OF ANEURYSM

Size, location, type, condition of patient and medical history give various for treatment of aneurysm. These treatments are;

Table 1.2: General treatment of Aneurysms

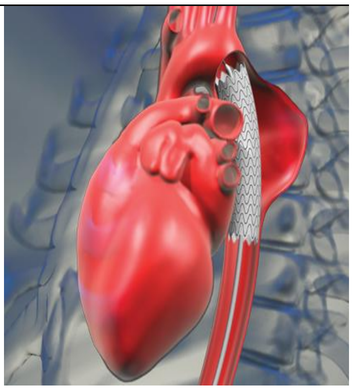
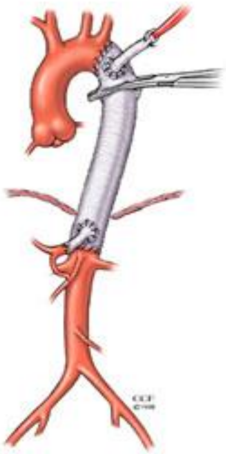
No.	Type of Aneurysm	Figure
1.	**Cerebral aneurysm** **Endovascular coiling**- Guido Guglielmi was introduced this treatment an aneurysm in 1991. A hollow plastis tube into the artery at leg , during the aorta, into the brain arteries, and finally at location aneurysm as show at figure right. This coils made of platinum so we can see this coil through the arteries with X-ray. **Surginal cliping**- Walter Dandy was introduce this method to treatment an anuerysm. This method use a clip on the aneurysm,s neck for block the blood into this aneurysm like figure right. To this method should uses microscope because a clip very small and must carefully to clip the anuerysm,s neck. To put this clip must be surgical procedure to open the brain and the blood vessels. **Medical treatment**- This is called medical therapy because this option for the the treatment unburst aneurysm. First, control the smoking ang checking the blood pressure to avoid the	 Endovascular coiling (Source: www.neurosurgerytoday.org)

anuerysm more larger. The patient must always meet a doctor to checking the size ang growth anuerysm with radiograhic like MRA.CT Scan or convebtional angiography.



Surginal cliping

(Source:aneurysmsymptoms.com)

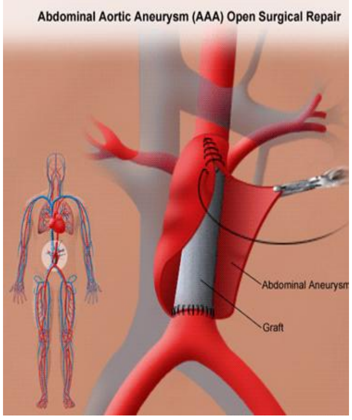
2.	**Thoracic aortic aneurysm(TAA)** **Endovascular stent graft**- Without open the chest, using a long thin tube through the blood vessels to deliver a stent-graft by metal wire stents (scaffold) at location of thoracic aortic aneurysm like figure right. To this method the surgeon must use live X-ray picture view to guide a stent-graft through blood vessel. **Open surgery** (**Surgical Repair)** - This produce must open the chest to replace the thoracic disease with a graft like figure right. This produce is the traditional method for treatment aneurysm. Take long time about 2 to 3 months for a recovery than use procedure of the endovascular stent graft. **Watchful Waiting**- This is for small aneurysm has detected at aorta by CT or MRI. Every 6-12 months must checking aneurysm to avoid size aneurysm larger. At this time must take medication for control blood pressure and cholesterol to maintain blood vessel.	 Endovascular stent graft (Source: www.uthscsa.edu)  Open surgical, replace by graft (Source: my.clevelandclinic.org)

3. **Abdominal Aortic Aneurysm(AAAs)**

Surgical Repair- This is surgery to open abdominal repair for remove the aneurysm and replaced with an artificial graft like figure right. So, the blood folw through at this stent graft to decrease the pressure on the wall to avoid the aneurysm from rupture.

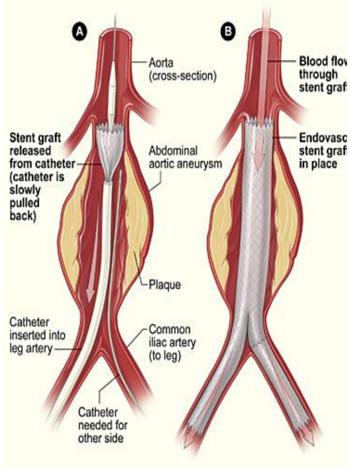
Interventional Repair- This treatment is not removing an aneurysm open an abdominal but a graft inserted at the location of aneurysm like figure right. By using X-ray image for guide a stent-graft inserted at aorta disease. The stent-graft make new wall in the blood vessel for the blood flow smoothly.

Watchful waiting- This is produce to reduce to get an aneurysm like don’t smoke, stable blood pressure, always checked cholesterol, exercise and maintain a healthy weight.



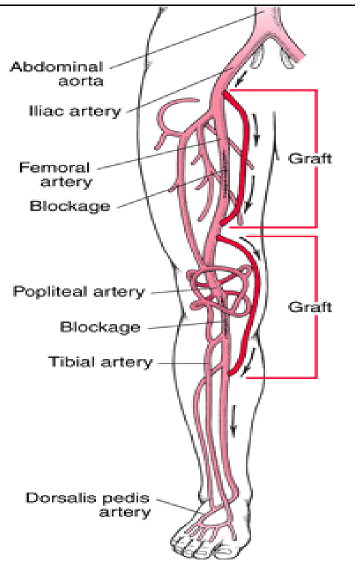
Surgical repair

(Source: intensivecare.hsnet.nsw.gov.au)



Interventional Repair

(Source: www.nhlbi.nih.gov)

4.	**Peripheral Aneurysm(Popliteal)** **Surgical Bypass or Replacement-** By using a graft to create new pathway to allow blood flow to pass around the leg like figure right. Why to use this procedure because the blood flow through the artery is blocked.	 Surgical bypass (Source: www.merck.com)

1.6 OBJECTIVES

The objectives of this study are to study flow phenomena on different aneurysm size. The flow of blood through the brain will be having disturbance if the aneurysm start to grow in our brain. The different size of the anueysms will affect the blood flow through the brain. If the size of aneurysms is still small, it will not have any effect on the flow of blood or any fluid that pass through it. When the size is become larger, the person who facing with this aneurysm symptom will feel pain at the aneurysm part in the brain. This is because the blood in the brain cannot flow uniformly cause bt the aneurysm stuck at the blood vessels. When it comes to giant size, aneurysm will burst and can cause serious injuries in the brain, Some will having coma, some will die.

To investigate the relationship between flow phenomena the neck and diameter of aneurysm. There are relationship between flow phenomena through the neck and diameter of aneurysm. The aneurysm that have diameter <12mm have the simple flow of blood through it.

1.7 PROJECT SCOPES

The scopes of the study are to analysis is on various aneurysm sizes. Studies have shown that the occurrence of brain aneurysms and risk of rupture vary aneurysm size. Research has indicated that aneurysm hemodynamics may be one of the important factors related to aneurysm growth and rupture, our aim was to analyze and compare the flow parameters in aneurysms at different size.

Non Pulsatile blood flow will be used. Evolving blood pump technology has formed user-friendly continuous-flow left ventricular assist devices, but improbability exists about the safety of chronic nonpulsatile circulation. Recent experimental and clinical evidence recommend that pulse pressure is not required from a blood pump. End-organ function is well maintained with nonpulsatile systems, even though pulse pressure may accelerate recovery from cardiogenic shock. Form follows function, so the effects of reduced pulse pressure on the arterial wall are not shocking. Doubts about the feasibility of long-term circulation with reduced pulse pressure are disappearing.

Solutions will be based on numerical approach only. A computational fluid dynamics approach was used to determine the velocity field, wall shear stress, and pressure distribution within a model of a basilar artery before and after a simulated occlusion of one vertebral artery. Blood is regarded incompressible and Non-Newtonian. The simulations were performed by a commercial Navier-Stokes finite-volume (FVM) code (STAR-CD®).

CHAPTER 2

LITERATURE REVIEW

2.1 DEFINITIONS CEREBRAL ANEURYSM

A cerebral aneurysm is an area where a blood vessel in the brain weakens, resulting in ballooning out of part of vessel wall. An aneurysm develop at the point where a blood vessel branches. Sometimes called berry aneurysm because the size of small berry. Cerebral aneurysm can rupture, causing bleeding into and around the brain (hemorrhage). This is a very serious medical condition that requires immediate treatment. Cerebral aneurysms do not show symptoms until they become large or burst. People can experience like pain around the eye area, numbness or weakness particularly on one side of the face and visualization changes. If an aneurysm rupture, patients may feel a sudden, extremely severe headache, nausea and changes in mental status.

These cerebral aneurysms are the maybe defect is present at birth, certain genetic diseases or circulatory disorders. It is predictable that between 10 and 15 million Americans have cerebral aneurysms. Of these, about 30,000 people experience an aneurysm rupture every year. Thus, the majority aneurysms do not burst. This because an aneurysm very small and stable and may not cause clear symptoms. Because of this, most aneurysms are not detected until they grow and rupture. Several tests may be used to diagnose a cerebral aneurysm by using Angiography, CAT scan or MRI may be used to confirm the aneurysm, assess the extent of damage from the hemorrhage and help plan treatment. Figure 2.1 show location of a cerebral aneurysm.

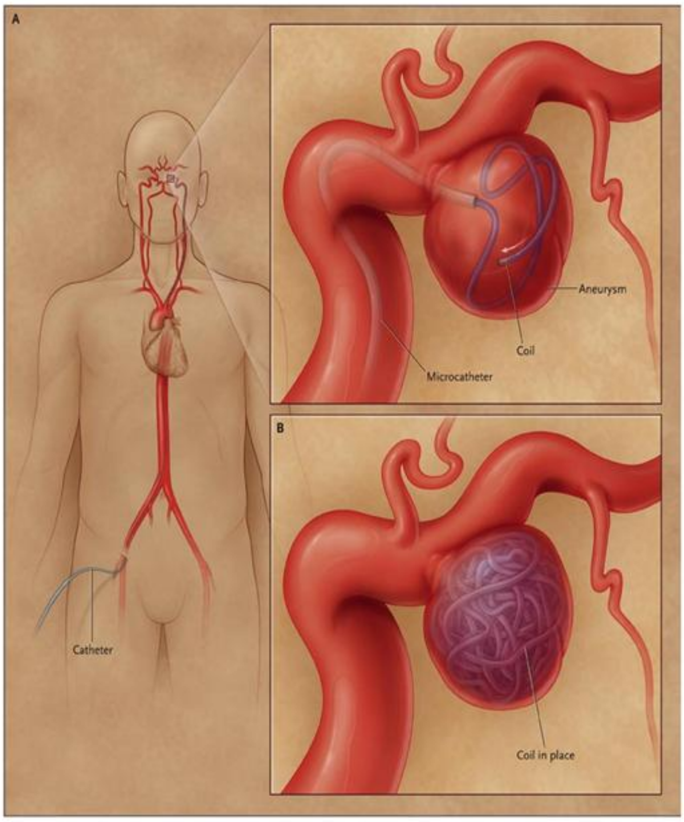


Figure 2.1: Cerebral Aneurysm with endovascular coiling

Source: content.nejm.org

2.2 TREATMENT OF CEREBRAL ANEURYSM

Size of aneurysm, location of aneurysm, type of aneurysm, condition of patient, medical history and other factors must consider first before treatment. Physicians may recommend surgery that involves clipping or clamping off the affected artery. The type of surgery choose to repair the aneurysm is based on number of factors. There are two surgical options for treatment cerebral aneurysm like therapy or clipping and endovascular therapy or coiling.

For cerebral aneurysm there have two surgical options for treatment cerebral aneurysm. There is surgical therapy or clipping and endovascular therapy or coiling. For surgical clipping, the first person who surgically treats the brain aneurysm is Victor Horsley, MD in 1855. Walter Dandy, MD introduced the method of clipping an aneurysm in 1937 which is applied a V-shaped, silver to the neck of cerebral aneurysm. The mechanical complexity of available clips, along with the advent of the operating microscope in the 1960s have made surgical clipping the gold standard in the treatment of both ruptured and unruptured cerebral aneurysms. To this method an aneurysm is clipped through a craniotomy where surgical procedure in which the brain and blood vessel and through an opening in the skull where aneurysm location. When aneurysm is detected, it is carefully separated from surrounding brain tissue to avoid effect another risk at the brain. This clip usually made from titanium to avoid from rust and strength. This small metal clip is applied to the neck of the aneurysm. This aneurysm clips come different shapes and size based on size and location of an aneurysm. The mechanism of this clip is has a spring which allows two jaws of the clip to close the neck of an aneurysm. This is for close around side of aneurysm, thus separating the aneurysm from the origin blood vessel. Figure 2.2 show the aneurysm clip at cerebral aneurysm.

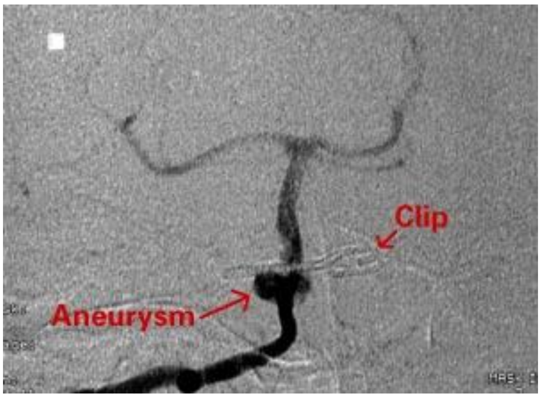


Figure 2.2: The aneurysm clip and the residual aneurysm under the clip

Source: Courtesy of Dr. Kieran Murphy, Johns Hopkins University, Department of Radiology

Second surgical options for treatment an aneurysm is endovascular coiling. This technique starts from 1970 with the introduction of proximal balloon occlusion. Fjodor A. Serbinenko, MD is first person to explain about this method to treatment of an aneurysm. In 1980 endovascular treatment of aneurysms with balloon angioplasty was associated with high procedural rate of rupture and complications. In 1995, the development of Guglielmi detachable coils (GDCs) and their FDA for revolutionized endovascular treatment of cerebral aneurysms. Guglielmi detachable coils, known as GDCs, are soft wire spirals made out of platinum. This technique is does not require open surgery or open the skull. There use real-time X-ray technology, called fluoroscopic imaging, to visualize the patient's vascular system and treat the disease from inside the blood vessel. Once the patient has been anesthetized, the doctor inserts a hollow plastic tube (a catheter) into an artery (usually in the groin) and threads it, using angiography, through the body to the site of the aneurysm. Using a guide wire, detachable coils (spirals of platinum wire) or small latex balloons are passed through the catheter and released into the aneurysm. The coils or balloons fill the aneurysm; block it from circulation, and cause the blood to clot, which effectively destroys the aneurysm. Figure 2.3 show that coiling and clipping at cerebral aneurysm.

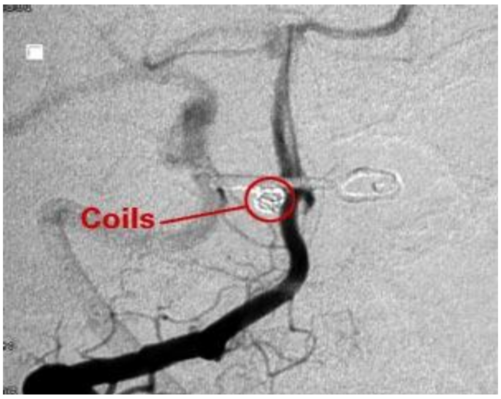


Figure 2.3: Coils were placed endovascularily in the residual aneurysm, and it was excluded from the circulation. This operation illustrates that many situations can require both the coiling and clipping procedures

Source: Courtesy of Dr. Kieran Murphy, Johns Hopkins University, Department of Radiology

2.3 HEMODYNAMIC OF CEREBRAL ANEURYSM

In this study hemodynamics of cerebral aneurysm which is a forces involved in the circulation of blood i.e. hemodynamics concerns the physical factors governing blood flow within the circulatory system. In this cases parameters are believed to be responsible for aneurysm initiation, growth and rupture (Steiger, 1990). The important hemodynamic parameters include pulsatile nature of blood flow, blood pressure and wall shear stress. These fluid mechanical forces also intricately regulate structure and function of endothelial cell layer, the innermost layer of a vessel wall (Barakat, 2000). Aneurysm and parent vessel geometry, neck size, blood viscosity, wall elasticity etc. affect the hemodynamics of cerebral aneurysms. However, in large vessels, wall elasticity, non-Newtonian viscosity, slurry particles in the fluid, body forces and temperature are often neglected because of their secondary importance (Wootton, 1999).

2.3.1 Pulsatile Flow

About pulsatile nature of blood flow dominates many of the problems in the cardiovascular system. The studies incorporating pulsatile flow reveal characteristic features of the cardiovascular system. For example, Fukushima et al. (Fukushima, 1998) carried out aneurysm flow experiments as well as two-dimensional simulations. They determined as the flow velocity increased, center of an intra-aneurysmal vortex moved from proximal end to distal end of an aneurysm. During a period of the cardiac cycle, transient reversal flow occurred, which caused the vortex to appear and disappear. They assume that pulsatile flow produced a flow pattern that was quite different than the steady flow. They determined that the presence of an oscillatory component in the flow velocity altered the steady flow pattern. A pair of vortices behind, and a horseshoe vortex in the front of the stenosis characterized the pulsatile flow pattern. Taylor et al. (Taylor, 1994) also showed periodic changes in the location and width of the above-mentioned vortex. They can induce vibrations of the aneurysm wall that contribute to progression and eventual rupture (Ortega, 1999). For the present CFD study to capture the pulsatile flow dynamics, which was done using physiological velocity waveform in a basilar artery. Figure 2.4 show that velocity vector field and figure 2.5 show that comparison of velocity profile.

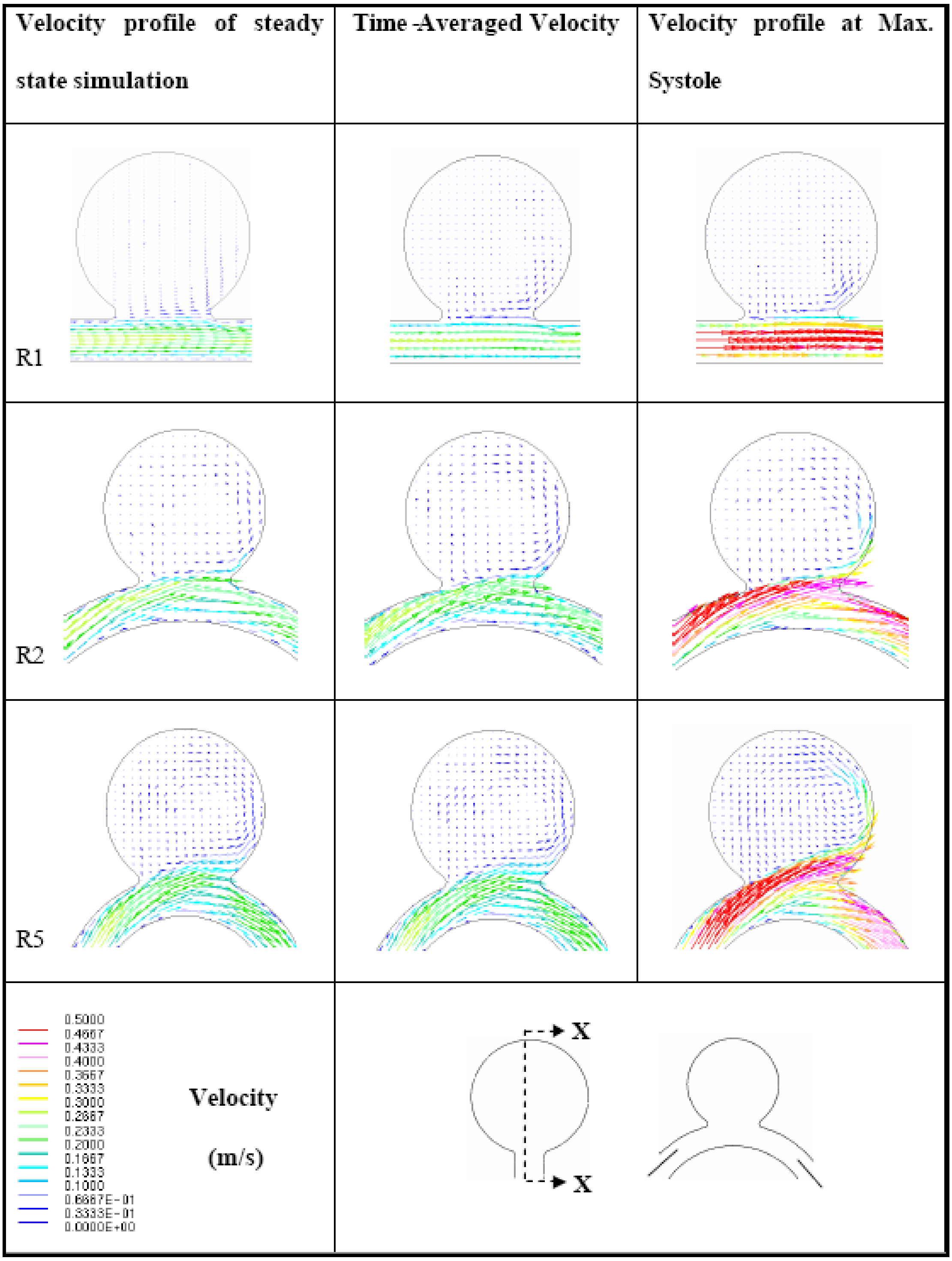


Figure 2.4: Velocity vector field and maximum sydtole of pulsatile flow simulation from Yie Meng Hoi, 2003

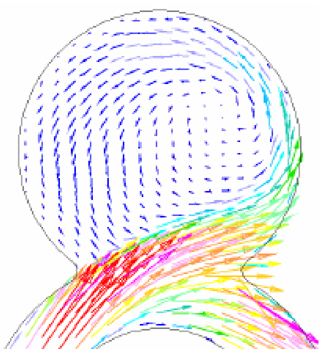
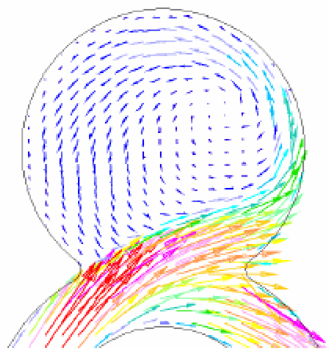
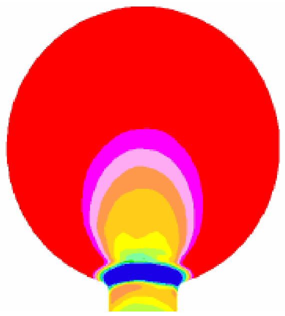
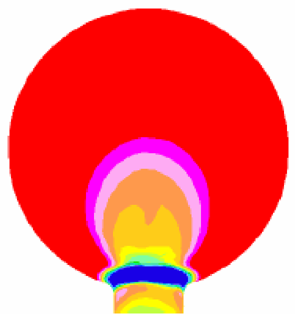
Steady-state simulation with Re equal to peak systole in pulsatile flow	Pulsatile simulation at peak systole
a) 	b) 
c) 	d) 

Figure 2.5: Comparison of velocity profile and WSS distribution from Yie Meng Hoi, 2003

2.3.2 Blood Pressure

In this stduy is about blood pressure that is across the thickness of a wall greatly influences cell and vascular remodeling. This pressure induces circumferential stress, referred to as Hoop stress. It is possible that the primary determinant of smooth muscle cell response is the local strain due to the Hoop stress acting on these cells. A study by Austin et al. (Austin, 1989) showed a reproducible relationship between aneurysm pressure and volume. This nonlinear relationship was described by an N-shaped pressure-volume curve. Increased pressure surges produced a linear increase in volume starting at the neck, until a threshold pressure was reached at a high nonlinear compliance. At this point there was an abrupt jump in volume to a new stable equilibrium. A gradual further linear increase in aneurysm pressure could eventually result in aneurysm rupture, which always occurred in the thinner and more compliant part of the wall (Austin, 1989). From equation as the blood pressure increases, the Hoop stress will proportionally increase. As a consequence, he arterial wall may remodel in response to the elevated Hoop stress by secretion and organization of collagen and elastin (Wootton, 1999). This can be estimated by Laplace's law as:

$$s = 0.5\times P\times D\times t\ \text{-}1 \quad (2.1)$$

2.3.3. Wall Shear Stress (WSS)

Wall shear stress is about the endothelial cells, an innermost layer of a vessel wall, sense and respond to the blood wall shear stress (WSS). Besides that the WSS also modulates diameter adaptive responses, intimal thickening and platelet thrombosis and thus central to the vascular response to hemodynamics. An increase in flow causes dilation of the artery until the *WSS* reaches the baseline level of the artery. This baseline level is thought to be 15-20 dyne/cm2 for human arteries (Wootton, 1999). The *WSS* is a product of the shear rate, at the wall and the fluid dynamic viscosity, m. Shear stress for a laminar steady flow in a straight tube is

$$\mathcal{T} = \frac{32\mathcal{U}q}{\pi D^2} \quad (2.2)$$

This approximation is a reasonable estimate of the mean *WSS* in arteries (Wootton, 1999). In Ortega, 1999 said that on a histological level, aneurysms are formed by damage to endothelium and internal elastic lamina, believed to be caused by high levels of shear stress. The endothelial cells exposed to large spatial gradients of shear stress migrate away from these gradients, while cells exposed to relatively small shear stress gradients do not exhibit such behavior (Depaola, 1992). Thus, the elevated levels of shear stress affect the integrity of the endothelial cell lining of blood vessels, contributing to weakness of the wall, and thereby to rupture of the vessel (Atkinson, 2001)

2.4 SHAPE OF CEREBRAL ANEURYSM

An aneurysm is classified by size, shape, location, origin, vessel type and whether other diseases are present. In figure 2.6(a) show that secular or berry aneurysm is most common type intracranial aneurysm. They are usually spherical in shape with an irregular appearance. In figure 2.6(b) show that some aneurysm grows, the neck broadens and sometimes incorporates branches. Most saccular aneurysm which rupture have diameters of 5 to 15 millimeters. Fusiform, mycotic and traumatic is other type of aneurysm. In figure 2.6(c) show that fusiform aneurysm are spindle-like diatations, that encompass the entire vessel with no distinguishable neck. For mycotic aneurysm is rare to develop at cerebral aneurysm. Figure 2.6(d) show that shape of mycotic aneurysm.

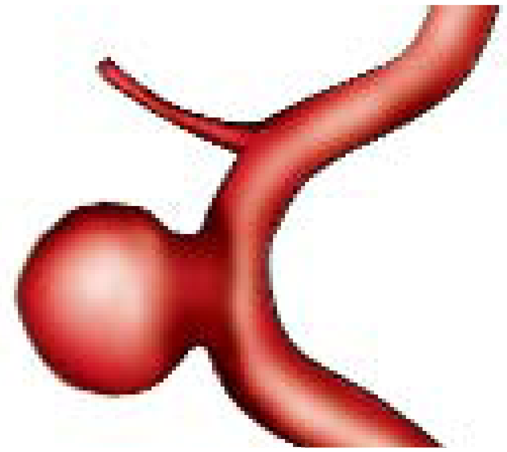


Figure 2.6(a): Saccular berry aneurysm with narrow neck

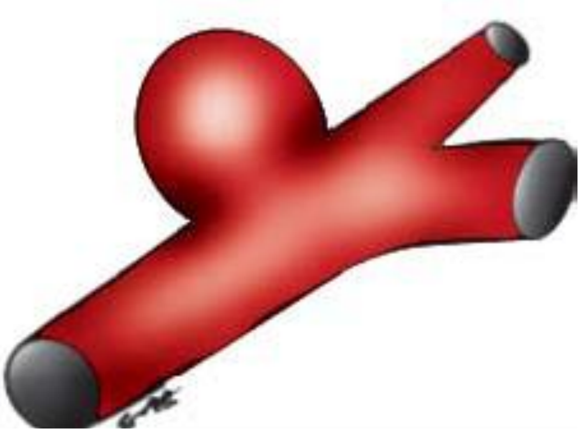


Figure 2.6(b): Fusiform (short section of artery bulges all the way around the vessel like a spindle.

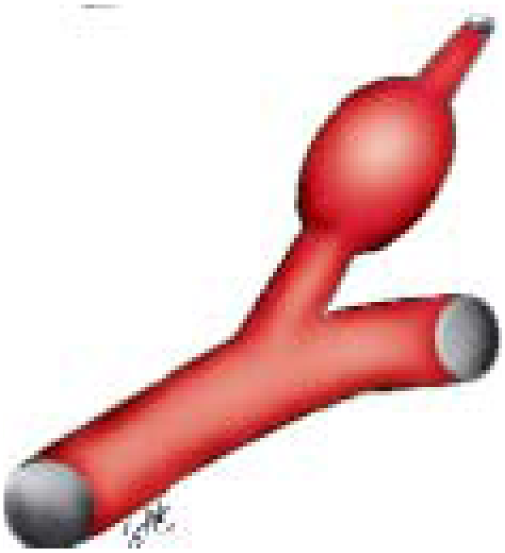


Figure 2.6(c): Saccular aneurysm with a broad neck. These aneurysm do not lend themselves to coiling

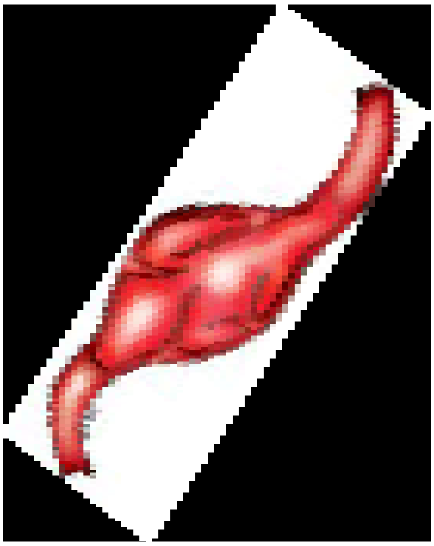


Figure 2.6(d): Mycotic (rare, caused by infection)

Source: Journal flow-assisited aneurysm surgery, F.T. Charbel, MD, G. Meglio MD, 2004

2.5 SIZE OF CEREBRAL ANEURYSM

Aneurysm size is both supposedly and empirically a key prognostic factor for rupture. However, the critical size at which an aneurysm becomes hazardous is unknown (Kassel, 1983). In a study by Kassel and Torner (Kassel, 1983), the angiographic size of aneurysms in 1092 patients was measured. The results found that 71% of the sacs were smaller than 10 mm and 13% were less than 5 mm in diameter. These data suggested that aneurysms greater than 5 mm in diameter were hazardous and treatment should be considered immediately. A study by Weir *et al.*(Weir , 2002) on 22-ruptured aneurysms showed that all aneurysms with diameters greater than 4 mm contained ruptured points in their domes. These studies enhance the importance of aneurysm size. The present computational analysis uses aneurysm sizes, which are in range of critical values.

Many researchers have attempted to determine whether there is a critical size at which an aneurysm is likely to rupture (Forget Tr Jr, 2001). Members of the Stroke Council concluded that incidental aneurysms smaller than 10mm should be observed rather than treated (Bederson JB, 2000). In a study conducted by Rosenorn et al., among the 908 ruptured aneurysms that had a maximum diameter less than 25 mm, 162 ruptured aneurysms were less than 5 mm, 474 and 272 were between 5-10 mm and 11-24 mm, respectively (Rosenorn J, Eskesen V, 1994). They recommended that unruptured aneurysms with a size 10 mm or less should be seriously considered for operative closure of the aneurysm. Kassel et al. suggested aneurysm greater than 5mm in diameter were hazardous and treatment should be considered immediately, whereas Crompton suggested the critical size at which an aneurysm is about to rupture is between 2 and 5mm (Kassell, N.F, 1983). However, a lot of clinical reports revealed that aneurysm can rupture at smaller than 5mm or remain unruptured at greater than 10mm. In vitro experiment showed that as the aneurysm size increases, the inflow angle to the aneurysm decreases, thereby reducing the flow activity in the aneurysm (Liou T, Liao C, 1997). Thus, the aneurysm becomes more susceptible to thrombosis. It is, therefore, possible that large aneurysm remains unruptured. Consequently, although there is a critical size for the rupture of each aneurysm, it is quite unlikely that this size is identical in each aneurysm (Burleson A, 1995). Thus, the risk assessment based on aneurysm size alone is insufficient to predict the outcome of aneurysm therapy. Table 2.1 shows that size of cerebral aneurysm. Figure 2.7(a), 2.7(b), 2.7(c) shows that flow at cerebral aneurysm with different size.

About aspect ratio of aneurysm neck and size defines the volume and velocity of flow into and out of the aneurysm, thereby affects the distribution of hemodynamic stresses (Ujiie H, Tachibana H, Hiramatsu O, 1999). In study Ujiie et al. defined the geometrical parameter, aspect ratio as the ratio of aneurysm depth to aneurysm neck width. This parameter includes the aneurysm neck width in addition to the aneurysm size alone. Besides that, Ujiie et al. showed that 80% of all aneurysms with aspect ratio of 1.6 or higher were ruptured aneurysms. The difference in aspect ratios between the ruptured aneurysm and unruptured aneurysms was statistically significant (Ujiie H, Tamano Y, 1983). However, in the same study, 20% of ruptured aneurysms are associated with aspect ratio less than 1.6, which cannot be excluded from treatment. Nevertheless, Ujiie et al. have shown that the aneurysm geometry is important to address the development and risks. The development of aneurysm into non-spherical shape, as seen inclinical cases, is intuitively relevant to the hemodynamic stresses.

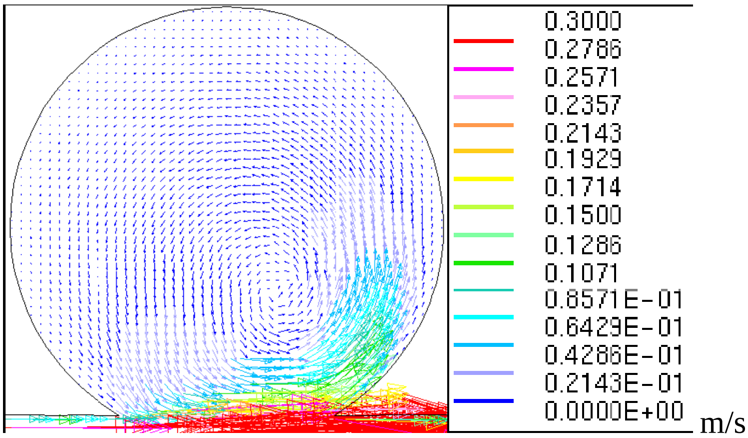


Figure 2.7(a): Small aneurysm

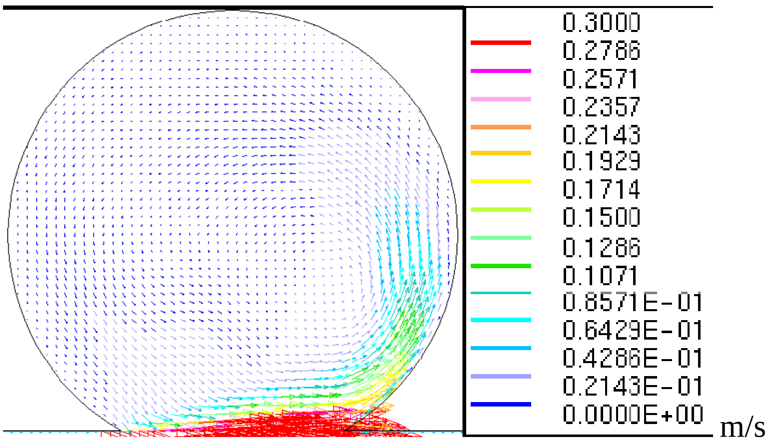


Figure 2.7(b): Large aneurysm

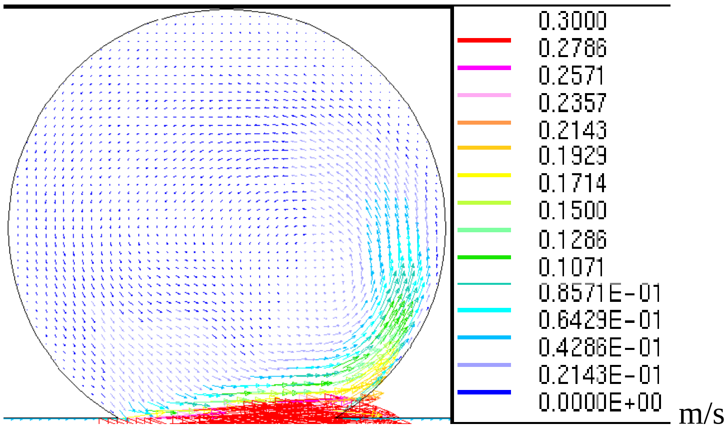


Figure 2.7(c): Giant aneurysm

Source: Journal computational modeling of cerebral aneurysm hemodynamic, Amol Suresh Mulay, 2002

Table 2.1: Sizes of cerebral aneurysm

Diameter of an aneurysm	**Classification**	**Percentage of Cases**
<12 mm	Small	79%
12-25 mm	Large	19%
>25 mm	Giant	2%

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

The main idea of this chapter is to describe the methodology used in the study to collect data and analyze of steady flow for various cerebral aneurysm size. The step and solution mentioned based on numerical approach only by various cosmos flow software.

3.2 FLOW CHART

This chapter focuses on how the analysis will be conducted. Based on guidelines stated in Chapter 2, this chapter will emphasize on how this project will be carried out from the beginning of the process until the end of the analysis of the project, which is to study the flow behavior of cerebral aneurysm. Next is to investigate the flow behavior with different size of aneurysm. Figure 3.1 illustrate the flowchart for the overall final year project and chronology if this project.

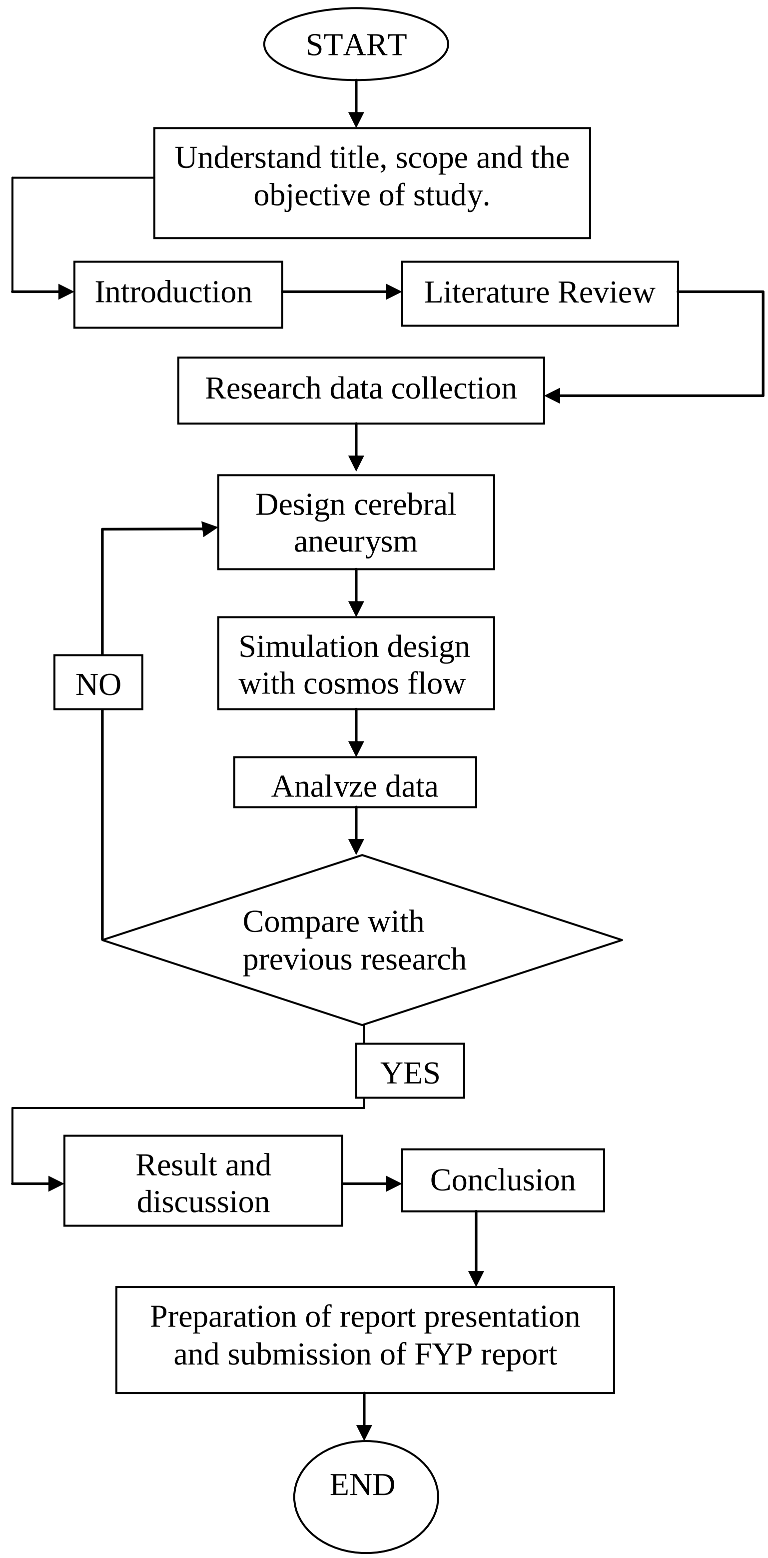


Figure 3.1: Flow chart for overall FYP

3.3 PROCESS IN CFD (Computational Fluid Dynamics)

From the literature study, hemodynamic parameters play an important role in formation, growth and bust of cerebral aneurysm. These parameters need to be quantifying for dissimilar aneurysm geometries. A Computational Fluid Dynamics (CFD) analysis was used for quantitative understanding and characterization of the hemodynamic parameters for threedimensional key generic aneurysm geometries. By applying the steady-state or time-dependent boundary conditions, the governing Navier-Stokes equations in each computational cell can be solved to obtain the entire flow field. In addition, other hemodynamic parameters, such as WSS, pressure, residence time, wall deformation, vorticity, and etc, can be accurately derived from the solution. The CFD analysis can be divided into three parts like pre-processing, solver and post processing like figure below;

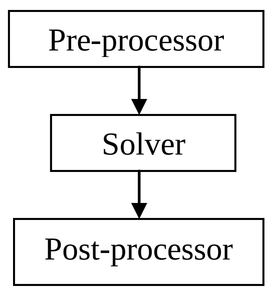


Figure 3.2: Process in CFD

3.3.1 Pre-processing

The first step of the simulation contains the input of the flow problem through a userfriendly interface and then transforming the input into a form applicable by the solver. In the pre-processing stage involves like to definition of the geometry of the region of interest as te computional domain. In pre-precessing alos has grid generation of the subdivision of the domain like a grid of cells and selection of the physucal and chemical phenomena that need to be modeled. Beside that, it also to definition of fliud properties. The pre-precessing stage involves also Specification of appropriate boundary conditions at cells which coincide with or touch the domain boundary and specification of intial conditions.

3.3.1.1 Geometry of model

Each geometry file was created using Solid Works. The dimensions chosen for these geometries were from literature study and recommendations by supervisors. The model of aneurysm at artery with diameter of 8mm and the aneurysm size is 8mm, 10mm, 12mm, 14mm, 16mm, 18mm, 20mm, 22mm, 24mm, 25mm and 26mm diameter with different aneurysm neck size. The wall aneurysm size is set 0.5mm. This wall is not effect to the flow aneurysm because this wall is not elastic. Example model of aneurysm size of 25mm diameter as show in figure 3.3;

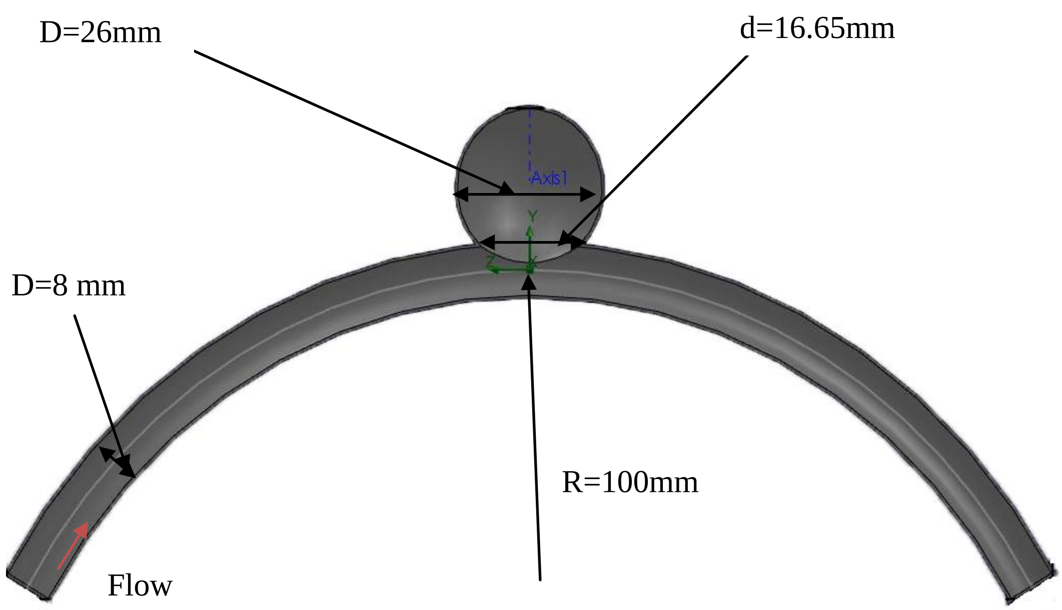


Figure 3.3: The geometry model of aneurysm size 25mm diameter.

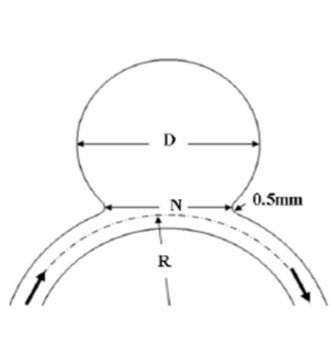


Figure 3.4: Geometry of aneurysm reference from journal Correlation of Hemodynamic Force and Aneurysm Geometry Yie Meng Hoi 2003

3.3.1.2 Velocity

Droppler ultrasound data measurement is used to set the initial condition of velocity to 0.7m/s (Marie Oshima et al, 2000). The velocity for cerebral is 0.7 m/s. As expected, the velocity profile inside the parent vessel was parabolic as show in figure 3.5(a). For the figure 3.5(b), the flow into the aneurysm was at the neck aneurysm. The flow at cerebral aneurysm is shear-driven. The intra-aneurysm flow was decided by a counterclockwise rotating vortex. Figure 3.5 show that flow inside the aneurysm was an order magnitude smaller than inside the parent vessel.

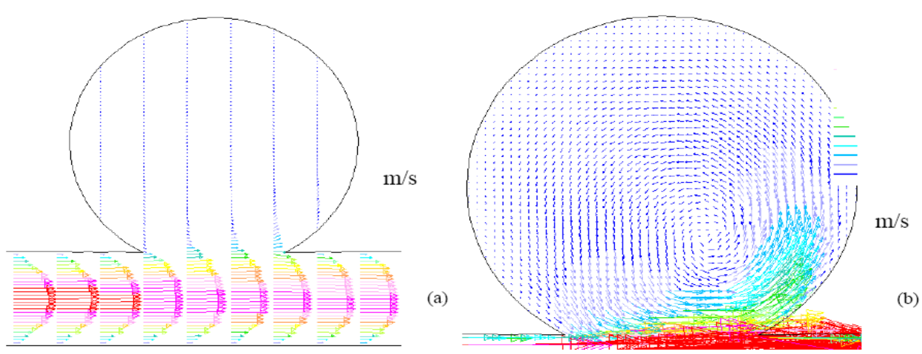


Figure 3.5: Velocity vector field in symmetry palane X=0 reference Amol Suresh Mulay,2002

3.3.1.3 Pressure Distribution

The pressure varied linearly across the parent vessel. The intra-aneurysmal pressure was more or less constant; except for a small pressure rise at the distal neck region. This pressure rise was due to vstagnation of impinging flow in that region. A rise in pressure at the distal part of the aneurysm was seen where flow impinged on the aneurysm wall. This increase in pressure is not significant as compared to the absolute value of pressure. However, the pressure difference between intra-aneurysmal stagnation pressure and the outside pressure may be significant enough to cause an imbalance of forces acting on aneurysmal wall.

3.3.1.4 Wall Shear Stress

Wall shear stress was constant about 1.4 N/m2 along the artery before into the aneurysm. Values of WSS are much smaller as compared to the parent vessel WSS. The maximal value of WSS was more than double the value along the parent vessel. The overall WSS distribution showed that the constant WSS along the parent vessel went to negative values as the flow entered the aneurysm region. The WSS increased in a negative direction, reached a negative maximum and again attained positive values. Just after the distal neck region, it reached its positive peak value. The variation of WSS from negative to positive values indicated that theaneurysm wall and parent vessel wall were stretched apart at the distal neck region. Figure 3.6(a) show WSS along the aneurysm wall and figure 3.6(b) show that WSS along the parent vessel increased dramatically just after distal neck region.

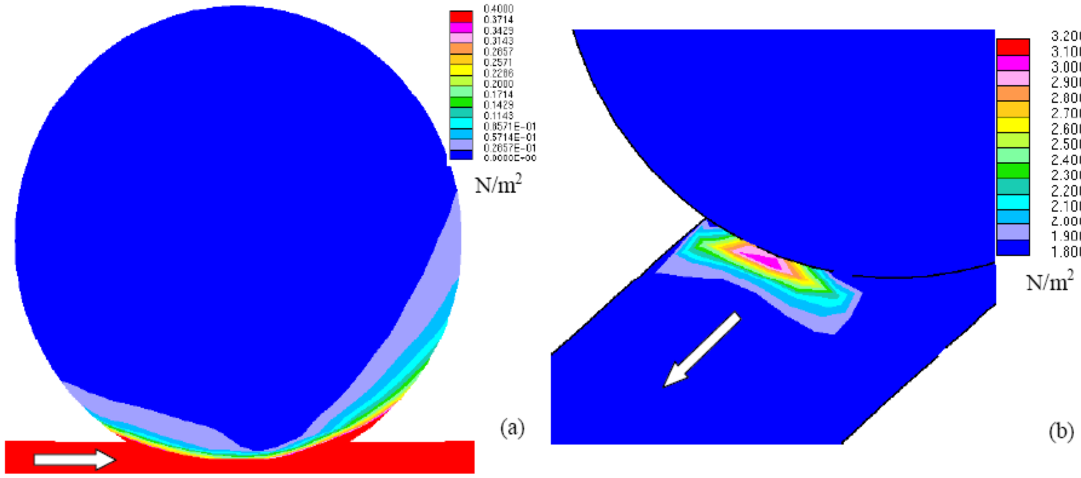


Figure 3.6: Wall shear stress distribution reffrence Amol Suresh Mulay,2002

3.3.1.5 Simulations Assumption, Parameter and Boundary Conditions

In this study, I make simulation assumptions, parameter and boundary conditions, it is assumed that blood is an incompressible, Newtonian fluid and that the flow is laminar and isothermal based on the findings of Perktold et al. (1989) and others who found minimal changes in arterial flow patterns when non-Newtonian effects were included. The parameter used in the simulation is listed in Table 3.1;

Table 3.1: Parameters used in the simulation

Parameters	**Value**
Density	1.12g/cm^3
Dynamic Viscosity	0.004Pa s
Specific Heat	3631.38 J/kgK
Thermal conductivity	0.3153 W/mK
Inlet Velocity	0.7 m/s
Static Pressure	463 pa

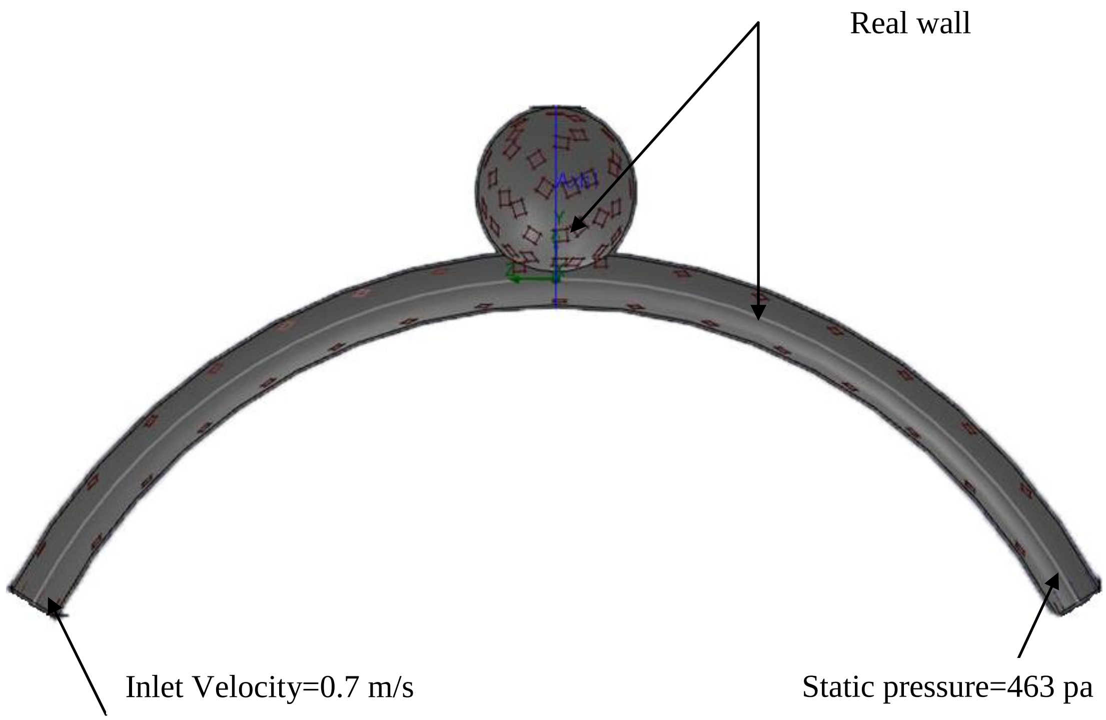


Figure 3.7: Boundary Condition of Aneurysm

3.3.1.6 Computational Mesh

The 3D aneurysm models were generated in CosmosFlow. This advanced solid modeling program allows precise control of dimensions and flexibility in generating the models. Once the 3D models were generated, these solid models were imported into CosmosFlow for mesh generation. CosmosFlow is an automated mesh generation program which supports structured and unstructured meshes. The boundary layers in each model were first generated in CosmosFlow. Then, the faces of each model were meshed accordingly using rectacgular mesh. The meshing of aneurysm show at figure 3.8;

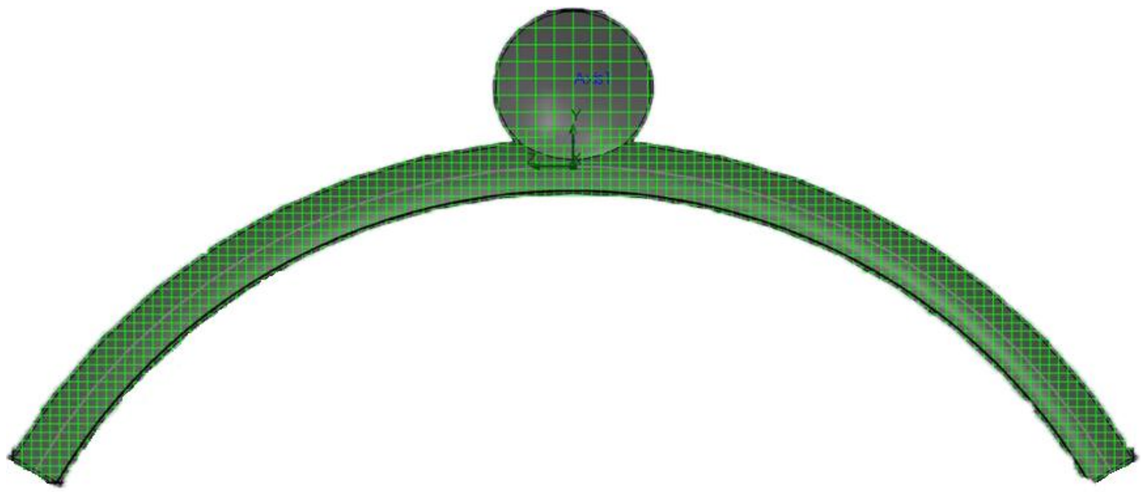


Figure 3.8: Meshing of model aneurysm

3.3.2 Solver (Numerical Solution)

There are three distinct streams of numerical solution techniques: finite difference, finite element and spectral methods. The following is an outline of the numerical methods that form the basis of the steps performed by the solver like approximation of the unknown flow variables by means of simple functions and discretization by substitution of the approximations into governing flow. In solver also Is about solution of algebraic equation like Navier-Stokes equations.

3.3.2.1 Computational Fluid Dynamics (CFD)

The CFD solver the flow calculations and produces the results. In this case I use Cosmos Flow to the analysis flow of aneurysm. CFD is one of the branches of fluid mechanics that uses numerical solutions and partial different to solve and analyze problems for fluid flows. It can perform the millions of calculations by computers to simulate the interaction of liquids with defined by boundary condition like meshing. The fundamental basic of any CFD is Navier-Strokes Equations to define any single-phase fluid flow like flow of aneurysm.

3.3.2.2 Governing Equation of Blood Flow

Blood flow is considered to be incompressible, consisting of the continuity and use Navier-Stokes equations. The governing equations of flow are written as follows for a computational domain Ώ:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{3.1}$$

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial P}{\partial x_j} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + f_i \tag{3.2}$$

u_i= velocity in the i^{th} direction

P = Pressure

f_i =Body force

ρ =Density

μ_i =Viscosity

∂_{ij} =Kronecker delta

The shear stress, τ at the wall of aneurysm calculated base on a function of velocity gradient only:

$$\tau = \mu \frac{\partial u}{\partial y} \tag{3.3}$$

Where ∂u/∂y is the velocity gradient along the aneurismal wall taking considerations of fluid viscosity. Therefore, the simple viscous fluids considered with linear correlation. The equation of motion in terms of vorticity, ω as follows:

$$\frac{\partial \omega}{\partial t} - \nabla\ X\ (V\ X\ \omega) = \frac{\mu}{\rho} \nabla^2 \omega \tag{3.4}$$

Where ω is the vorticity, ρ =Density and μ= viscosity with vector $\nabla^2 V$ evaluated as well. Solution of these equations in their finite volume form is accomplished through a commercial software package, CAE-CFD namely EFD Lab. The Navier-Stokes equations for 3D laminar flow with were solved using a finite-volume based CFD solver integrated in the EFD Lab software.

3.3.2.3 Finite-volume Method

Finite-volume is one numerical solution which is use differential equation and thus air-flow. This is similar with the finite difference method. This method was generated meshed geometry to calculated the values of modeling aneurysm. This method refer to the small volume at each node point on a mesh. In this method, by using divergence theorem that volume integrals in a partial differant equation are converted to surface integrals.

In this finite-volume method, many differential equations which we owuld like to solve come from conservation laws which are integrals over volumes. This is example partial equation has been carried onto the discretisation of such equations by instead of interpreting U_j as an approximation to a point value, $u(x_j)$, rather

$$U_j \sim \frac{1}{h} \int_{(j-1/2)h}^{(j+1/2)h} u(x)\mathrm{d}x. \tag{3.5}$$

In one sense we now reverse the process by which we arrived at the differential equation from a conservation law: take the differential equation and integrate

$$\int_{(j-1/2)h}^{(j+1/2)h} (-u'' + \kappa^2 u - f)\mathrm{d}x = 0. \tag{3.6}$$

If we integrate the first term and define

$$\bar{f}_j = \frac{1}{h}\int_{(j-1/2)h}^{(j+1/2)h} f(x)\mathrm{d}x, \tag{3.7}$$

then

$$-u'|_{(j-1/2)h}^{(j+1/2)h} + \kappa^2 h U_j - h\bar{f}_j = 0. \tag{3.8}$$

Alternately we can think of applying a conservation argument to the `volume' $((j - \frac{1}{2})h, (j + \frac{1}{2})h)$. The difficulty now is to represent the `fluxes' across the faces of the volume at $(j - \frac{1}{2})h$, $(j + \frac{1}{2})h$ in terms of the integral quantities, U_j. In this simple case we approximate

$$u'((j + \frac{1}{2})h) \sim \frac{U_{j+1} - U_j}{h}, \tag{3.9}$$

so that we end up with a coefficient matrix which is identical to the finite difference one we derived above, but the right hand side is now a vector of integrals of f

$$(\frac{1}{h^2}\mathbf{K} + \kappa^2\mathbf{I}^*)\mathbf{U} = \bar{\mathbf{f}}. \tag{3.10}$$

While this appears very similar to an ordinary finite difference method, if using unstructured meshes in two and three space dimensions (so that the `volumes' are either arbitrary triangles or quadrilaterals) the finite volume method is much easier to apply than conventional finite differences.

3.3.3 Post-Processor

This is final step of CFD simulation contain organization and interpretation of the results. The post-processor CFD is add-on for the data visualization in cosmos flow. It is process computational fluid dynamics results and allows the user to also display any function of the quantities like graphs like figure 3.10 and figure 3.11, histograms, graphical animation, generate particle trajectories, extract flow features, and estimate numerical like figure 3.9.

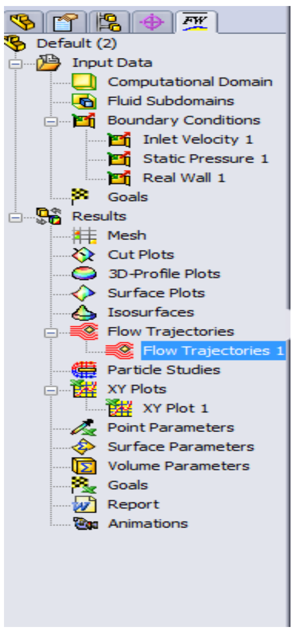


Figure 3.9:Post-processor in Cosmos Flow

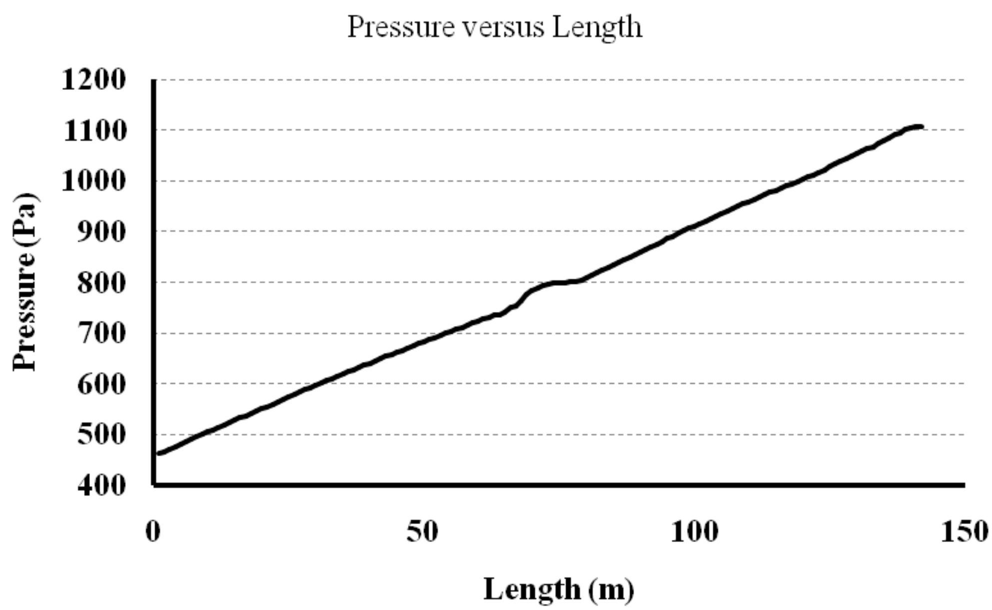


Figure 3.10: Graph Pressure versus Length about 25 mm diameter of aneurysm

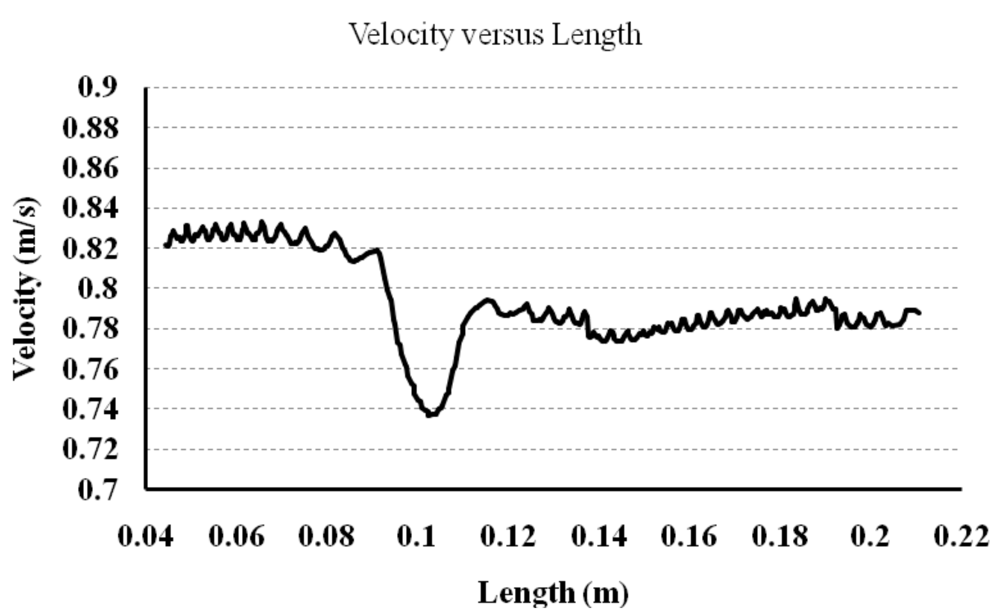


Figure 3.11: Graph Velocity versus Length about 25 mm diameter of aneurysm

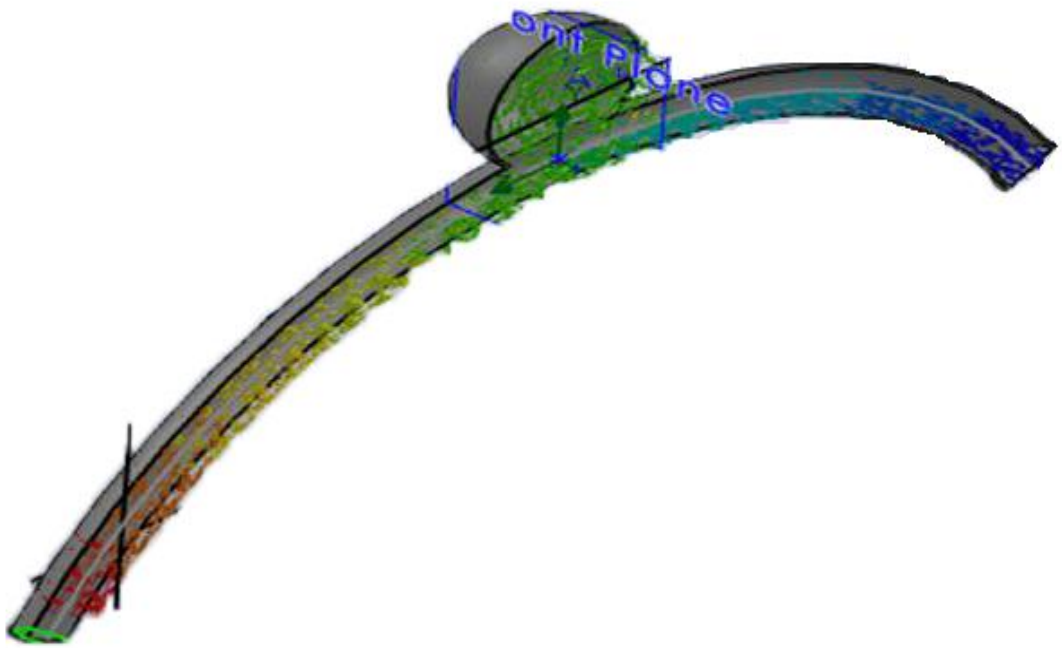


Figure 3.12: Visualization in cerebral aneurysm

CHAPTER 4

RESULT AND DISCUSSION

4.1 RESULTS

This is initial result for see flow behavior of cerebral aneurysm with different size aneurysm. In this case that aneurysm is classification by three different types which is small, large, and giant. For small below 12 mm diameter of an aneurysm is percentage of cases is about 79% to opportunity get aneurysm. For large is between 12 mm to 25 mm is percentage of cases is about 19%. At this range maybe that aneurysm ruptures. Lastly giant is above 25 mm is percentage of cases is 2% to chance get aneurysm. At this range very rare to get this diameter of an aneurysm. We can look at figure 4.1 and 4.2 that flow behavior of aneurysm. Figure 4.2(a) show pressure versus length for 8 mm diameter aneurysm. From that graph no aneurysm detected because the graph is smooth. From figure 4.2(b) until 4.22(b) show velocity versus length at inlet velocity is higher than outlet velocity because heat release by convection. About figure from 4.4(a) until 4.22(a) show that pressure versus length for 10 mm to 26 mm diameter aneurysm the graph in the middle sudden change. From that graph aneurysm was detected.

4.1.1 Small of Diameter Aneurysm

Figures 4.1 show the model of aneurysm 8mm with neck 7mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.2(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 8mm with neck 7mm not having any disturbance. This show at the graph which pressure of the blood flow is proportional to the length of aneurysm. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure is 788.79pa. At point 0.2m the pressure is 1150.97pa. Figures 4.2(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 8mm with neck 7mm show a small disturbance. (0.04m, 0.89m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.06m, 0.86m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.11m, 0.78m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.13m, 0.82m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.79m/s).

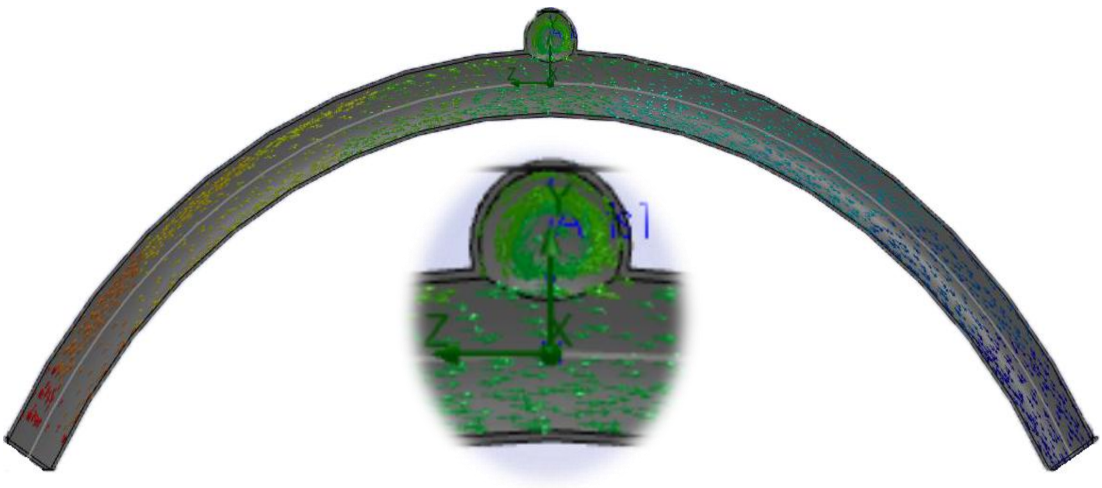


Figure 4.1: Diameter 8 mm with neck 7 mm

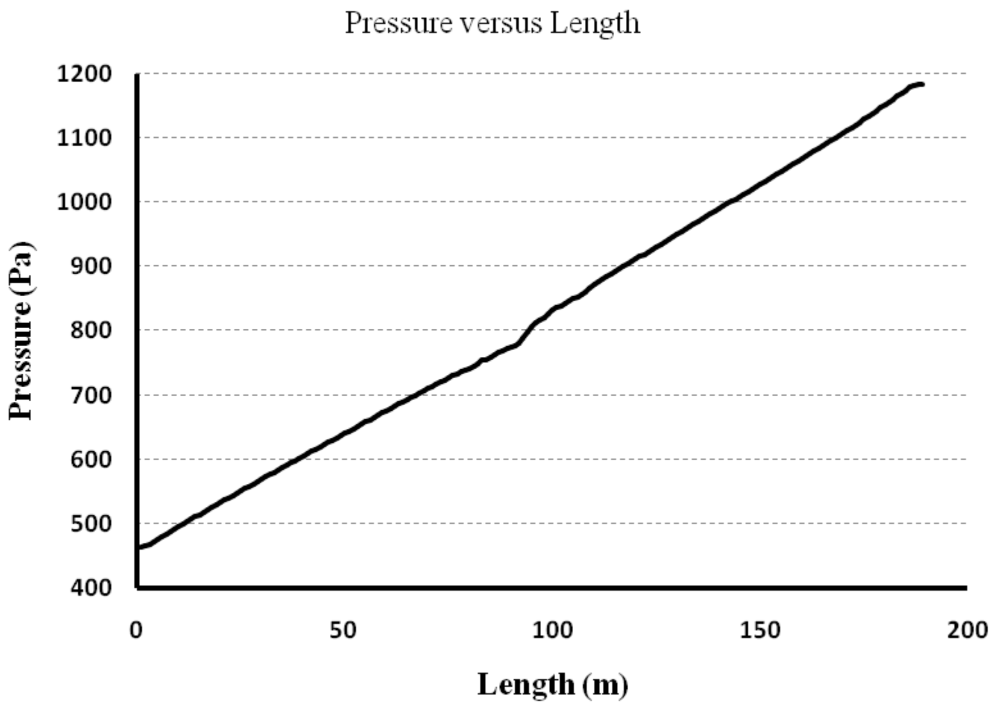


Figure 4.2(a): Pressure versus length of diameter 8 mm aneurysm

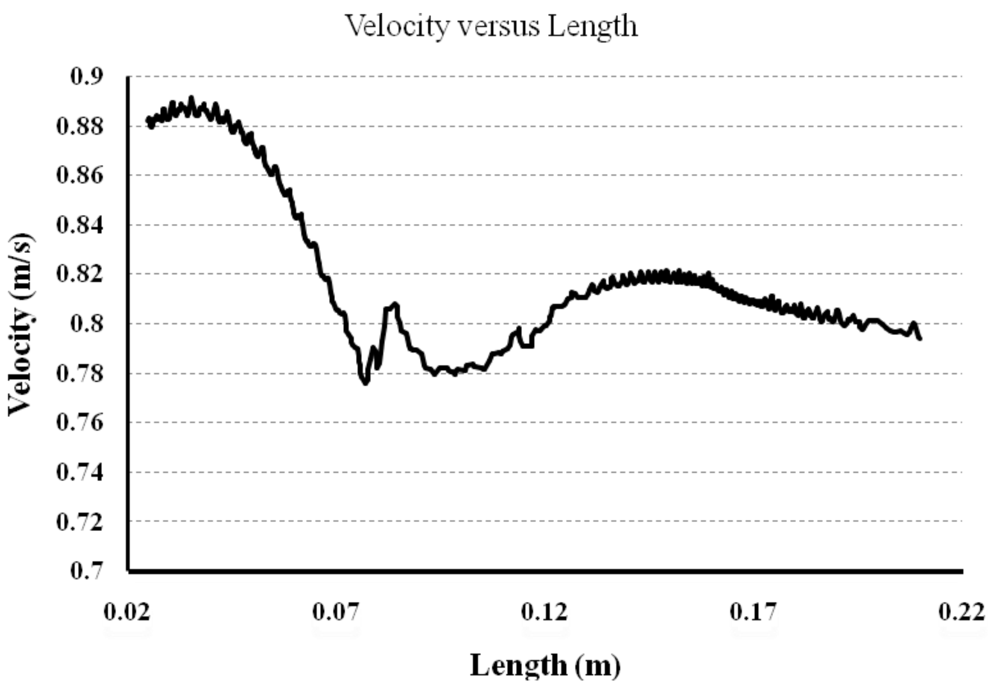


Figure 4.2(b): Velocity versus Length of diameter 8 mm aneurysm

Figures 4.3 show the model of aneurysm 10mm with neck 9.25mm diameter aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.4(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 10mm with neck 9.25mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 796.26pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1096.77pa. Figures 4.4(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 10mm with neck 9.25mm show a small disturbance. (0.04m, 0.87m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.07m, 0.81m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.09m, 0.72m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.11m, 0.79m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.81m/s).

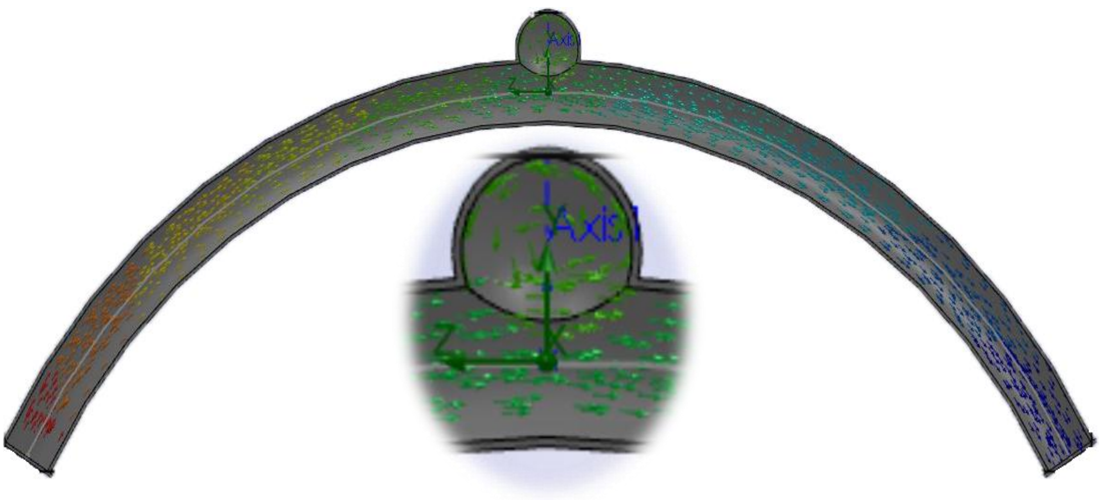


Figure 4.3: Diameter 10 mm with neck 9.25 mm

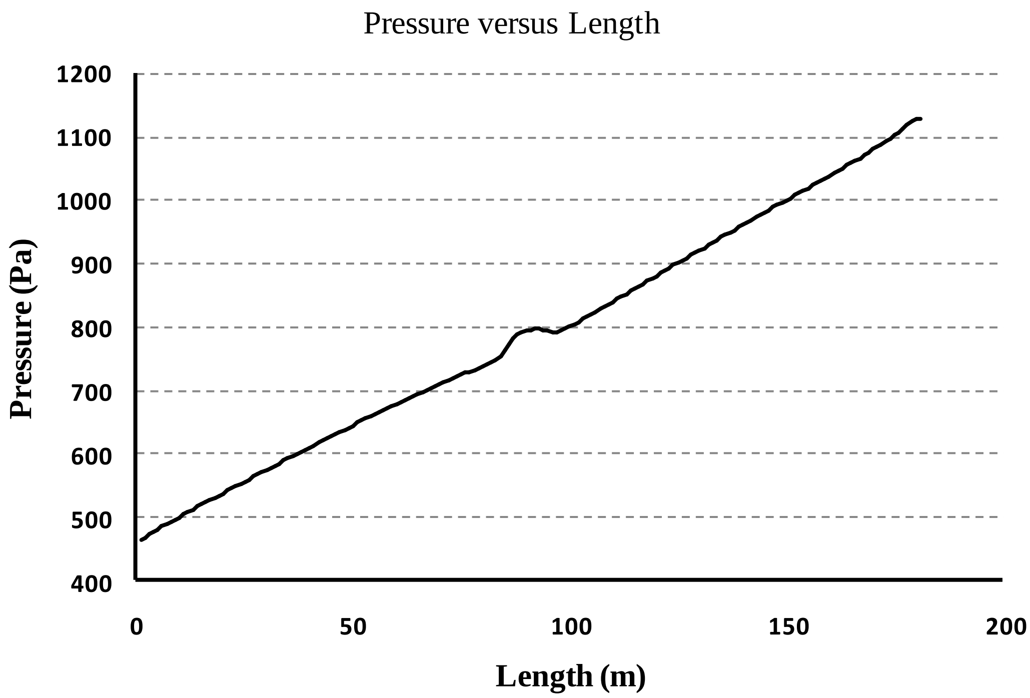


Figure 4.4(a): Pressure versus length of diameter 10 mm aneurysm

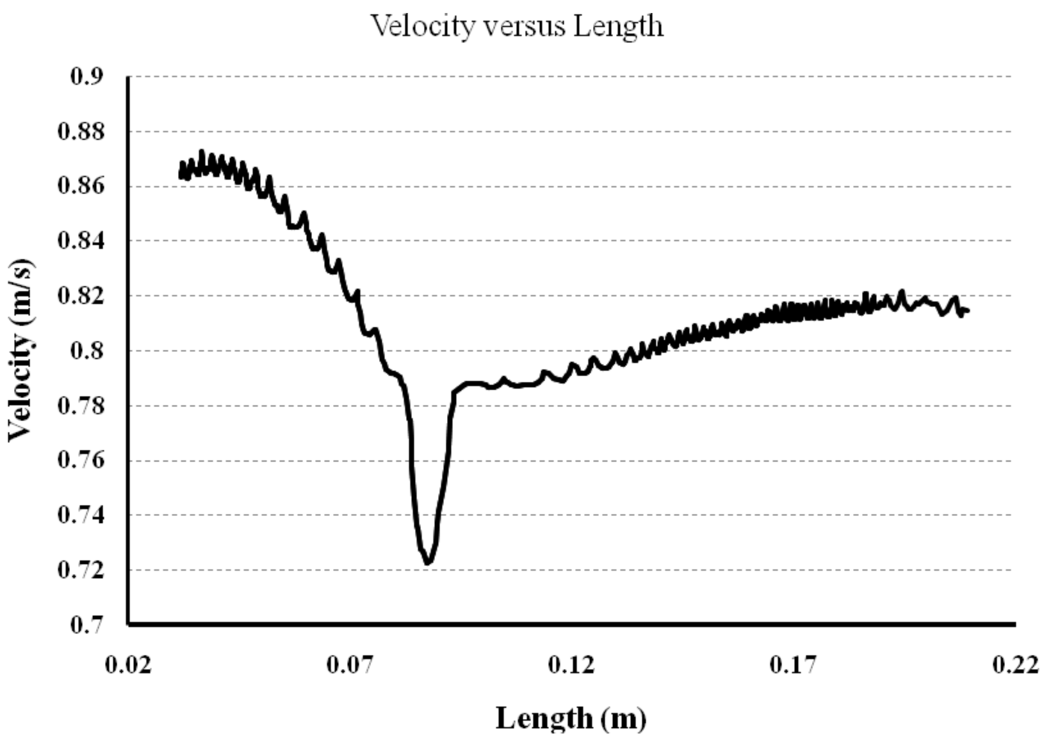


Figure 4.4(b): Velocity versus length of diameter 10 mm aneurysm

4.1.2 Large of Diameter

Figures 4.5 show the model of aneurysm 12mm with neck 9.50mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.6(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 12mm with neck 9.20mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 810.76pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1114.58pa. Figures 4.6(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 12mm with neck 9.50mm show a small disturbance. (0.04m, 0.86m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.09m, 0.80m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.12m, 0.78m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.12m, 0.78m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.78m/s).

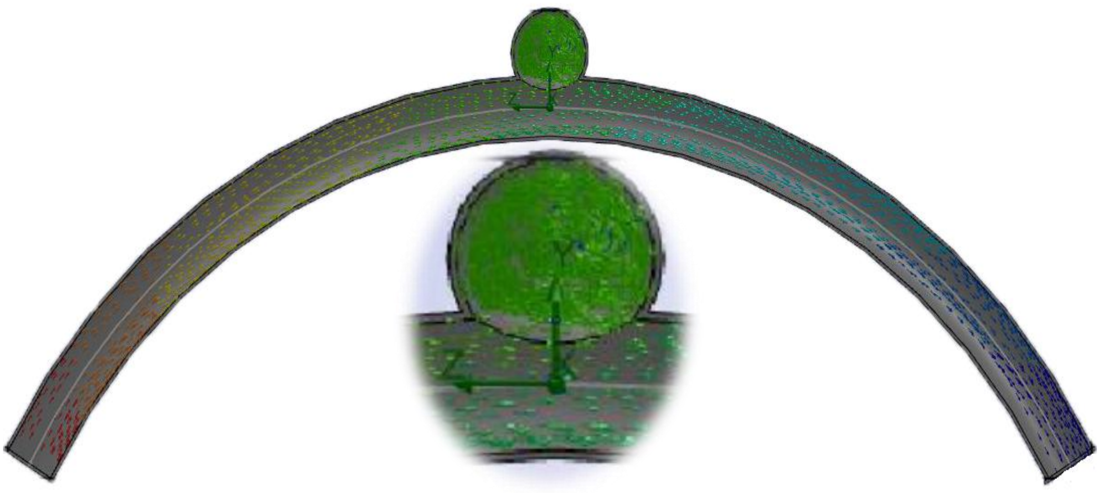


Figure 4.5: Diameter 12 mm with neck 9.50 mm

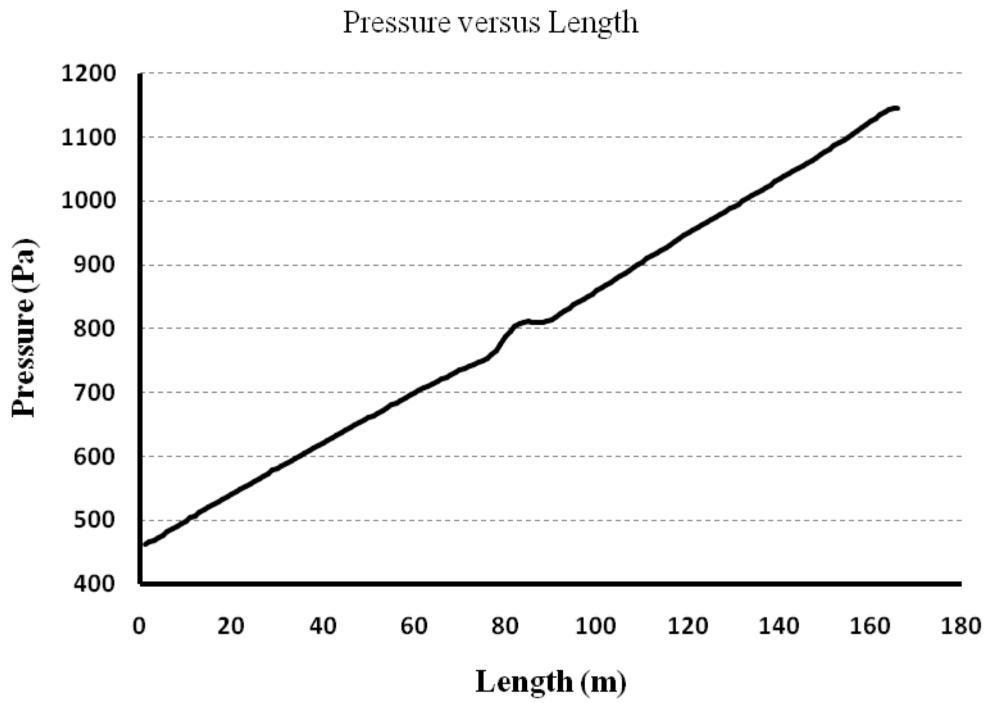


Figure 4.6(a): Pressure versus length of diameters 12 mm aneurysm

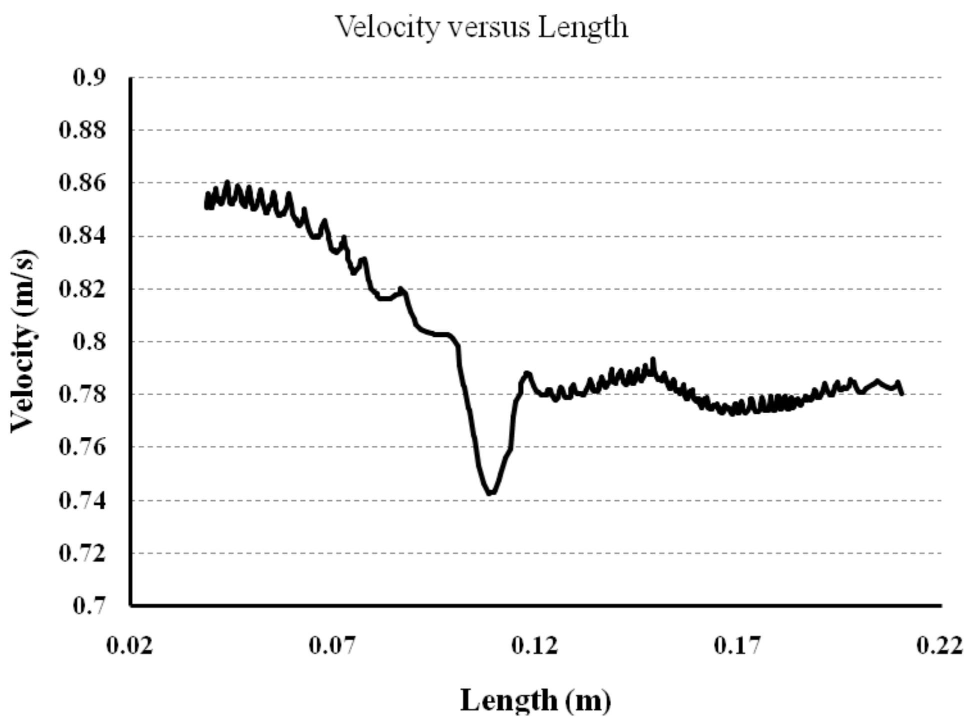


Figure 4.6(b): Velocity versus length of diameters 12 mm aneurysm

Figures 4.7 show the model of aneurysm 14mm with neck 11.80mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.8(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 14mm with neck 11.80mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 803.59pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1097.51pa. Figures 4.8(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 14mm with neck 11.80mm show a small disturbance. (0.04m, 0.85m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.09m, 0.84m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.10m, 0.79m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.11m, 0.85m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.81m/s).

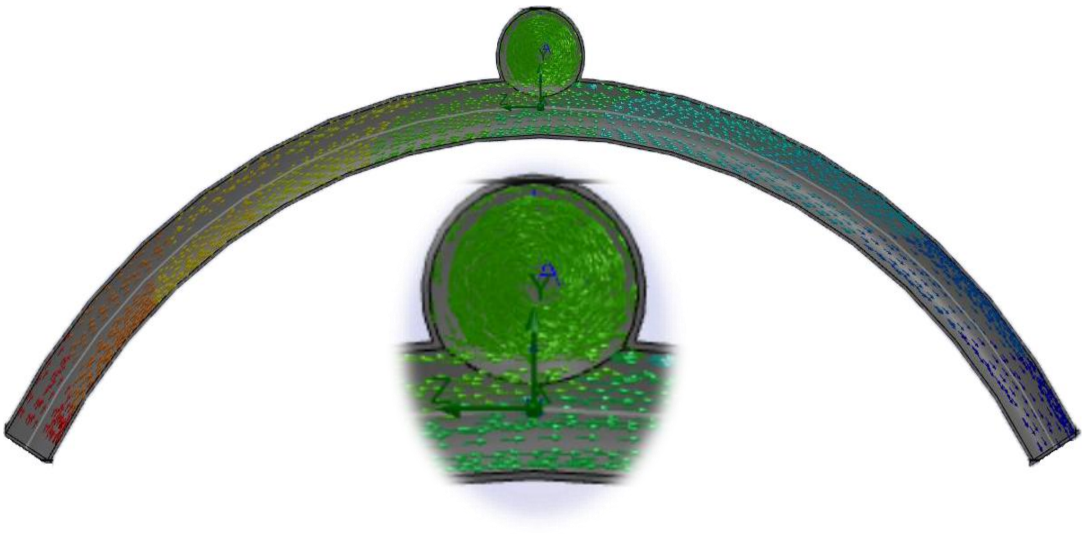


Figure 4.7: Diameter 14 mm with neck 11.80 mm

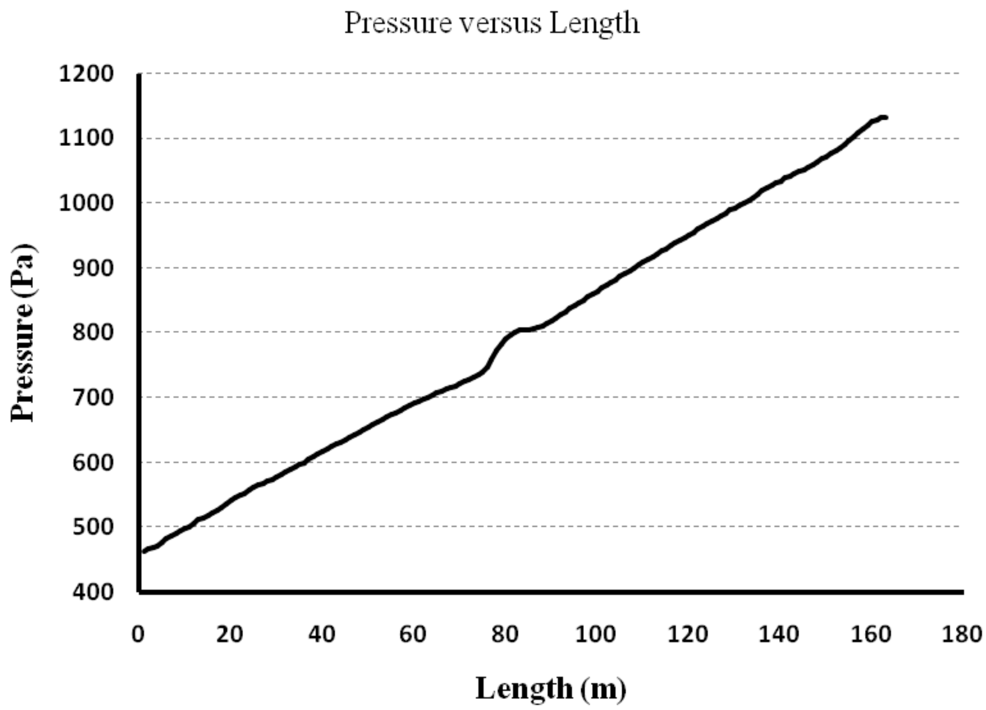


Figure 4.8(a): Pressure versus length of diameters 14 mm aneurysm

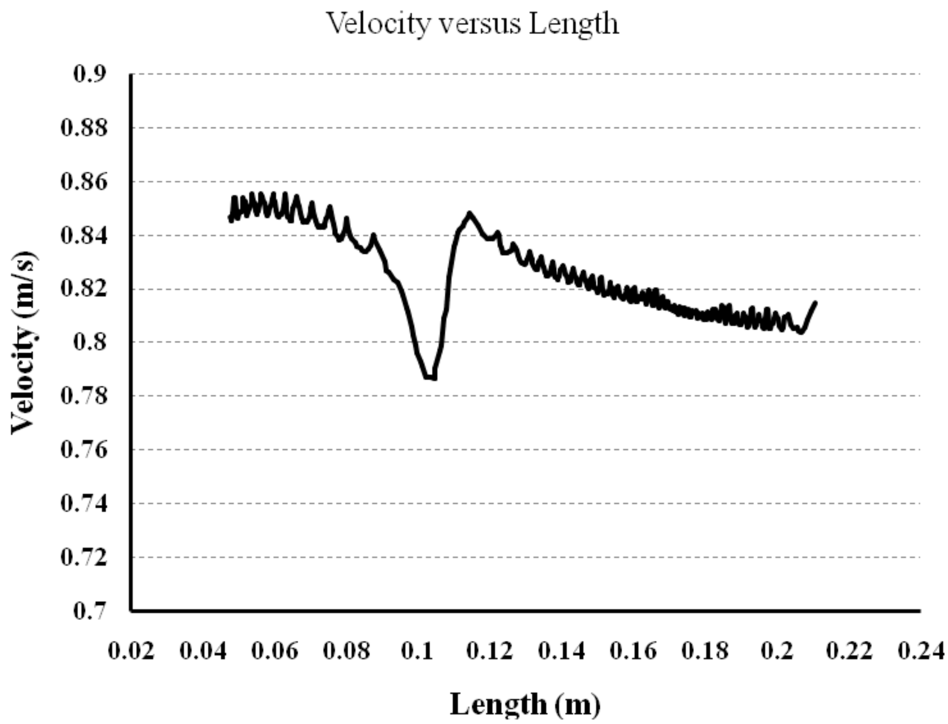


Figure 4.8(b): Velocity versus length of diameters 14 mm aneurysm

Figures 4.9 show the model of aneurysm 16mm with neck 12mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.10(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 16mm with neck 12mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 823.32pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1163.27pa. Figures 4.10(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 16mm with neck 12mm show a small disturbance. (0.04m, 0.87m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.09m, 0.79m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.11m, 0.71m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.12m, 0.86m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.78m/s).

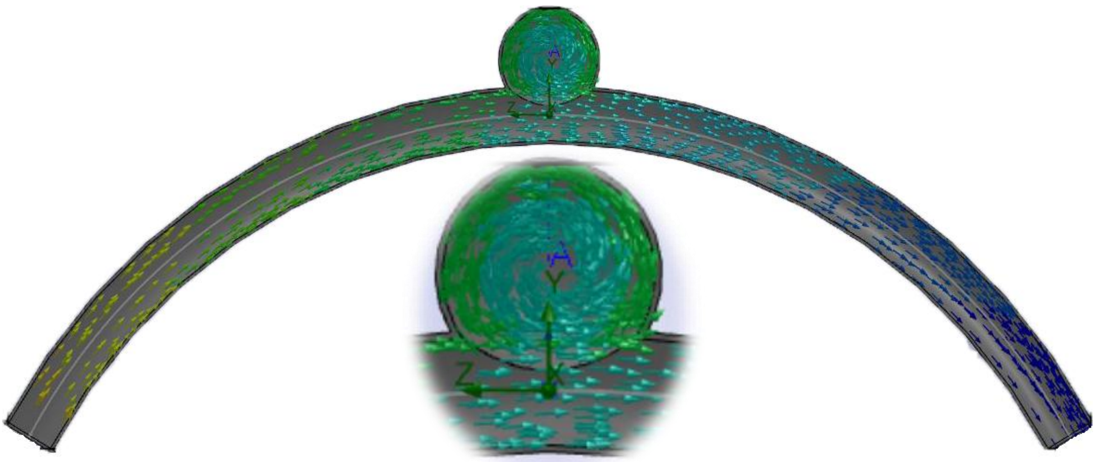


Figure 4.9: Diameter 16 mm with neck 12 mm

Figure 4.10(a): Pressure versus length of diameters 16 mm aneurysm

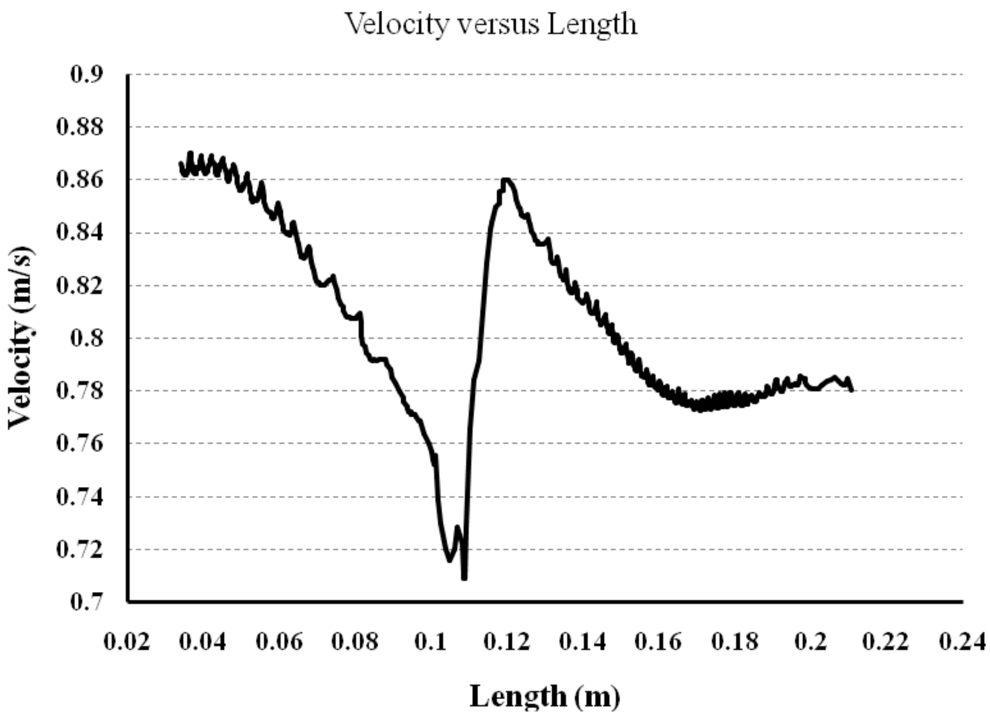


Figure 4.10(b): Velocity versus length of diameters 16 mm aneurysm

Figures 4.11 show the model of aneurysm 18mm with neck 12.50mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.12(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 18mm with neck 12.50mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 826.52pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1166.76pa. Figures 4.12(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 18mm with neck 12.50mm show a small disturbance. (0.04m, 0.86m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.07m, 0.81m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.09m, 0.75m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.12m, 0.86m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.78m/s).

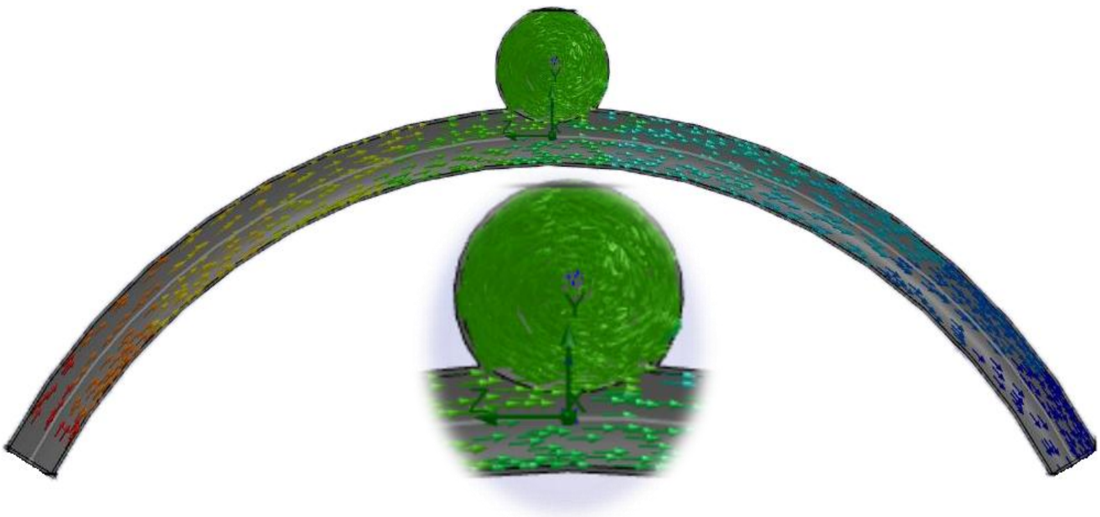


Figure 4.11: Diameter 18 mm with neck 12.50 mm

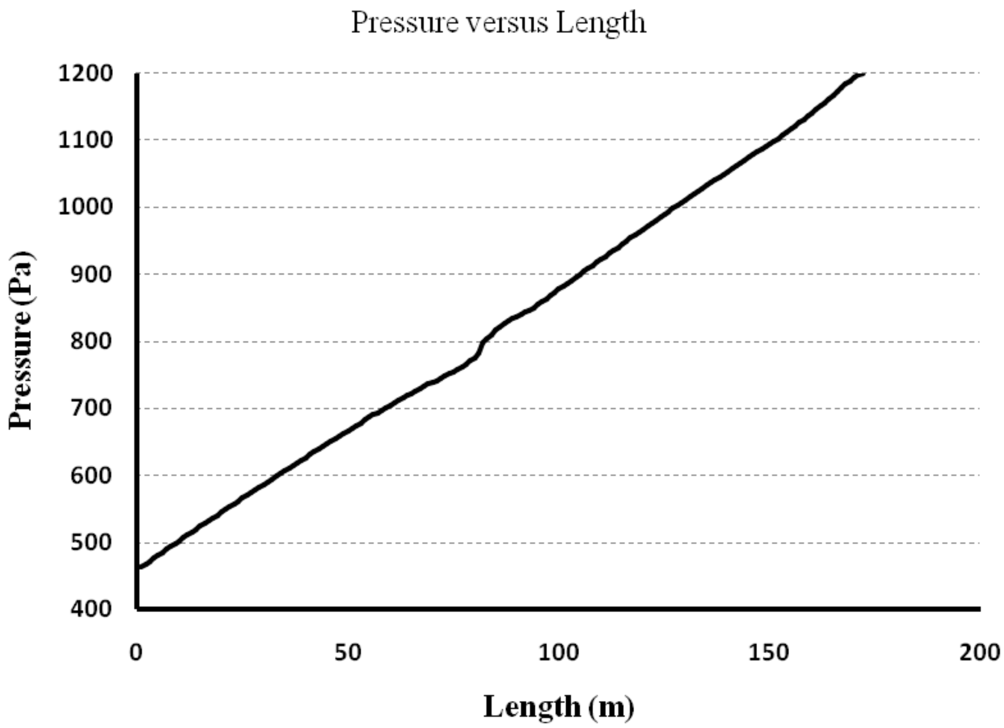


Figure 4.12(a): Pressure versus length of diameters 18 mm aneurysm

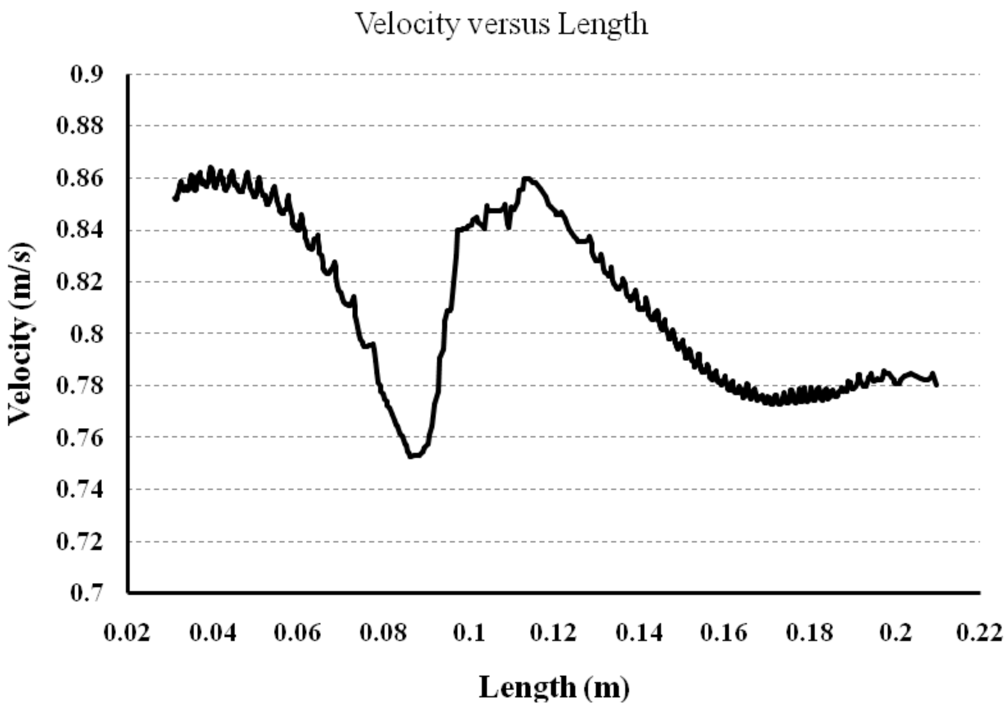


Figure 4.12(b): Velocity versus length of diameters 18 mm aneurysm

Figures 4.13 show the model of aneurysm 20mm with neck 14.20mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.14(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 20mm with neck 14.20mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 804.59pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1089.38pa. Figures 4.14(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 20mm with neck 14.20mm show a small disturbance. (0.04m, 0.84m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.09m, 0.81m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.10m, 0.74m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.12m, 0.81m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.79m/s).

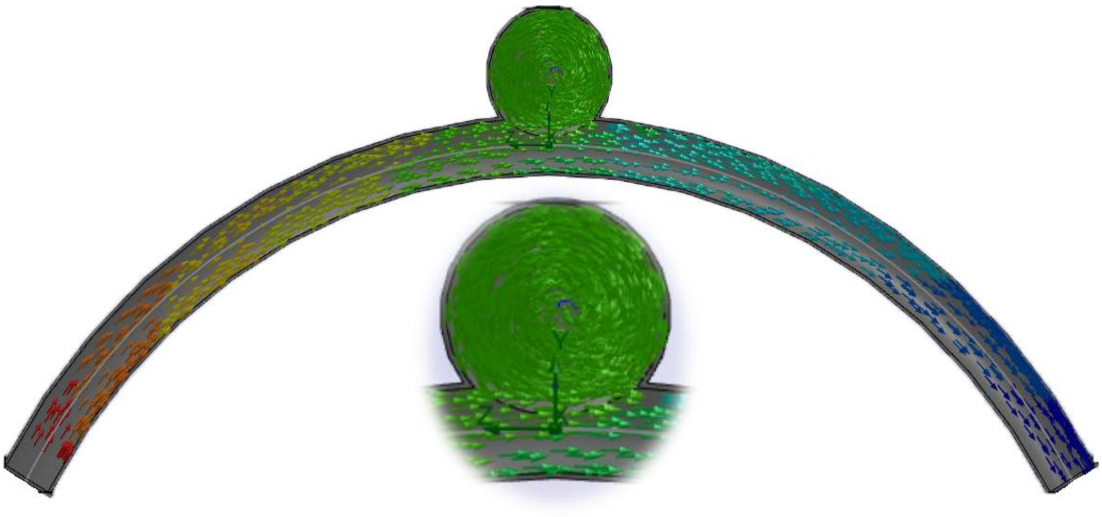


Figure 4.13: Diameter 20 mm with 14.20 mm

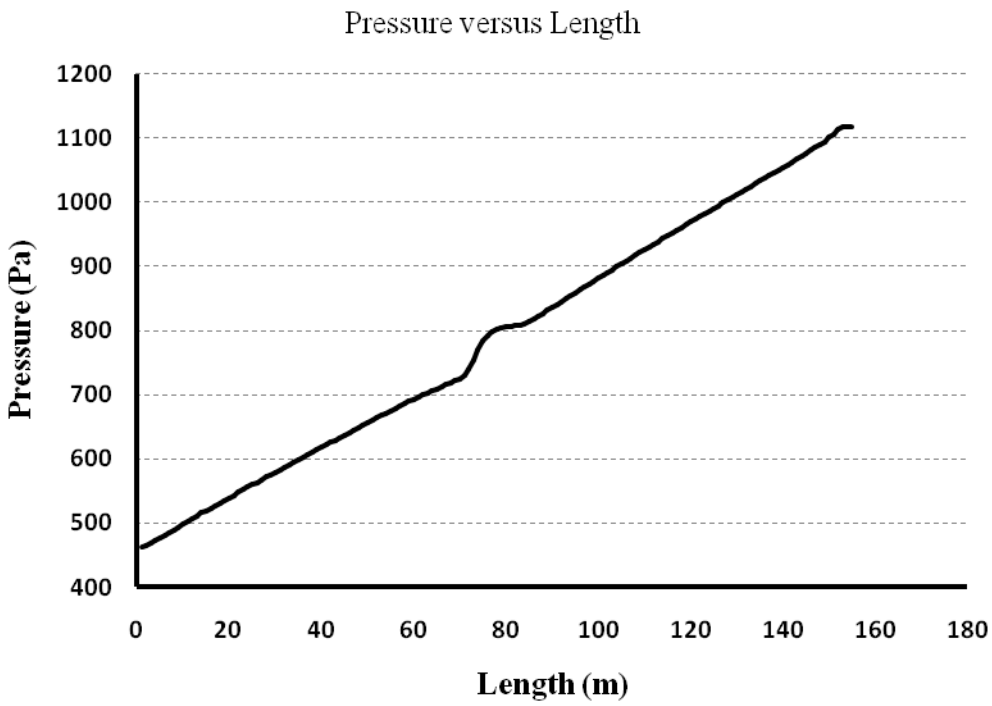


Figure 4.14(a): Pressure versus length of diameters 20 mm aneurysm

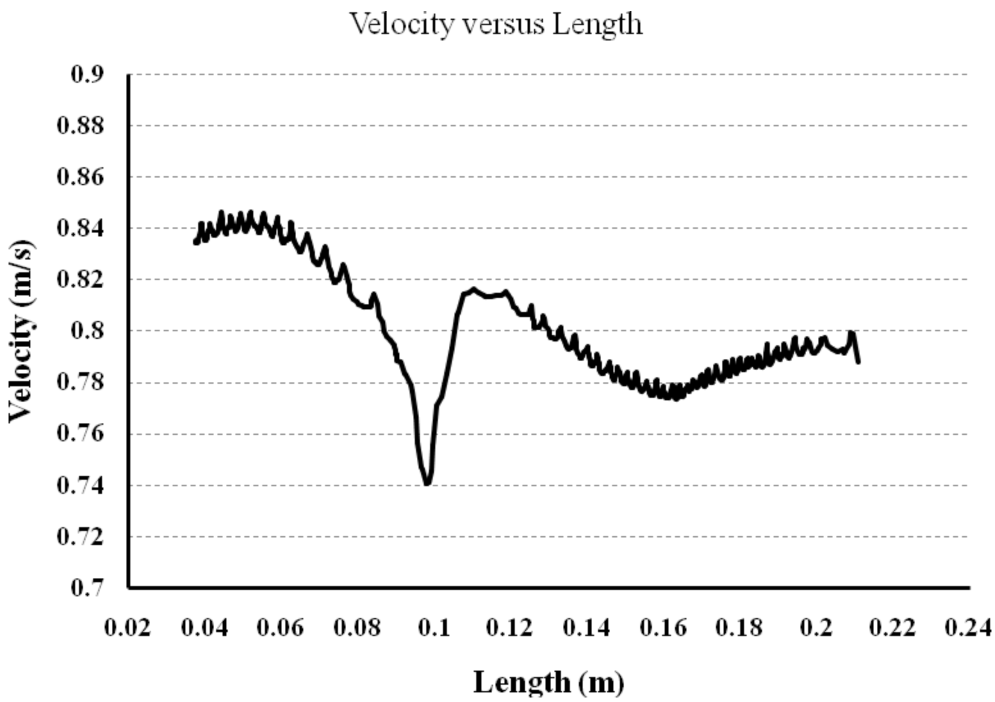


Figure 4.14(b): Velocity versus length of diameters 20 mm aneurysm

Figures 4.15 show the model of aneurysm 22mm with neck 15.50mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.16(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 22mm with neck 15.50mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 804.16pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1066.18pa. Figures 4.16(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 22mm with neck 15.50mm show a small disturbance. (0.04m, 0.83m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.09m, 0.81m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.10m, 0.71m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.12m, 0.79m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.79m/s).

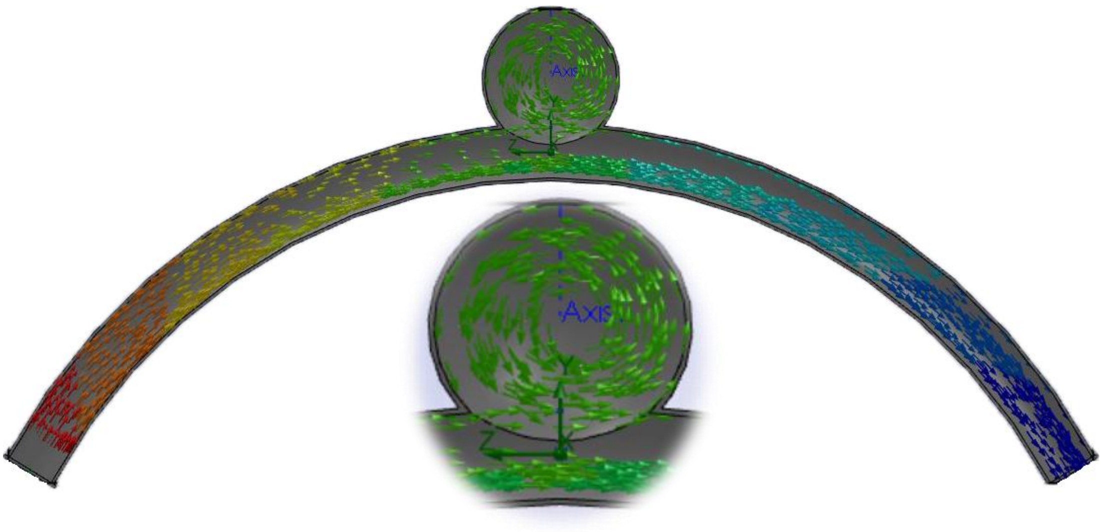


Figure 4.15: Diameter 22 mm with neck 15.50 mm

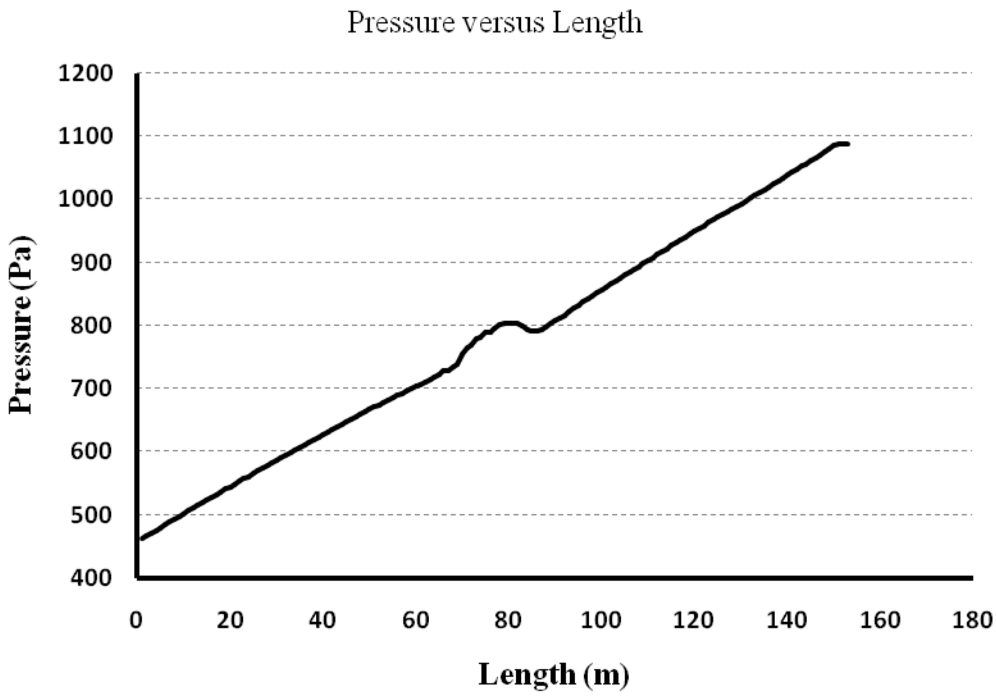


Figure 4.16(a): Pressure versus length of diameters 22 mm aneurysm

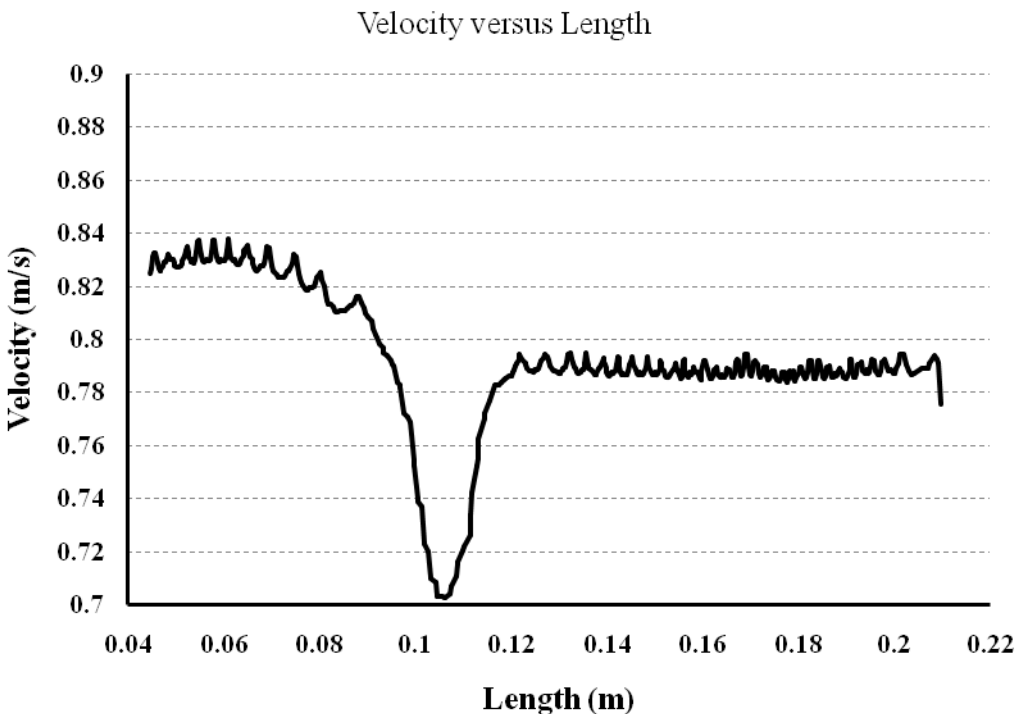


Figure 4.16(b): Velocity versus length of diameters 22 mm aneurysm

Figures 4.17 show the model of aneurysm 24mm with neck 16.30mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.18(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 24mm with neck 16.30mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 800.23pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1092.66pa. Figures 4.18(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 24mm with neck 16.30mm show a small disturbance. (0.04m, 0.83m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.08m, 0.81m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.09m, 0.77m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.11m, 0.90m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.79m/s).

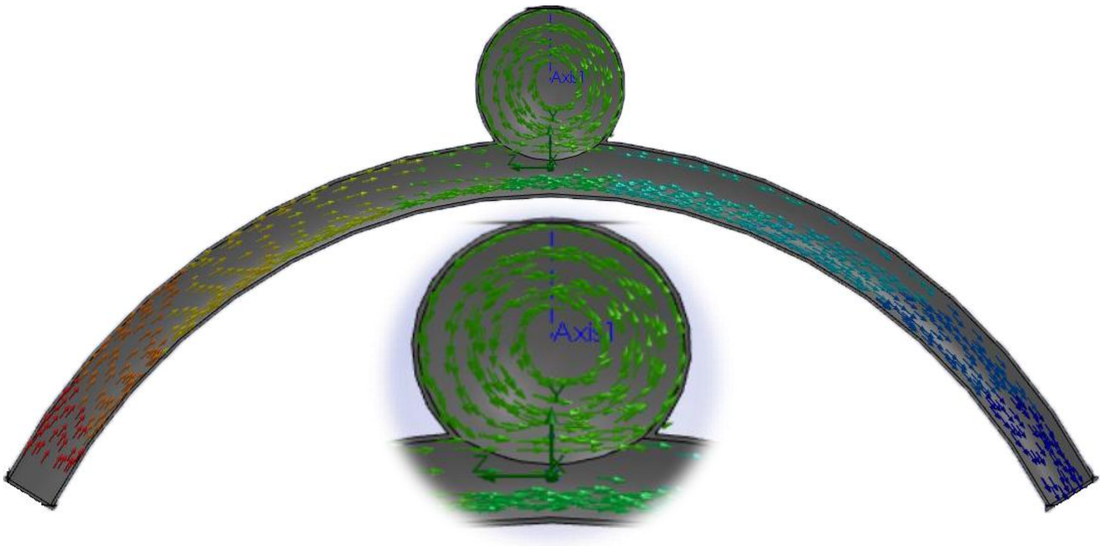


Figure 4.17: Diameter 24 mm with neck 16.30 mm

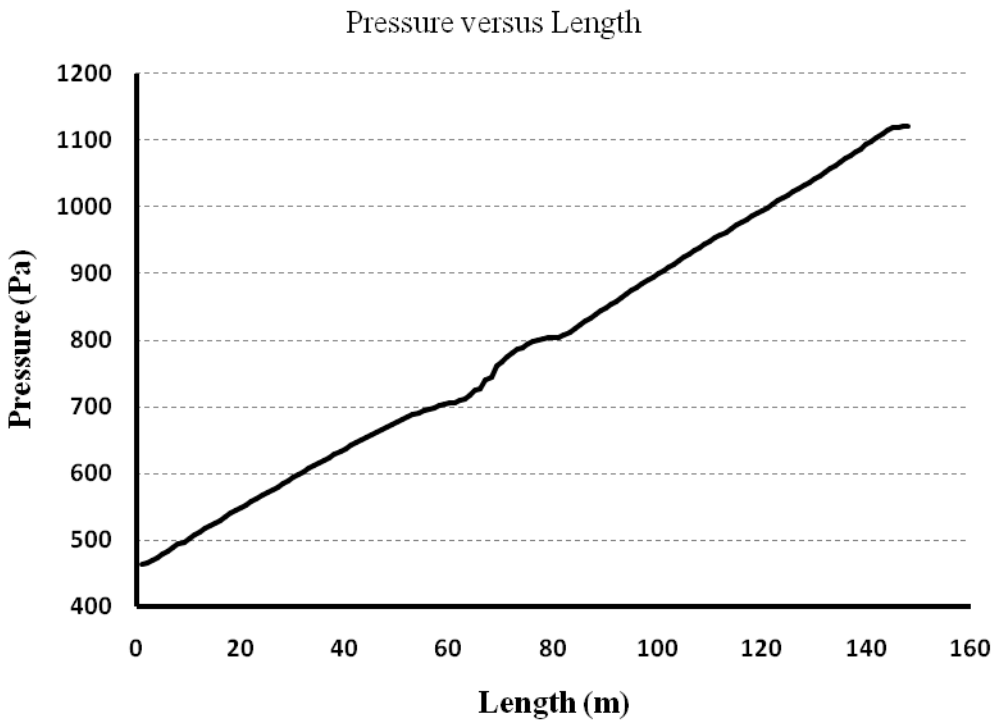


Figure 4.18(a): Pressure versus length of diameters 24 mm aneurysm

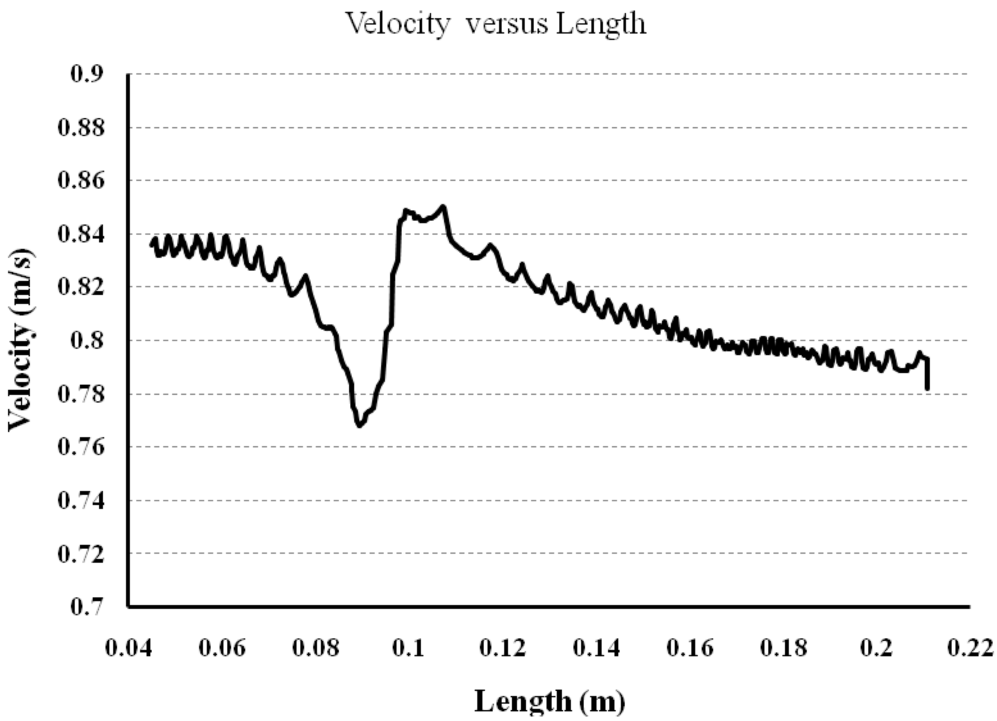


Figure 4.18(b): Velocity versus length of diameters 24 mm aneurysm

4.1.3 Giant of Diameter Aneurysm

Figures 4.19 show the model of aneurysm 25mm with neck 16.65mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.20(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 25mm with neck 16.65mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 769.92pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1079.25pa. Figures 4.20(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 25mm with neck 16.65mm show a small disturbance. (0.04m, 0.82m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.09m, 0.81m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.10m, 0.75m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.12m, 0.79m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.78m/s).

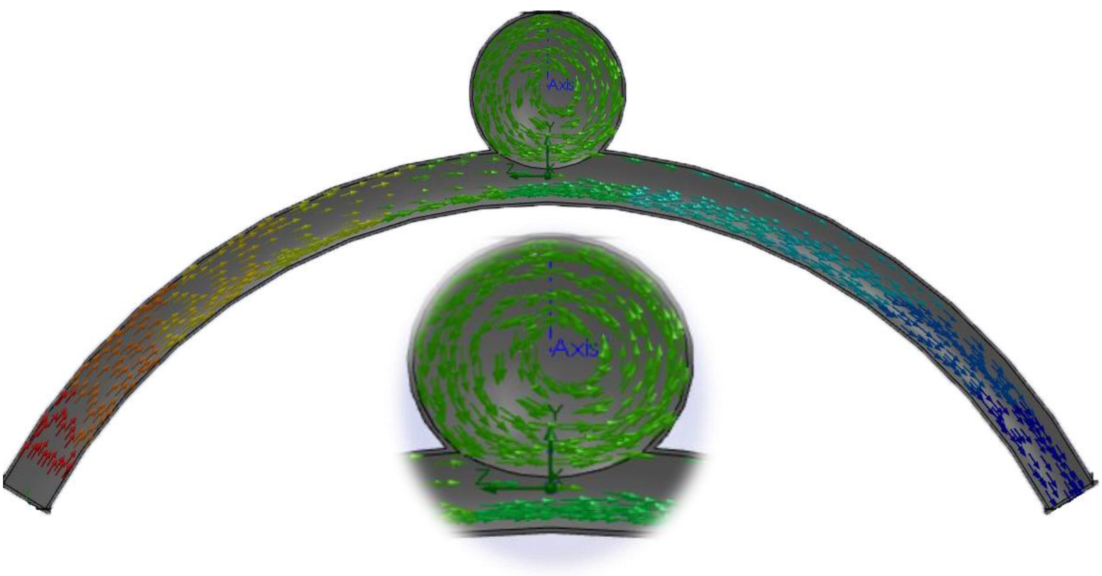


Figure 4.19: Diameter 25 mm with neck 16.65 mm

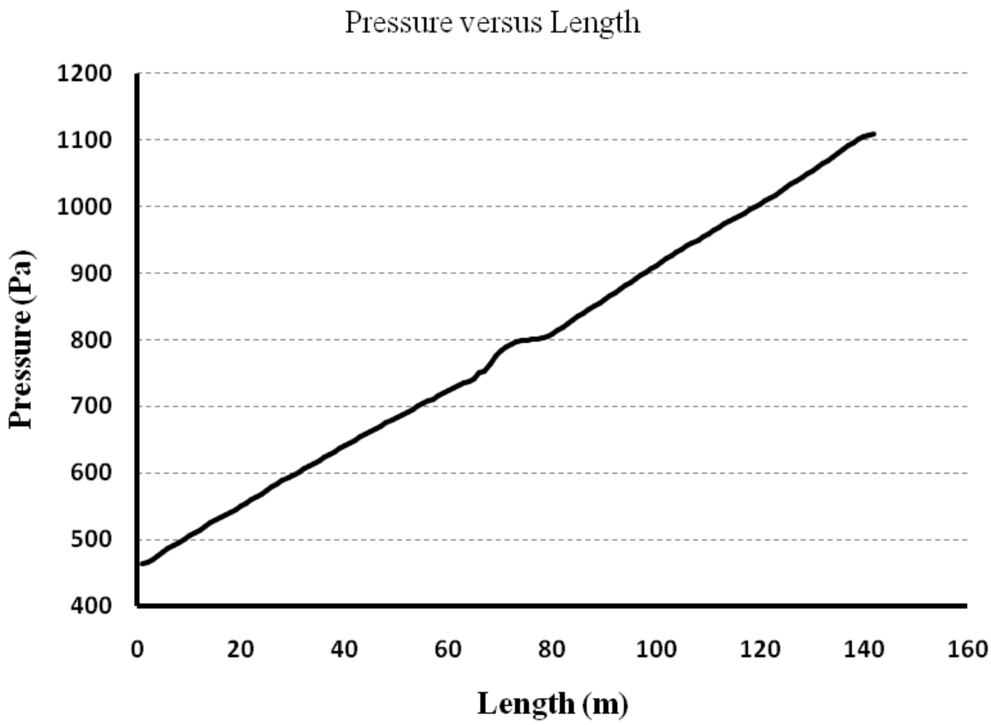


Figure 4.20(a): Pressure versus length of diameters 25 mm aneurysm

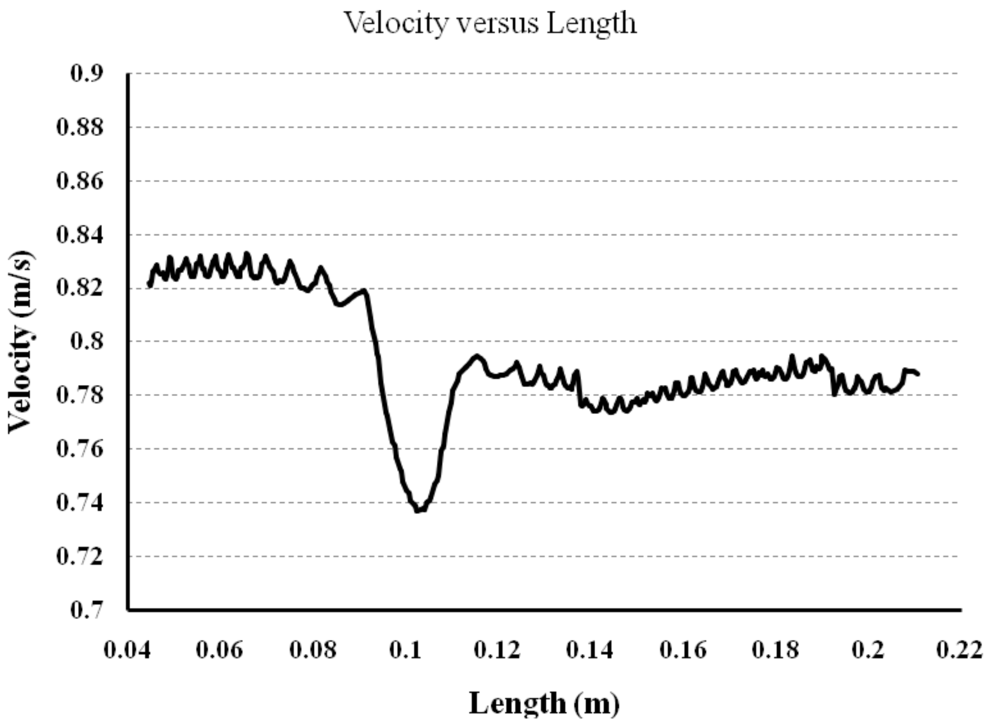


Figure 4.20(b): Velocity versus length of diameters 25 mm aneurysm

Figures 4.21 show the model of aneurysm 26mm with neck 17mm diameter of aneurysm. From this figure it show the formation of vortex clearly been seen inside the aneurysm. Figures 4.22(a) show the pressure versus length graph. From this figure the blood through the aneurysm that have diameter 26mm with neck 17mm got a little increasing disturbance . This show at the graph which pressure of the blood flow is increasing to show aneurysm was detected. From the graph at point 0m the pressure is 463pa. At point 0.11m the pressure increase drastically to 839.96pa. These due to the disturbance at flow occur because of aneurysm. The pressures continually increase until the outlet. At point 0.2m the pressure is 1129.26pa. Figures 4.22(b) show the velocity versus length graph. From this figure flow of blood through the aneurysm that have diameter 26mm with neck 17mm show a small disturbance. (0.04m, 0.82m/s) The velocity for blood flow starts to decrease. When the blood flow closed to the aneurysm the value show in the graph is (0.09m, 0.88m/s). When the blood starting to enter the aneurysm the velocity is drastically dropped as the blood flow stuck inside the aneurysm (0.10m, 0.76m/s). However, when the blood start to flow out of the aneurysm it regain speed at value (0.12m, 0.85m/s). When the blood flow outside the aneurysm, the velocity is decreasing at the end point of model aneurysm(0.2m, 0.79m/s).

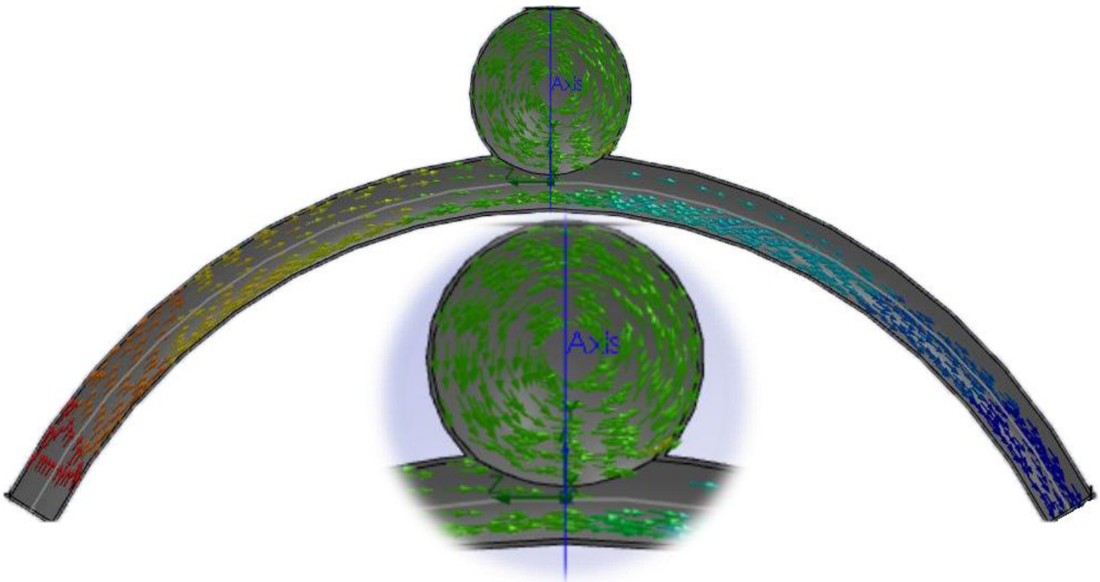


Figure 4.21: Diameter 26 mm with neck 17 mm

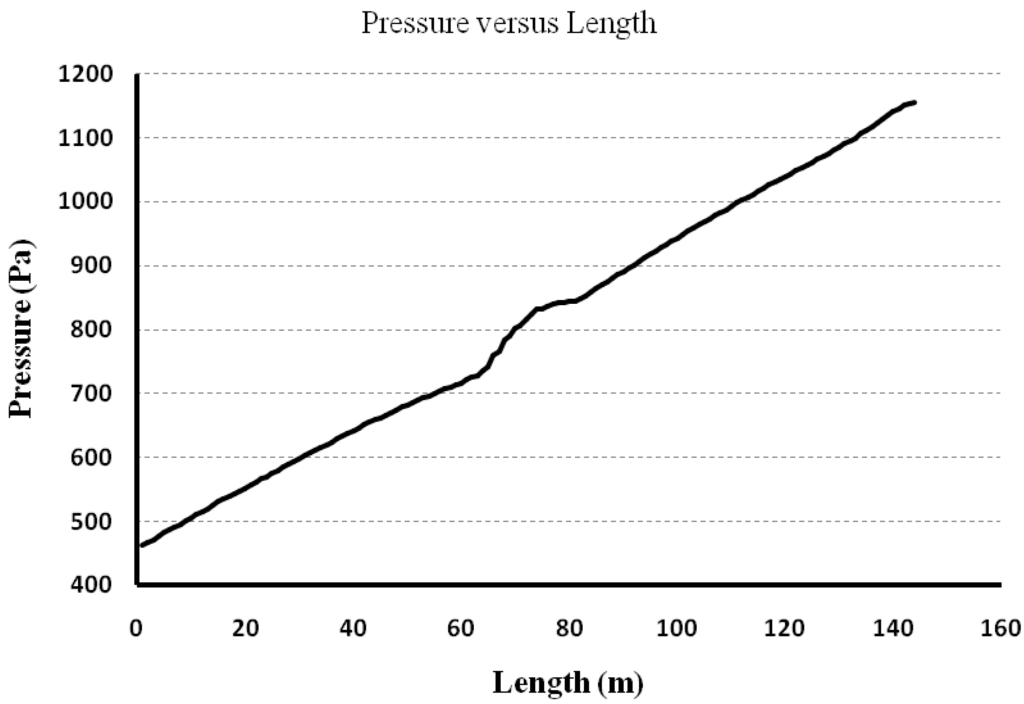


Figure 4.22(a): Pressure versus length of diameters 26 mm aneurysm

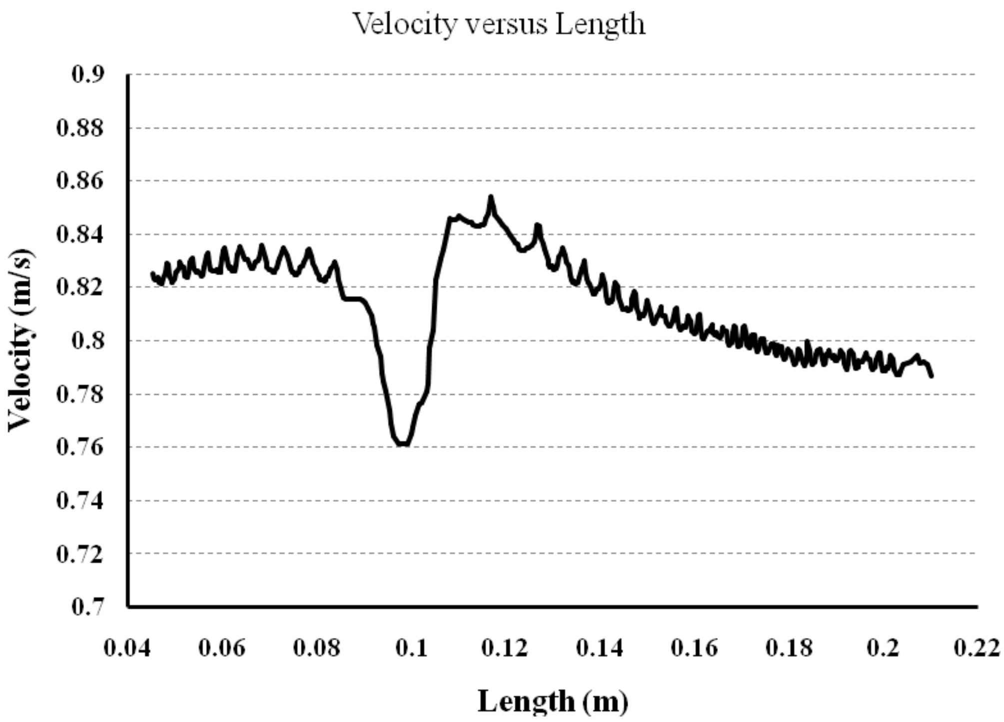


Figure 4.22(b): Velocity versus length of diameters 26 mm aneurysm

4.2 Analysis Graph of Velocity

From graph 4.23 and graph 4.24 min velocity does not influenced by size of neck and also diameter of aneurysm is because there is no correlation shown in the graph min velocity versus size diameter and min velocity versus size of neck.

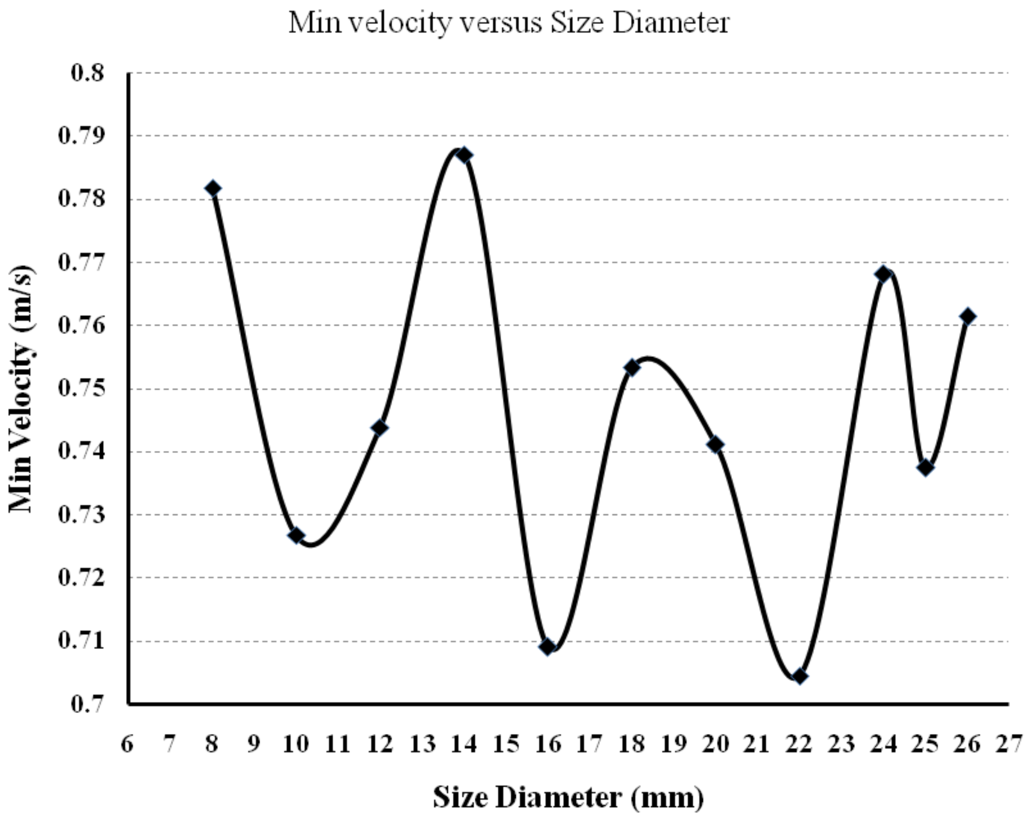


Figure 4.23: Min Velocity versus size diameter of aneurysm

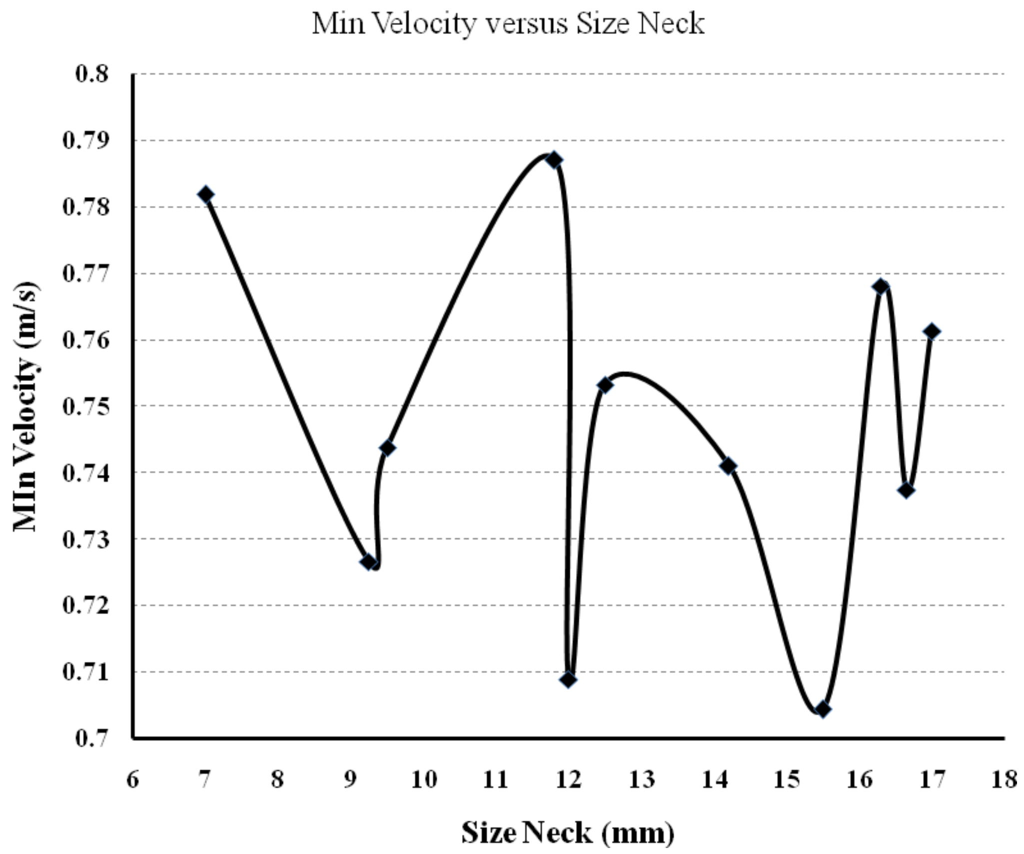


Figure 4.24: Min Velocity versus size neck of aneurysm

4.3 Analysis Graph of Pressure

For this section, graph aneurysm pressure will be analyzing figure 4.25 shows the pressure versus size diameter of aneurysm while figure 4.26 shows pressure versus size neck of aneurysm. Both graphs indicate that velocity is directly proportional to the pressure.

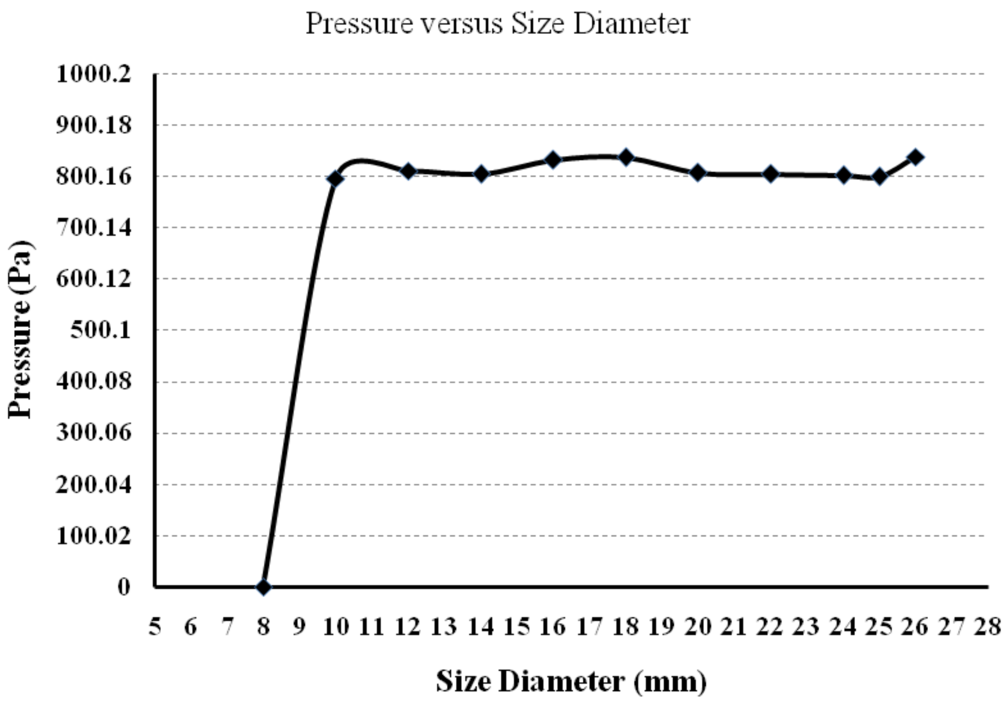


Figure 4.25: Pressure versus size diameter of aneurysm

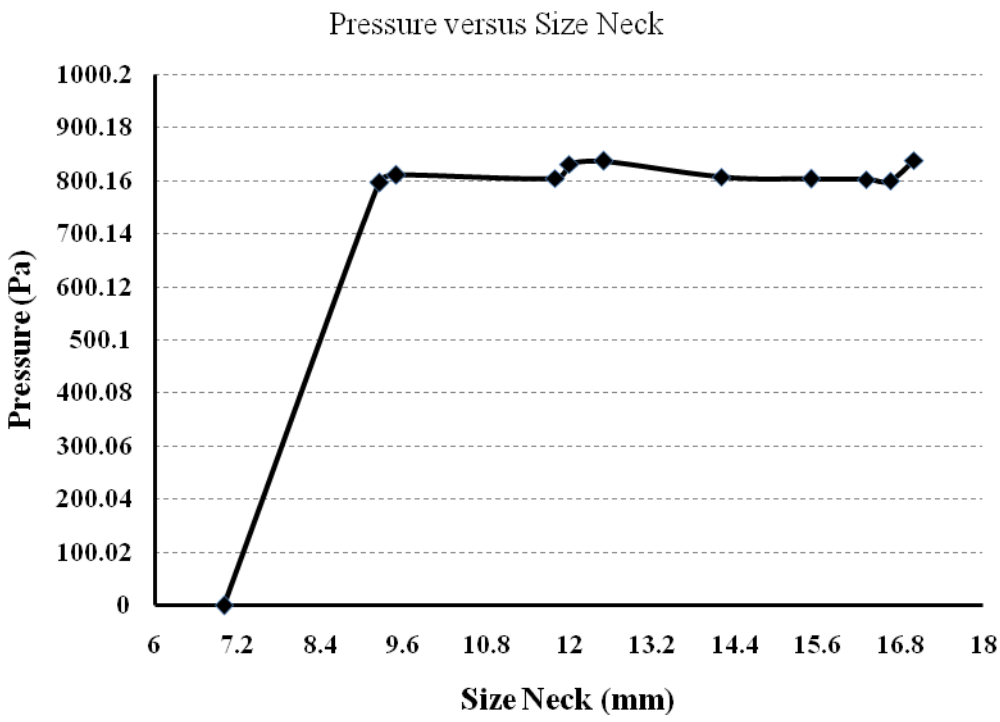


Figure 4.26: Pressure versus size neck of aneurysm

4.4 Comparison with Previous Research.

A part of this research methodology is by comparing results from this research with result from previous research. The purpose of this comparison is to ensure the data from this research are reliable. Figure 4.27 and 4.28 show the previous research on flow behavior of cerebral aneurysm. The figure show vortex formation occurs in the aneurysm. Figure 4.27 show result of flow behavior get from this study. Both researched shows that vortex formation occurs inside the aneurysm. This validate that this research result is reliable.

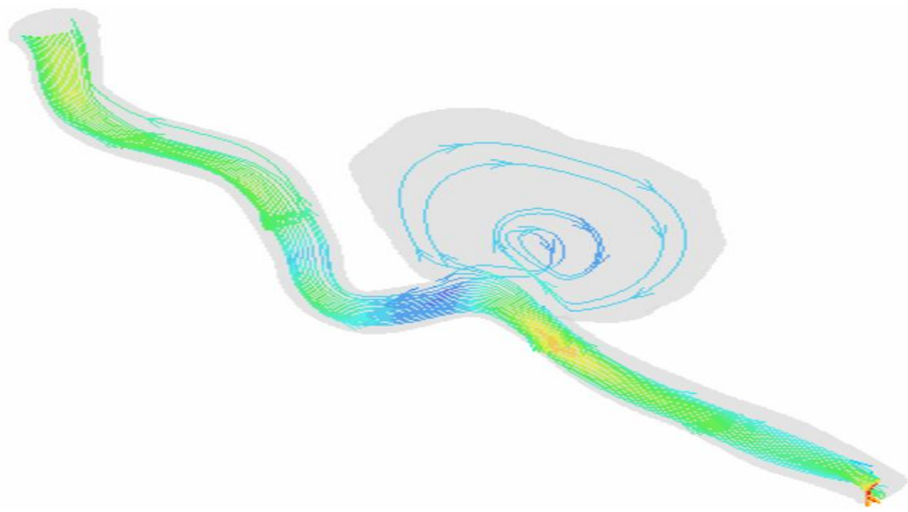


Figure 4.27: Flow behavior of cerebral aneurysm

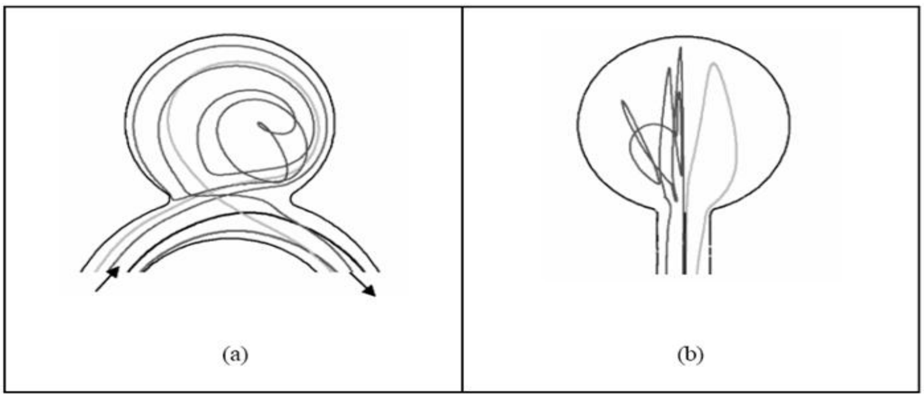


Figure 4.28: Flow skecth of cerebral aneurysm

Beside that, the velocity graf also need to be validate. Figure 4.29 and figure 4.30 show the previous research on velocity profile in aneurysm. Both researchs on velocity profile in aneurysm. Both research that there is avelocity drop in aneurysm region compared to result gather from this study, velocity drop also happen at the aneurysm region. It is reflect that result from this study is reliable.

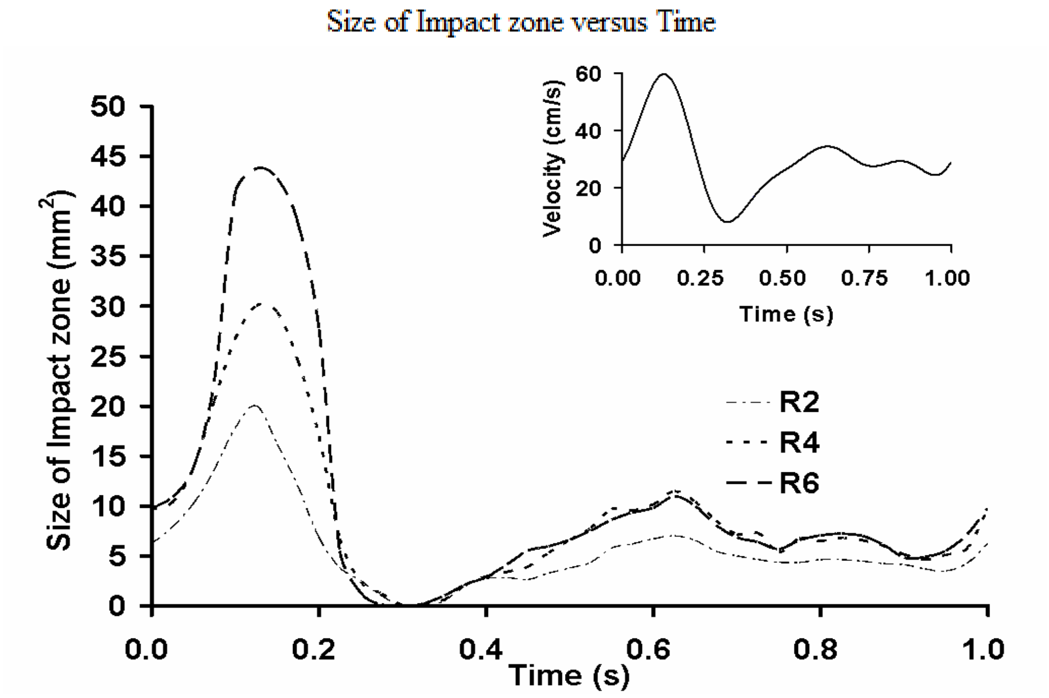


Figure 4.29: Velocity versus Time, Size versus Time

Source: Journal of hemodynamic forces and aneurysm geometry Yie Meng Hoi, 2003

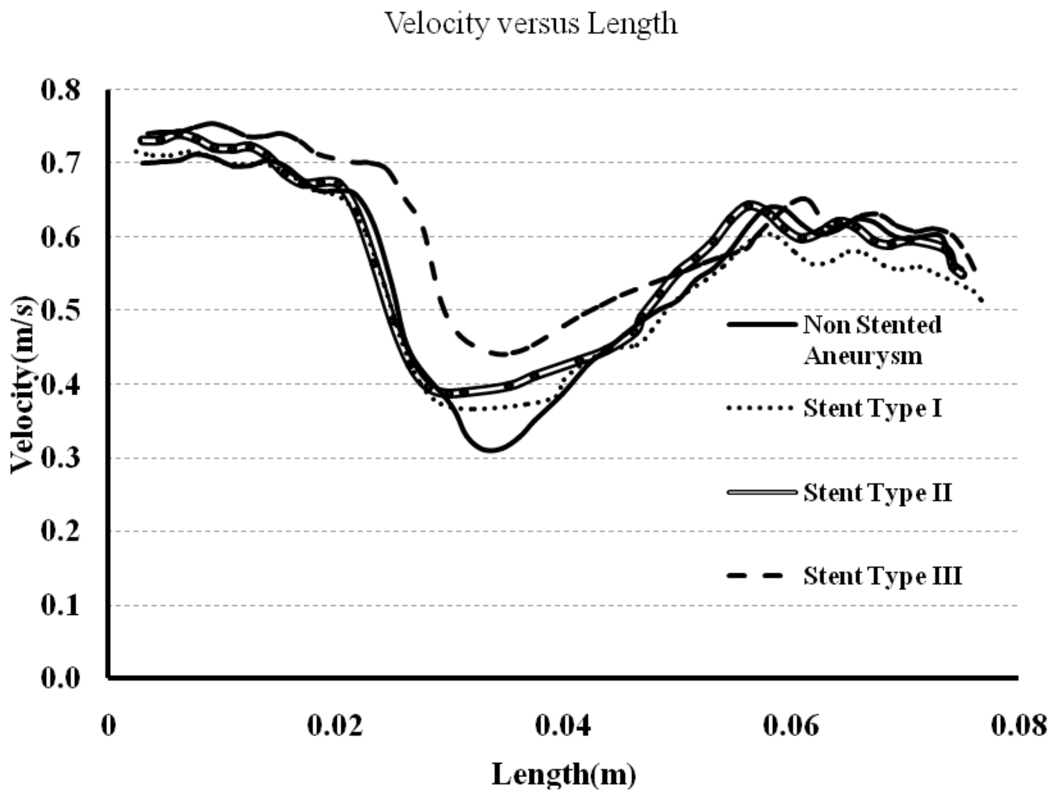


Figure 4.30: Velocity profile in aneurysm region

Source: Journal the effect of stent structural parameters to flow in stented aneurysms, Mohamad Mazwan Mahat, 2008

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

This study reputable the steady flow for various cerebral aneurysms size. Base on the analysis with Commos Flow and the plotted results that disturbance on graph only happen if the diameter of aneurysm exceed 10 mm. This disturbance is because velocity drop as the blood tends to flow in the aneurysm from 0.87m/s to 0.72m/s.

Meanwhile, when there is a flow in aneurysm will affect the flow pressure as the blood flow start to fulfill the aneurysm. The blood quantity inside the aneurysm will be increase by time as it failed to flow at increasing pressure flow.

From this project, pressure distribution and velocity profile is not depending on the aneurysm size. Min velocity does not influenced by size of neck and also diameter of aneurysm is because there is no correlation shown in the graph min velocity versus size diameter and min velocity versus size of neck. Velocity is indirectly proportional to the pressure.

5.2 RECOMMENDATIONS

In order to obtain strong correlation between flow phenomena the neck and diameter of aneurysm and the best velocity, the recommendations are as instead of only analyzing graph velocity versus length, graph velocity versus time also needs to be analyzed.

Replace current analysis software cosmos flow with fluent software. Instead of only varying neck dimension without considers a ratio between neck and diameter of aneurysm should be set to obtain better result in the future.

Pulse may have effect on the rupture of aneurysms in their growth rate. Therefore, future studies should consider the pulsatile condition of blood flow simulation by introducing the different Reynolds number.

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APPENDIX A: Data for Plotted Results

Velocity with diameter 8mm	
0.024817884	0.882254188
0.025098148	0.882888086
0.02523828	0.881265922
0.030122893	0.885159176
0.0302634	0.886938553
0.040161419	0.883756783
0.040428732	0.884937425
0.050623623	0.869302877
0.050771394	0.868222677
0.051065634	0.867611303
0.062342885	0.834362768
0.062672306	0.833367737
0.072258877	0.80004851
0.072392156	0.797488038
0.086981484	0.794068503
0.087268112	0.791582216
0.087554741	0.789743621
0.102560677	0.783674141
0.102892625	0.782912324
0.103179179	0.782907068
0.116816018	0.795111095
0.117478601	0.797920069
0.117863425	0.796999201
0.126318291	0.81294053
0.127012161	0.81212676
0.127369701	0.811134433
0.143200851	0.81804643
0.14331135	0.817157225
0.143532349	0.817064118
0.167046089	0.811220339
0.167184051	0.809901336
0.167322012	0.809072159
0.184687032	0.805061831
0.184943111	0.806706868
0.20813628	0.800263749
0.208426371	0.80003368
0.209212042	0.794876821
0.209471192	0.793954198

Pressure with diameter 8mm	
0	464.0145362
0.000799991	466.4053361
0.017120376	525.1187791
0.018172035	528.8682111
0.02984188	569.3593497
0.030802777	572.5512512
0.049963761	636.8306463
0.051065634	640.4670745
0.059538145	668.5795109
0.060588332	671.8592144
0.07964989	733.0015178
0.080708608	735.9619424
0.098915214	788.7917351
0.098915214	788.7917351
0.101026788	797.4886064
0.103179179	805.9434125
0.105288964	811.8643265
0.107398897	816.4614527
0.10950912	821.113383
0.111668021	826.5419138
0.113618375	832.0826689
0.114669019	835.5892569
0.115769272	839.1042624
0.116816018	842.3775167
0.117863425	845.8502635
0.118911551	849.8528738
0.119960455	853.0596308
0.121010197	856.5117457
0.139047245	919.0305863
0.140123645	922.9748534
0.169852013	1031.378343
0.170891675	1035.418491
0.198499293	1142.051984
0.199550013	1146.493094
0.200597269	1150.970672
0.203744053	1164.761953
0.204848117	1169.584067
0.205893591	1174.018132
0.206977808	1178.281372
0.20813628	1181.594746
0.209212042	1183.363152
0.209471192	1183.677193
0.209572566	1183.857646

Velocity with diameter 10mm	
0.039866812	0.86414172
0.040024199	0.864165212
0.059701087	0.850349186
0.060006419	0.847895894
0.079761396	0.791560784
0.080362876	0.791083143
0.099440045	0.78781156
0.100604069	0.787283871
0.104144321	0.788667782
0.104580475	0.789647976
0.105338787	0.788632628
0.105654882	0.788212416
0.106484831	0.787641205
0.106729408	0.787655887
0.10767426	0.787174973
0.108879302	0.78740507
0.109954911	0.787418307
0.111089755	0.787362076
0.111259497	0.787508541
0.112423986	0.788529854
0.113228179	0.789721863
0.113615699	0.79227311
0.114777151	0.791551969
0.139996076	0.802566116
0.140155765	0.804507649
0.159862845	0.808241589
0.160023617	0.80786013
0.169921612	0.812603995
0.170050759	0.811557836
0.179979145	0.817149058
0.180151552	0.817711281
0.18032396	0.815667324
0.189985599	0.8162826
0.190270556	0.816469618
0.190420787	0.817110045
0.204624224	0.814783385
0.205789557	0.818437085
0.20664065	0.819277464
0.207137334	0.814120992
0.207780405	0.812596387
0.208009454	0.814866588
0.209179404	0.814394683
0.209534464	0.814268638

Pressure with diameter 10mm	
0	463.6016916
0.001378519	468.0099018
0.019047174	526.0180984
0.020238414	529.9731879
0.039118519	588.7885882
0.040336093	592.4926113
0.059243088	648.2492648
0.060410307	651.8686874
0.079324391	704.3986719
0.080481347	707.6668778
0.099440045	761.6827785
0.100604069	771.7653391
0.109954911	791.9149033
0.111259497	793.9928426
0.112423986	797.0515555
0.113615699	800.7080477
0.114777151	804.5011103
0.115969326	808.6385494
0.117168876	812.7569807
0.118318144	816.326433
0.119520751	820.0495176
0.120655462	823.7965781
0.121856277	827.8870898
0.139564863	888.6693836
0.140729017	892.4582674
0.159703262	957.2712994
0.160866902	961.0097941
0.169137189	988.5566464
0.170334784	992.2700899
0.179806737	1023.209648
0.180969363	1026.94441
0.189238293	1054.528175
0.190420787	1058.631329
0.191621188	1062.865471
0.197514654	1083.923783
0.198711804	1088.246452
0.199856268	1092.438112
0.201001487	1096.765761
0.205789557	1118.031063
0.207137334	1124.02939
0.208009454	1126.954586
0.209179404	1129.086955
0.209964866	1130.246466

Velocity with diameter 12mm	
0.038706289	0.850919512
0.038898538	0.852403245
0.039996463	0.850669391
0.04018906	0.851344447
0.041977389	0.853886924
0.042277101	0.852230543
0.049939635	0.851937796
0.050135343	0.850961607
0.05031786	0.850401985
0.050588853	0.850199937
0.059232102	0.853635051
0.05966904	0.851487379
0.059988998	0.848235298
0.060269422	0.847133407
0.078864925	0.82235219
0.079354598	0.820204324
0.080179436	0.818818257
0.089949438	0.808230501
0.09042261	0.806307495
0.102065118	0.783633644
0.10234567	0.782619374
0.103374183	0.774952588
0.103533348	0.773831039
0.104613022	0.76485771
0.104720852	0.763376842
0.105908344	0.753291764
0.107095989	0.746287886
0.108375715	0.742582555
0.108558515	0.742721107
0.10966589	0.743126107
0.109831861	0.743846689
0.110956064	0.747711832
0.129923891	0.780843639
0.130308683	0.780099453
0.149935901	0.785771949
0.150210501	0.785461322
0.169951396	0.77284948
0.170127745	0.773317913
0.189998818	0.779078934
0.190340923	0.779756638
0.209324841	0.784918963
0.200300558	0.780337889
0.201525866	0.780055666

Pressure with diameter 12mm	
0	463
0.00096886	466.8369827
0.029849233	560.9970296
0.031133326	564.9991612
0.03231395	568.8018874
0.049206746	621.1271573
0.050588853	625.071292
0.069863162	683.9516251
0.071147689	687.7495859
0.089122433	738.0640251
0.09042261	741.3060934
0.099500653	775.1896938
0.100808996	786.7626223
0.102065118	796.5910476
0.103374183	803.8425654
0.104613022	808.2090209
0.105908344	810.7553338
0.107095989	811.1550201
0.108558515	810.3624028
0.109472515	809.7698057
0.109831861	809.8934479
0.111135204	811.1798672
0.112405555	814.3133436
0.113711074	818.5056839
0.129199585	872.7745524
0.130477371	877.2859103
0.149935901	945.5799793
0.1510978	949.4371422
0.169191657	1008.288479
0.17046601	1012.182877
0.188572133	1072.615297
0.189998818	1077.566296
0.191049284	1081.122012
0.200132768	1114.58433
0.201451307	1119.53667
0.202853832	1124.883122
0.204039261	1129.439581
0.205448625	1134.836258
0.206710707	1139.33125
0.207752081	1142.557907
0.209324841	1144.580497
0.200300558	1145.96619
0.201235336	1145.83638

Velocity with diameter 14mm	
0.04745902	0.84681251
0.047797923	0.845728409
0.048902796	0.853836915
0.049279167	0.848859333
0.050747091	0.848390913
0.051046704	0.850080455
0.052760325	0.848540763
0.053165083	0.85124184
0.054973292	0.847575667
0.055076266	0.847952092
0.056861059	0.852620052
0.057226038	0.851956476
0.058899879	0.850881231
0.065128599	0.849923536
0.067790266	0.845203745
0.068061917	0.844877817
0.077797724	0.838768913
0.078084608	0.838278304
0.089312943	0.834287125
0.090600722	0.829845107
0.099474617	0.798820682
0.099705039	0.796293193
0.100783479	0.792872576
0.100959707	0.791211316
0.102213777	0.78708115
0.103467446	0.787091237
0.104710067	0.786765119
0.10472091	0.790533519
0.106018929	0.797228172
0.106421966	0.79904402
0.10722804	0.809033422
0.107712565	0.812088721
0.10848211	0.824396059
0.109003362	0.82717784
0.109945517	0.835627902
0.205895325	0.804370666
0.206801342	0.803893892
0.207098469	0.804080687
0.207692723	0.80563334
0.208432274	0.808558264
0.209419778	0.812022843
0.200728996	0.814506083
0.201023388	0.815383866

Pressure with diameter 14mm	
0	463
0.000678968	466.0844904
0.01996122	526.2716422
0.021024814	529.9877815
0.029078394	556.8732591
0.030372437	560.7738857
0.059305041	643.0920245
0.060451934	646.4718258
0.078788001	697.713464
0.08011921	700.7233611
0.099705039	772.1741277
0.100959707	782.6782477
0.102213777	791.0297684
0.103467446	796.7252962
0.10472091	800.1842348
0.106421966	803.5873589
0.107712565	804.967219
0.109003362	805.4046916
0.110294425	805.9971169
0.111585819	807.6671144
0.112877612	810.5722314
0.129819374	868.6299323
0.131122312	872.7579953
0.149519931	933.9396621
0.15077297	937.8487957
0.159922688	968.2838029
0.161317742	972.9801336
0.162522307	976.3418981
0.179697007	1030.986514
0.180786221	1034.242098
0.182232648	1038.580759
0.196657658	1081.443948
0.1976571	1085.139634
0.199133376	1091.362427
0.200594292	1097.512753
0.201803229	1102.660059
0.203173817	1108.664092
0.204414616	1114.131058
0.205895325	1120.481054
0.207098469	1125.380274
0.208432274	1129.029011
0.209419778	1131.300667
0.209533777	1132.456766

Velocity with diameter 16mm	
0.034042993	0.866131759
0.03415463	0.864560913
0.039698556	0.865982223
0.040032422	0.86449816
0.04974883	0.856124795
0.050048499	0.856525748
0.059851584	0.849446731
0.060184375	0.847985996
0.069897045	0.820920092
0.070218919	0.820976839
0.079995653	0.807413476
0.08061572	0.808435521
0.089432404	0.784968537
0.090535882	0.782555295
0.099988346	0.756990221
0.100310665	0.754333604
0.100583596	0.752296175
0.101129459	0.75548534
0.10140239	0.747281256
0.101680022	0.738680838
0.102512919	0.729684972
0.103883685	0.720329631
0.104714371	0.71597439
0.106179401	0.720260842
0.106915824	0.72843441
0.108015589	0.722035659
0.108291278	0.711107072
0.108566967	0.709003072
0.108842656	0.70899748
0.109118345	0.728287795
0.110220006	0.765856534
0.129431034	0.835653503
0.13018291	0.836111109
0.149899185	0.794872205
0.150032942	0.794412716
0.16989624	0.775297708
0.170053698	0.774950108
0.200480349	0.780730514
0.208988887	0.782358966
0.209203433	0.783232662
0.209417979	0.784918963
0.209520179	0.780337889
0.209645667	0.780575666

Pressure with diameter 16mm	
0	463.0502845
0.000218917	464.9383226
0.019990001	533.1473365
0.021083169	536.8812961
0.039698556	598.096525
0.040927322	602.1040041
0.059685189	662.394696
0.060777145	665.8876113
0.079517707	720.6905373
0.08061572	723.5048922
0.099208736	799.9645839
0.100310665	812.5508095
0.101680022	821.582047
0.103242166	826.853612
0.103883685	828.3168686
0.106179401	832.1614205
0.108291278	835.2196791
0.110220006	839.1643322
0.119071092	868.9540018
0.120184033	872.571752
0.129063811	903.4931232
0.13018291	907.75328
0.139040845	939.6641368
0.14012454	943.4844789
0.159957268	1012.756791
0.161071654	1016.392023
0.164309343	1027.766146
0.178694652	1077.247536
0.179813181	1081.641133
0.180767814	1085.034021
0.198507662	1150.552805
0.199628894	1154.988829
0.200757837	1159.382108
0.20173445	1163.268704
0.202940466	1168.27489
0.204060744	1173.025085
0.205173625	1177.568854
0.20612678	1181.301917
0.207330274	1185.49943
0.208540149	1188.277615
0.209417979	1190.02237
0.200520179	1190.011502
0.200567666	1190.857636

Velocity with diameter 18mm	
0.030999372	0.852206755
0.031170616	0.851850778
0.039812555	0.862298383
0.040079274	0.85890084
0.059688243	0.840194047
0.059856184	0.840138718
0.060024126	0.840245456
0.060192067	0.841359649
0.060360008	0.843673967
0.060527949	0.844371701
0.079903347	0.776728346
0.080077102	0.775045439
0.080674651	0.773942848
0.089450227	0.756047256
0.090296301	0.757607135
0.098449551	0.840413607
0.099366996	0.84051415
0.099705006	0.841446632
0.100611867	0.842172702
0.100959672	0.844085644
0.101856542	0.845150151
0.102213746	0.843047155
0.103055293	0.842205485
0.103467426	0.84027593
0.10415789	0.849259627
0.104298645	0.848282314
0.10472091	0.847449132
0.108028899	0.848371716
0.108482152	0.849678927
0.109117789	0.842240999
0.109272547	0.841041657
0.109892056	0.849116474
0.110516393	0.847991511
0.111446374	0.851020637
0.129744946	0.828196131
0.13005997	0.828349878
0.149750316	0.796636315
0.15003696	0.797555846
0.179961382	0.776993723
0.180126407	0.779450205
0.199949756	0.780730514
0.200567206	0.780613799
0.200572338	0.780536869

Pressure with diameter 18mm	
0	463
0.001507337	468.2949054
0.018768746	528.8126402
0.020016737	532.9560135
0.039812555	598.4964266
0.041080156	602.7221581
0.059688243	662.8392982
0.060935908	666.7851805
0.079382082	722.3247376
0.080674651	725.625169
0.09999819	804.1987194
0.100611867	809.103158
0.101856542	816.6051555
0.103055293	821.8702115
0.104298645	826.5221893
0.105541997	830.4834617
0.106785399	833.9735667
0.108028899	837.1142804
0.109272547	839.9682434
0.110516393	842.9724511
0.111760486	846.4507102
0.119146735	872.5148352
0.1204398	877.4466026
0.13900008	944.8928291
0.140271855	949.4806804
0.148955874	980.3328631
0.150136426	984.4930817
0.158893924	1015.128584
0.160059635	1019.340987
0.179961382	1086.557408
0.181173762	1090.369452
0.189839963	1121.314332
0.191136069	1126.240432
0.199758772	1161.301679
0.201023079	1166.755582
0.202143735	1171.643886
0.203527824	1177.900058
0.204772994	1183.568621
0.205900025	1188.528829
0.207397619	1194.156189
0.208628385	1196.904089
0.209555754	1199.045253
0.209673939	1199.246699

Velocity with diameter 20mm	
0.037538604	0.835449554
0.037711669	0.834526321
0.041846947	0.838726806
0.042018431	0.839473993
0.043720918	0.841364558
0.043987652	0.843525056
0.044949089	0.839841644
0.045121308	0.83874773
0.046843495	0.843673035
0.047013896	0.843428313
0.048926105	0.843587091
0.049094327	0.843862288
0.054908246	0.84385987
0.055109995	0.844489909
0.057906238	0.838140742
0.058130128	0.839268182
0.079739423	0.811609234
0.0800817	0.810420152
0.089725682	0.792547113
0.089897622	0.790923433
0.099576352	0.755716733
0.100738414	0.770842727
0.102066333	0.774719527
0.103393776	0.783434231
0.104720978	0.793316331
0.10608674	0.806256629
0.106270865	0.807293136
0.107641496	0.814357037
0.109012229	0.814658508
0.11038479	0.816224005
0.110714393	0.816075568
0.12385068	0.806394346
0.124188802	0.80634218
0.139952304	0.794103728
0.140145032	0.792122545
0.159992085	0.776740675
0.160165185	0.776048852
0.179968576	0.789460445
0.180140795	0.78737997
0.199944155	0.792290464
0.209417979	0.799153536
0.209795729	0.788098454
0.209867673	0.788286369

Pressure with diameter 20mm	
0	463
0.000302978	465.6196793
0.019566292	523.4997743
0.020934576	527.4095012
0.038700904	579.1321851
0.040145136	583.1489075
0.059387608	637.0110187
0.060739723	640.7362203
0.07870611	689.493103
0.0800817	692.8346401
0.099303888	769.2632164
0.100738414	783.946504
0.102066333	792.3495917
0.103393776	798.2296535
0.104720978	802.2012009
0.106270865	804.5794262
0.107641496	805.5636834
0.109012229	806.380907
0.11038479	807.0657454
0.111780198	807.9476839
0.113150351	809.8037955
0.114520782	813.2647709
0.115923638	817.8328124
0.117293415	822.2766593
0.118663673	826.6419619
0.120034462	831.0433762
0.121413097	835.4570041
0.148976638	925.6657712
0.150356905	929.9789069
0.169648823	989.859232
0.171017556	994.1851734
0.179279701	1020.236012
0.180584406	1024.211145
0.199944155	1084.527178
0.201362451	1089.384484
0.202706944	1094.320091
0.204260567	1100.660104
0.205456126	1106.168517
0.206992819	1112.580258
0.208407494	1116.501469
0.209417979	1118.146198
0.209795729	1118.195159
0.209823839	1118.539649

Velocity with diameter 22mm	
0.044792202	0.824873971
0.044815521	0.827024039
0.059799691	0.829623687
0.060120301	0.829538514
0.07975283	0.824038164
0.08013308	0.825268517
0.099905538	0.752451019
0.10048936	0.740076644
0.100648174	0.738726809
0.101358036	0.736984243
0.101900393	0.723218324
0.102810394	0.720250467
0.103310865	0.710020311
0.104313612	0.708311764
0.104721056	0.703257744
0.105761221	0.703181115
0.106131245	0.702772619
0.107208923	0.704416224
0.107541712	0.707284622
0.108659014	0.7108834
0.10880918	0.715698694
0.108952736	0.71631071
0.109975169	0.720601094
0.110169883	0.722085641
0.111441488	0.726252135
0.111609534	0.733942222
0.11177758	0.742161914
0.114491088	0.770376229
0.114608048	0.772407903
0.115429647	0.777087522
0.116026112	0.780231878
0.116757915	0.782869074
0.117446455	0.782969911
0.118015011	0.78392304
0.118583568	0.784983711
0.118869376	0.785064646
0.119456532	0.786036689
0.179330842	0.784463737
0.179591497	0.785621288
0.208860946	0.792564463
0.209273323	0.791266149
0.209685701	0.775746458
0.20978266	0.766629639

Pressure with diameter 22mm	
0	463
0.000343408	465.8414003
0.019375711	523.7630054
0.02089625	528.1687016
0.039915373	582.8291554
0.041336005	586.7445105
0.058929015	635.3108749
0.060407003	639.2848844
0.079372581	688.8880861
0.080933535	692.3303494
0.099905538	781.0230592
0.101177251	788.5681712
0.101358036	789.4560244
0.102810394	795.8321739
0.104313612	800.8206984
0.105761221	803.5654568
0.107042529	804.1605754
0.107208923	804.1476435
0.108659014	802.4027325
0.114491088	793.2158009
0.116026112	797.7042487
0.117446455	802.6177018
0.118869376	807.4108111
0.12029518	811.8462082
0.121724176	816.236058
0.129229701	841.3029624
0.130695222	846.1553182
0.149764432	907.9208178
0.151269977	912.7354241
0.168914335	967.3182366
0.170417913	971.6632648
0.187999894	1024.114836
0.189523009	1029.004413
0.190702871	1032.871499
0.198081986	1056.152466
0.199778264	1061.54485
0.201253566	1066.175158
0.202450791	1069.962337
0.206976104	1084.712793
0.208294115	1087.313884
0.209273323	1088.077535
0.209685701	1087.847661
0.209723356	1088.282382

Velocity with diameter 24mm	
0.045171745	0.835691998
0.045498955	0.837548832
0.059853788	0.831724671
0.060228584	0.83261309
0.079430086	0.814335456
0.079802476	0.81273559
0.089943754	0.769123327
0.09057265	0.76993158
0.09974737	0.848143681
0.100489377	0.847765855
0.100882051	0.847972969
0.101095296	0.846582231
0.101308542	0.84607407
0.101900394	0.846185422
0.10257236	0.845103055
0.10331086	0.84517101
0.104100327	0.845906012
0.104721052	0.846029767
0.105582138	0.84668144
0.106131247	0.848028134
0.10868161	0.839917555
0.109273884	0.837278588
0.109916154	0.836064653
0.110140384	0.835194547
0.111421838	0.833854939
0.111777591	0.832832928
0.119959025	0.826524997
0.120455942	0.825524336
0.139638146	0.813568219
0.140029833	0.812045379
0.149963351	0.80735153
0.150266486	0.806302328
0.159610139	0.801428681
0.16001439	0.800614804
0.169868356	0.797225809
0.17005015	0.797880999
0.179890393	0.796368395
0.180246783	0.794903353
0.1999047	0.791425045
0.20025719	0.791686915
0.200798196	0.793142729
0.200798205	0.782243606
0.200866656	0.778366378

Pressure with diameter 24mm	
0	463
0.000383804	465.2898387
0.019943126	525.8702017
0.021180564	529.7308254
0.039390496	584.322449
0.040994922	589.2527456
0.059100946	641.6795309
0.060448224	645.3934062
0.078487018	690.6505106
0.080157667	693.4640477
0.089146737	706.4240798
0.09057265	709.0124263
0.09974737	779.7132894
0.100882051	786.4958998
0.101095296	787.4407061
0.10257236	793.2430163
0.104100327	797.4141749
0.105582138	800.2268419
0.107117098	801.8741572
0.10868161	802.6979755
0.110140384	803.0866609
0.111777591	804.1999866
0.113059743	806.8356707
0.11460802	811.489458
0.116026046	816.6751059
0.117446335	821.8083192
0.119286514	828.023978
0.120849289	833.0770759
0.138885304	894.3450865
0.140389497	899.5156784
0.159610139	961.6341986
0.16127225	966.494208
0.169048004	990.3556185
0.170519932	994.5926227
0.188259272	1050.506294
0.190088529	1056.573047
0.19884723	1086.720174
0.200492594	1092.66069
0.201977843	1097.893716
0.209292112	1119.490913
0.200798196	1120.184663
0.200798205	1120.184665

Velocity with diameter 25mm	
0.044531601	0.821840231
0.044826342	0.821144661
0.049938778	0.824183055
0.050338324	0.823487121
0.06978178	0.831744649
0.070168083	0.829655029
0.089239088	0.817728621
0.090379276	0.818514981
0.099361461	0.74766593
0.100207153	0.744441002
0.100675404	0.743649443
0.100882799	0.740758415
0.10171238	0.739118957
0.10220077	0.738728262
0.102404002	0.737040545
0.103925136	0.737461197
0.104721136	0.740169003
0.105251502	0.740891845
0.105446271	0.741969715
0.106967475	0.75046059
0.107729899	0.759237776
0.108302234	0.761452814
0.108488814	0.765356037
0.109235135	0.773487505
0.1098276	0.777539433
0.11001036	0.781596141
0.11114911	0.785769545
0.111532178	0.788074336
0.112878333	0.79026424
0.129964576	0.785610956
0.130271792	0.784355503
0.149858673	0.778947864
0.150205382	0.777128258
0.16973957	0.783747144
0.170107128	0.784583343
0.189842817	0.794695906
0.19025741	0.793485807
0.190672002	0.793422125
0.199824199	0.781197456
0.200100608	0.781483785
0.209740113	0.789153536
0.209503005	0.788098454
0.209673333	0.787669639

Pressure with diameter 25mm	
0	463
0.000404005	466.6504096
0.018629851	524.7337138
0.020212344	529.8599887
0.038268165	583.1772334
0.040069995	588.621348
0.059584637	644.5730878
0.061249122	649.1563866
0.079685591	699.8613092
0.081218103	704.0433024
0.099361461	775.1468611
0.100882799	783.3883804
0.102404002	789.4754109
0.103925136	793.81763
0.105446271	796.9198116
0.106967475	798.7926138
0.108488814	799.6494222
0.11001036	800.08252
0.111532178	800.8275173
0.11317168	802.5627745
0.114692396	805.2649433
0.116356346	809.4558135
0.11787734	814.0492573
0.119399909	818.7881066
0.120924239	823.855107
0.122450521	829.3788403
0.139221892	886.4844429
0.140446124	890.3971381
0.158926117	949.6414396
0.160546022	954.4130699
0.169372012	981.2612132
0.171175707	986.1702223
0.189463398	1043.559574
0.190984825	1048.502936
0.196942107	1068.038285
0.198670169	1074.006296
0.200100608	1079.251916
0.201706686	1085.219851
0.206288706	1101.20442
0.207733515	1104.882609
0.209740113	1107.109065
0.209603005	1108.043674
0.209733388	1108.536866

Velocity with diameter 26mm	
0.045215356	0.825511792
0.045623055	0.823607268
0.049799428	0.823398056
0.050156054	0.825999578
0.069926517	0.826798565
0.070324605	0.826964077
0.089235404	0.815608358
0.089622718	0.814973059
0.090002646	0.814822786
0.099299587	0.761342097
0.100130071	0.7654229
0.100207198	0.767438336
0.100857064	0.772205729
0.101712405	0.77631455
0.102181524	0.777026959
0.107729887	0.841313043
0.108154634	0.845804225
0.108514797	0.84553609
0.10930019	0.845636241
0.109699683	0.846104604
0.110046916	0.847031218
0.111244731	0.845700929
0.111579493	0.844842079
0.112249017	0.844454788
0.112789779	0.844544957
0.116181127	0.848099175
0.118635114	0.845076808
0.119395002	0.843377483
0.120167526	0.842146324
0.129405805	0.827890435
0.129785309	0.828055136
0.130182186	0.826784639
0.132875406	0.829535069
0.133289835	0.82811375
0.149870936	0.815223361
0.150257198	0.813165839
0.169956563	0.800640105
0.170304937	0.805294174
0.18984106	0.792453132
0.19004219	0.792861574
0.20936465	0.791370488
0.200129076	0.786803933
0.200139077	0.785804955

Pressure with diameter 26mm	
0	463
0.000424208	466.2350446
0.018894975	524.769528
0.020473148	529.8636796
0.039011982	584.3780854
0.040463935	588.1483438
0.059148313	642.0232956
0.060588272	646.1718769
0.078863975	692.5540723
0.080416673	695.5388889
0.099299587	805.7064546
0.100857064	816.2508051
0.102181524	824.1701004
0.10351949	831.0688706
0.103719764	831.6464522
0.105258005	835.7022277
0.106833646	838.9591337
0.108514797	841.4262434
0.110046916	842.3556582
0.111579493	843.0096968
0.113112642	844.4836632
0.114646481	847.439702
0.116181127	852.0353153
0.117716701	857.843355
0.119395002	864.6364563
0.120929175	870.4739593
0.13938604	932.3467903
0.140952049	937.3522401
0.159482074	997.4909349
0.160966258	1001.94023
0.16868559	1025.866127
0.170304937	1030.778513
0.179663236	1056.674027
0.181134352	1061.113331
0.182624577	1065.892711
0.199518996	1122.34439
0.201216799	1129.261913
0.202810497	1135.45474
0.205858037	1145.977705
0.207386827	1150.208334
0.208600226	1152.479817
0.200129076	1154.290401