T.C.
FATIH UNIVERSITY
INSTITUTE OF BIOMEDICAL ENGINEERING

ANALYSIS OF CORONARY STENT IMPLANTATION EFFECTS ON BLOOD FLOW IN STEADY AND PULSATILE FLOW CONDITIONS BY USING LASER DOPPLER ANEMOMETRY

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MSc THESIS

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ASSOC. PROF. DR. NURULLAH ARSLAN

ISTANBUL, JULY/ 2014

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FATİH ÜNİVERSİTESİ
BİYOMEDİKAL MÜHENDİSLİK ENSTİTÜSÜ

KORONER STENT İMPLANTASYONUNUN SÜREKLİ VE PULSATİL AKIŞ ŞARTLARINDA KAN AKIŞINA ETKİSİNİN LAZER DOPPLER İLE İNCELENMESİ

KIYOUMARS ASHOUROUN

YÜKSEK LİSANS
BİYOMEDİKAL MÜHENDİSLİĞİ PROGRAMI

DANIŞMAN
DOÇ. DR. NURULLAH ARSLAN

İSTANBUL, TEMUZ / 2014

T.C.
FATIH UNIVERSITY
INSTITUTE OF BIOMEDICAL ENGINEERING

Kıyoumars ASHOUROUN, a **MSc** student of Fatih University **Institute of Biomedical Engineering** student ID 520112006, successfully defended the **thesis** entitled "**ANALYSIS OF CORONARY STENT IMPLANTATION EFFECTS ON BLOOD FLOW IN STEADY AND PULSATILE FLOW CONDITIONS BY USING LASER DOPPLER ANEMOMETRY**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Prof. Dr. Sadık KARA
Director

Date of Submission: 6 June 2014
Date of Defense: 4 July 2014

To me,

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July 2014 Kiyoumars ASHOUROUN

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LIST OF SYMBOLS

R_e	Reynold Number
μ	Viscosity
D	Inner diamater of the tube
ρ	Density
U_m	Mean velocity
Q	Flow rate
A	Cross section area
t	Time
s	Second
N	Index of refraction
V	Velocity
V_{max}	Maximum Velocity

ABBREVIATIONS

min : Minute
LDA :Left main Coronary artery
PSP :Polyamid seeding particles
Lda : laser Doppler anemometry
CVD : Cardiovascular disease
WSS : Wall Shear Stress
SS : Stent Strut
PCI : Percutaneous Coronary Intervention

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SUMMARY

ANALYSIS OF CORONARY STENT IMPLANTATION EFFECTS ON BLOOD FLOW IN STEADY AND PULSATILE FLOW CONDITIONS BY USING LASER DOPPLER ANEMOMETRY

Kiyoumars ASHOUROUN

Biomedical Engineering Programme

MSc Thesis

Advisor: Assoc.Prof. Dr.Nurullah ARSLAN

In this research flow velocity profile in both Steady and Pulsatile flow produced by peristaltic pump inside a silicon rubber tube that imitating the coronary artery has observed by using Laser Doppler Anemometry before and after implementation of stent in both laminar and turbulant flow and comparing the velocity datas and profiles achieved in 10 cm starting from outlet of the stent and continue down stream of flow between two flow conditions in stented and stent free models is done.

Key words: Flow, Steady, Pulsatile, Stent, Laser Doppler.

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ÖZET

KORONER STENT İMPLANTASYONUNUN SÜREKLİ VE PULSATİL AKIŞ ŞARTLARINDA KAN AKIŞINA ETKİSİNİN LAZER DOPPLER İLE İNCELENMESİ

Kiyoumars ASHOUROUN

Biyomedikal Mühendisliği Programı
Yüksek Lisans Tezi

Danışman: Doç.Dr. Nurullah ARSLAN

Bu araştırmada koroner atar damarını temsil eden silikon tüpün içerisindeki stentin Peristaltik pompa vasıtasıyla sağlanan sürekli ve pulsatil akışlarına etkisi Lazer Doppler ile stent implantasyonundan önce ve sonra incelenmiştir ve her iki akış şartlarındaki hız dataları ve profilleri stentin çıkış noktasından itibaren 10 cm boyunca çıkartılıp ve grafikler elde edildikten sonra kıyaslanmıştır.

Anahtar Kelimeler: Akış, Sürekli, Pulsatil, Stent, Lazer dopler

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FATİH ÜNİVERSİTESİ -BİYOMEDİKAL MÜHENDİSLİK ENSTİTÜSÜ

CHAPTER 1

INTRODUCTION

Cardiovascular disease (CVD) is sometimescogitated to be a problem of modern countries.

Actually, major cause of death in whole world is known as CVD. In all developed nations and low and middle income countries, it reports for almost 30 percent of all deaths. The prevalence risk factors for CardioVascular Deseases and associated chronic diseases in modernizing countries, including tobacco, unhealthy dietary changes, , increasing blood fatty acids, reduced physical activity and hypertension, reflects significant worldwidel changes in characteristics and life model[1].

From adolescent, cholesterolplaque would begin to lay in the blood vessel inner walls. As we get older, the plaque makes up, provoke the blood vessel iner walls and increasing the risk of blood clots formation and heart attack. The deposited plaques release chemicals that start the process of curing but make the inner walls of the blood vessel viscid. Then, other materials, such as lipoproteins, inflammatory cells and calcium that moving in our bloodstream start gumming to the inside of the vessel inner walls.

Finally, a narrowed artery may make new blood vessels that find a new way to get blood to the heart. Also, during times of increased effort or stress, the new arteries may not be able to provide enough oxygenated blood to the cardiac muscle [2].

An interventional operation is a non-surgical curing used to open narrowed coronary arteries to enhance blood flow to the heart. An interventional procedure can be implemented during an identification cardiac catheterization when congestion is determined, or it may be set after a catheterization has approved the availability of coronary artery disease.

An interventional method begins out the same way as a cardiac catheterization. When the catheter is in position, one of these interventional procedures is implemented to open the artery: stent placement, balloon angioplasty, rotablation or cutting balloon.

Stenting: In almost all cases, balloon angioplasty is implemented in integration with the stenting method. Stent is a small, metal mesh tube that roles as a wharf to ensure support inside the coronary artery. A balloon catheter, put on a guide wire, is used to insert the stent into the narrowed artery. When in place, the balloon is blown up and the stent enlarges to the size of the artery and keeps it open. The balloon is deflated and took away, and the stent remains in place permanently. During a period of several weeks, the artery recovers around the stent. Thence, restenosis is alittle diminished [3].

The sudy of blood flow profile by using laser doppler anemometry in Steady and Pulsatile characteristics of flow before and after implementation of a stent inside the coronary artery is done in this research, so the velocity profile and turbulances at the outlet of the stented region can be observed and compare with the stent free region of the artery and the effect of stent implementation on blood flow profile is examined.

Blood flow velocity profile is one of the most important parameters in promoting cardiovascular diseases such as restenosis, red blood cell deformation and malfunctioning of endothelial cells. One of the reasons of these problems is stent implementation. In a healthy person in various parts of the cardiovascular system there is different blood velocity profile in various arteries such as Carotid arteris, Coronary arteries and etc. and this is because of the blood flow presure and structure of the artery at that region and this is also related to the anatomical place of the artery and its function.

1.1 Literature Review

Stenting influences coronary flow types that have been incorporated with stent thrombosis and restenosis rates [4]. Actually, changed geometry and incorporated blood flow deformities induced by stenting can effects restenosis [5]. Deformed flow may also simplify the aggregation of other blood thrombogenic factors and platelets close to the wall.

Presentation of stents struts into the coronary artery with endemicbulge into the lumen, which change the original flow condition. Stent struts change flow conditions in both inside the vessel lumen and near to the vessel wall [6].

Coronary artery stents are being studied in severalclinical research organizations, with the aim of avoidingcoronary artery restenosis consequent balloon angioplasty [7]. In this method, a coronary stentis positioned over the angioplasty balloon and applyedto the region of the lesion. The stent enlarges with theballoon and remains in place after the balloon isdeflated and removed, so working as a mechanicalwharf to prevent renarrowing orrestenosis ofthe vessel lumen.

In the latest results indicate that coronary artery stents stimulate flow unsteadinesses that are detected 1 cm downstream under induced mild exercise conditions. We did not detect anyunsteadinesses 5 cm downstream. These unsteadinesses are therefore best explained as flow unsteadinesses, since the definition of complete turbulence implements only to unsteadinesses which do not decease as they propagate downstream [8].

Stent implantationin the carotid artery bifurcation stimulatechanges of the physiologic flow behavior. Depending on the stent structural design the flow changes are positioned in different regions [9].

The fluid flow interaction between stent mesh and blood flow changes the WSS [10]. Flow unsteadinesses and reduced blood flow have been incorporated with higher restenosis rates and contrary events after coronary interventions. We searched to investigate flow changes that happend after stent implantation in a coronary model, within and near to the stented part. A stentwasapplied in the left anterior descending artery (LAD) of a real scaled silicon coronary model design. The model was assembledinto an artificial circulation and showed stretchability and rheologic characteristics comparable to human coronaries. Flow profiles were achieved using laser-Doppler anemometry. Stentstimulated a transitional flow within the stents, in the meshed branch as well as in the nearparts. This study reveals accurately that stent implantation stimulates flow unsteadinesses in parts known to be prone for restenosis. Examinations using laser-Doppler measurements may brighten rheologic stimulating inducing restenosis and makes it easier to optimizing stent design and opening techniques[11].Turbulence is one of the hydraulic unsteadinesses mingled in thrombus formation, even if absolute proof of itsassistance effect is lacking [12].The mechanism of thrombus creation stimulated by turbulence is probably related to the effectsof turbulence on created elements in the bloodSuch effects could have been caused by [13] shear,[14] collision with the walls of the tubing, or [15]prolonged contact with the foreign surface. Bothagitated random flow and high shear are intrinsicbehavios of turbulence [16].

The probabilitythat high rates of shear lend to the activationof platelets has been aforethought [17].

Collision of builed elements with the walls of thetubing does happen, since turbulence causes eddiesof flow perpendicular to the wall. Deformationof theblood cells due to collisions could have lended to the deposition of thrombi.

Sloshed random movement of the blood within theturbulent region can cause the blood cellsto be in touch with the walls of the for a long time in the turbulent system in contrast with the laminar flowsystem. This condiition can lended tothe observed increase in thrombus formation in theturbulent system. Such a mechanism, could apply

To the mechanism of thrombus creation in some clinical conditions such as thrombosis in the environs of intravascular prostheses [12].

Laser Doppler anemometers are inherently precise, linear, and non-invasive. Calibration generally is not necessary; frequency measurements andlengt cover to build velocity at a spatial point. Measurements could made at points in the cross-sections of channels containing fluid flow [18].

Coronary flow velocity changes immediately after stent implantation arterial restenosis after stent delatation may be stimulated by the local flow condition within and around the stent [19].

Simulations have showed the presence of flow recirculation andseparation immediately downstream of stents. In steady flow within straight vessels, the prolong of flow unsteadinesses downstream of the stent increases with both stent wire thickness andReynolds number but is relatively insensible to stent struts. In semi circular vessels, flow disturbance downstream of the stent happens along both the inner and outer vessel walls with the prolong of disturbance linked on the angle of vessel curvature. In pulsatile flow, the segments of flow disturbance time dependantly increase and decrease in size. Non-Newtonian fluid properties lead to a small reduction in flow disturbance downstream of the stent [20].

CHAPTER 2

MATERIALS AND METHODS

2.1 Coronary Artery

Coronary circulation is the circulation of blood in the blood vessels of the heart muscle (myocardium). The vessels that carry oxygenated blood to the myocardium are known as coronary arteries.

We know that right and left coronary arteries position on the surface of the heart, they can be called epicardial coronary arteries. Coronary arteriesare capable of autoregulation to protect coronary blood flow at levels suitable to the needs of the heart muscle. These relatively narrow vessels are mostlyinfluenced by atherosclerosis and can become blocked, causing angina or a heart attack.

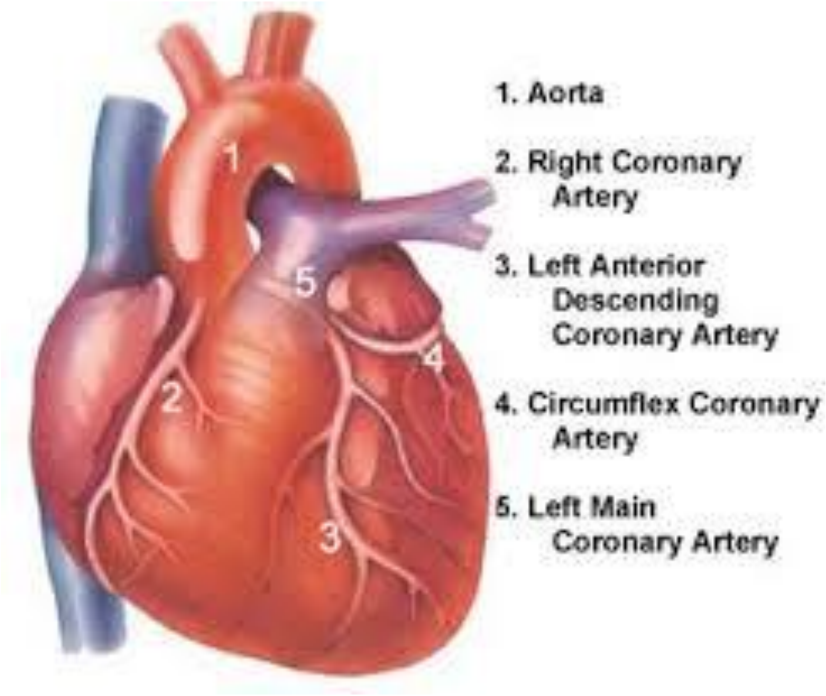


Figure 2.1 Carotid arteries of Heart [21]

2.1.1 Coronary Stenosis

Coronary stenosis is a situation in which a coronary artery becomes coned and blocked with materials like cholesterol or fat. A coronary artery is a blood vessel located in the heart that is incharge of supplying the heart with blood. If the artery becomes blocked, it can severely affect the heart's functioning and may eventually become fatal.

If the coronary artery gets wounded, it can result in coronary stenosis. Cholesterol is a solid material that can bind to the inside of blood vessels wall and affect their performance to carry blood to the heart. Containing high levels of cholesterol in the blood can damage the coronary artery, as can cause hypertention.

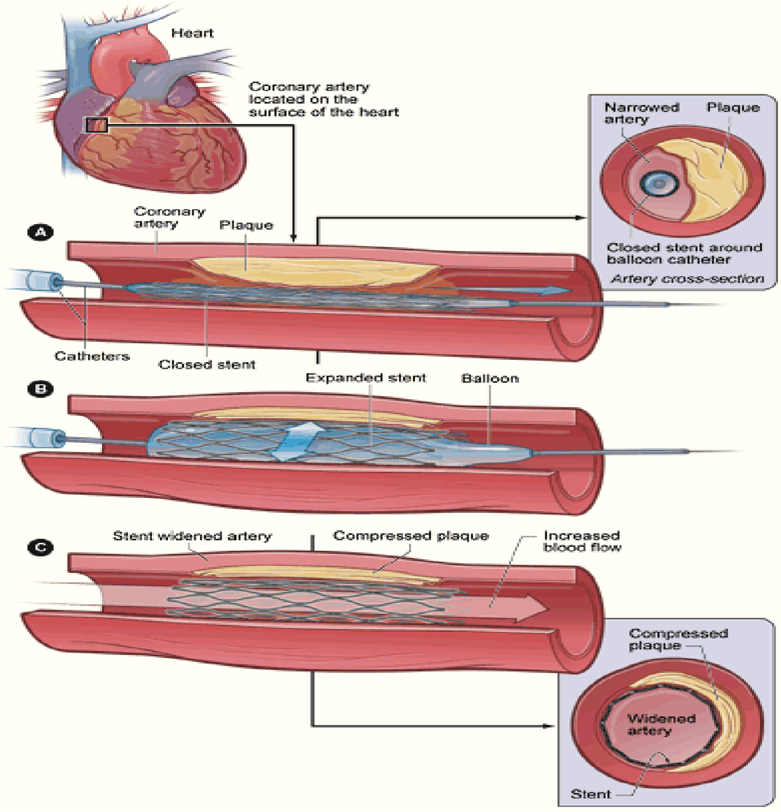


Figure 2.2Proces of stenosis and stent implantation [22]

2.1.2Coronary Stent

A coronary stent is a tube like metal positioned in the injured coronary arteries that supply the heart, to maintain the arteries open in the treatment of coronary heart disease. It is used in a operation called percutaneous coronary intervention (PCI). Stents decrease chest pain and have been observed to advance life time in the case of an acute myocardial infarction[23].Stents generally are made of metal mesh, but sometimes they're made of drape. Drape stents, also called stent grafts, are employed in larger arteries.

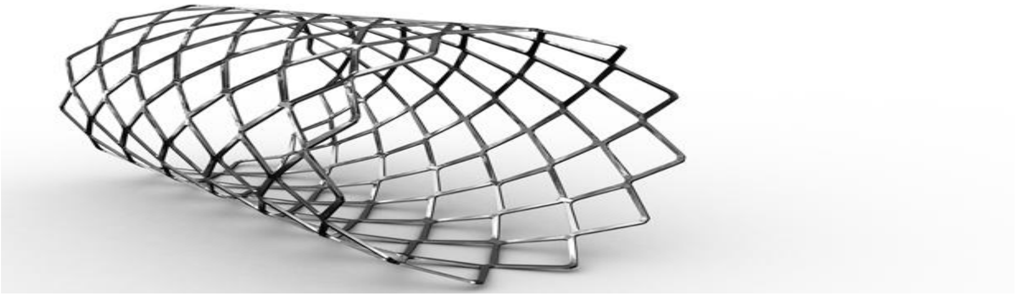


Figure 2.3 Typical Stent Schematic[24]

In this research a stainless steal spring with outer diameter of 7,8 mm was used insteed of using stent, beause there is not any real stent with the outer diameter of 7,8 mm that used in stent implementation, also in the used spring there was grooves that could imitate as struts of the stent.

Figure 2.4 Stainless Steel Spring

2.2Flow through Coronary Artery

2.2.1 Steady Flow

Pressure, Velocity and other properties of fluid flow can be functions of time separate from being functions of space. If a flow that the properties at every point in the flow is independant upon time, it is called a steady flow. Mathematically formulafor steady flows:

$$\frac{\partial P}{\partial t} = 0 \tag{2.1}$$

Where P is any property like density, velocity or pressure [25].

In other word when all the time involutions of a flow field disappear, the flow is concieved to be a steady flow. Steady-state flow refers to the situation where the fluid characteristics at a point in the system do not change over time.

Laminar flow over a sphere is steady in the frame of reference that is constant with respect to the sphere

Laminar flow is the normal situation for blood flow throughout most of the circulatory system. Its properties are concentric layers of blood moving in parallel down the length of a blood vessel. The highest velocity in laminar flow (V_{max}) is found in the center of the vessel. The lowest velocity (V=0) is found along the vessel wall. If the flow is fully developed, so the flow profile is parabolic. This occurs in straight, long blood vessels, under steady flow conditions.

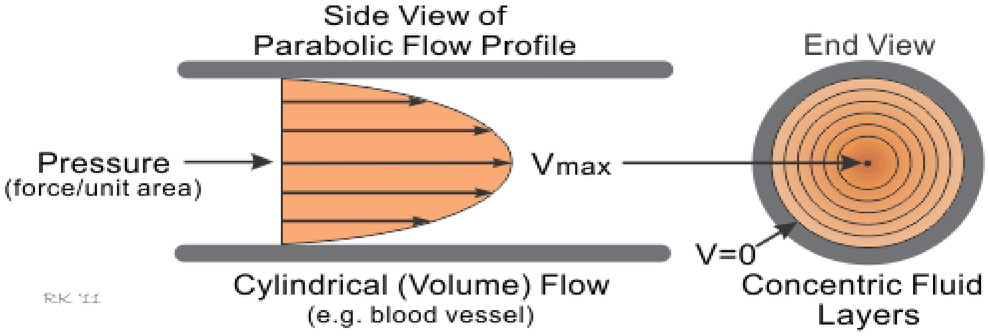


Figure 2.5Steady Laminar Flow Velocity Profile [26]

Largely in the body, blood flow is laminar. However, in conditions of high flow, especially in the ascending aorta, laminar flow can be dispersed and become turbulent. When this occurs, blood does not flow smoothly and linearly in near layers, but in return the flow can be characterised as chaotic. Turbulent flow also happens in large arteries at bifurcation regions, in diseased and narrowed (stenotic) arteries (see figure below), and across calcificated heart valves.

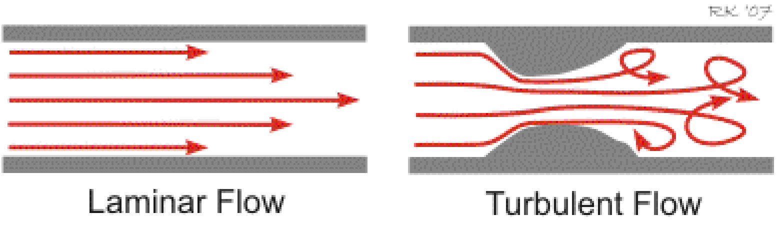


Figure 2.6 Steady vs Turbulent Flow Schematics [27]

2.2.1 Pulsatile Flow

In a reference frame that is constant with respect to a background flow, the flow is unsteady. Turbulent flows are unsteady by definition turbulence does not happen until it reach high velocity that the flow lamina break apart. Therefore, when blood flow velocity increases in a across a heart valve or blood vessel, the step by step increase in turbulance is not common. Instead, when a critical Reynolds number (Re) is exceeded turbulance occures. Reynolds number is a formula to calculate under ideal conditions whenturbulence will occur [28].

The equation for Reynolds number is:

Basic Reynold number formula: $R_e = \frac{\rho.U.D}{\mu}$ (2.2)

Under resting conditions, wave form of coronary flow remained laminar, even after stent placement. However, unsteadinesses were found downstream from a stent placed in the proximal LAD under light exercise conditions. These disturbances were found 5 mm distal to the stent, in the LAD [29].

2.3Modeling and Setup the System

2.3.1 General Schematic of the System

The system includes parts that are listed below:

- LDA signal processing unit
- Laser doppler probe
- Blood like fluid
- Peristaltic pump
- Humusoft DAQ card
- Motor driver
- Stent implanted tube
- Matlab installed pc

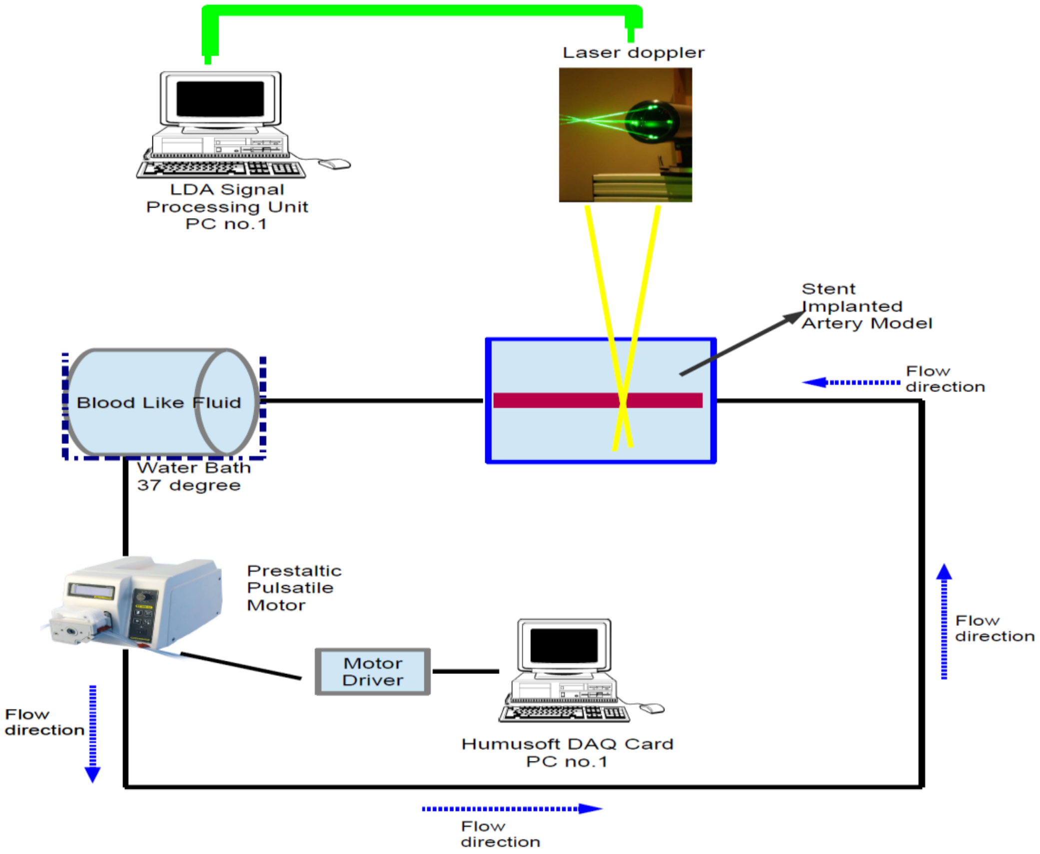


Figure 2.7General Schematic of the System

2.3.2 Silicone Rubber Tube

A sillicon rubber tube selected to be imitate the coronary artery because it‘s compliance is similar in compare with the artery and also it has fully peneterance with inside diameter of 7.9 mm. So calculations made by dynamic similarity to get the original Reynold number at LDA coronary artery constant and find the other parameters coresponding to the diameter of the tube(7.9mm)[equation 2.2.]. Thein vivo and in vitro parameters are written in section 2.3.10.

Figure2.8 Silicone Rubber Tube

2.3.3 Index of Refraction

The index of refraction of silicone rubber is 1,44 and for air is 1. So for correcting the bending of laser beam in the wall of the silicone tube we prepare some water (n=1,333) and oil mixture to make the index of refraction of medium equal to index of refraction of silicone.

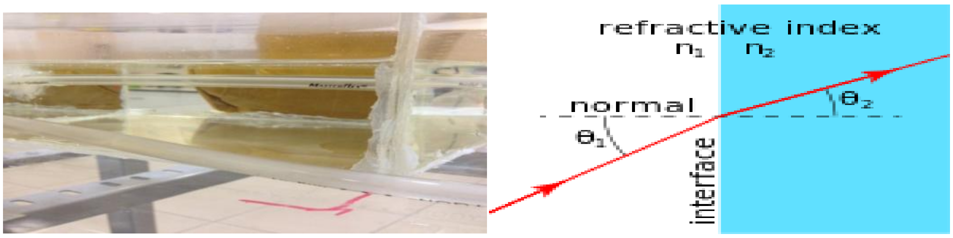


Figure2.9Index of Refraction of the Medium

2.3.4 Peristaltic Pump

Natural system of pumping materials in the case of most physiological fluids is peristaltic transport. Separate from physiological fluids, some other fluids also show peristaltic behaviour. When the flow is influenced by a advancing wave of segment contraction/relaxation along the length of the border of a fluid-filled stretchable tube peristalsis occures [30, 31].

A peristaltic pump (Master flex inc.) used to produce flow with the flow rate of 132 ml/min that calculated with dynamic similarity formulas in both laminar and pulsatile flow.

Figure 2.10 Peristaltic pump (Master flex Inc.)

2.3.5 Laser Doppler Anemometry

Laser Doppler anemometry (LDA), is the technique of using the Doppler shift in a laser beam to measure the velocity in semi-transparent or transparent fluid flows, or the linear or vibratory motion of opaque, reflecting, surfaces.

By using laser doppler anemometry with wavelenght of the 512nm the velocity profile and mean velocity inside the tube can be achieved by getting the information of the back scattered laser beam from the flowing PSPs inside the tube. LDA is connected to the BSA flow software [32], so the information collected in the system and the data calculated by the software.

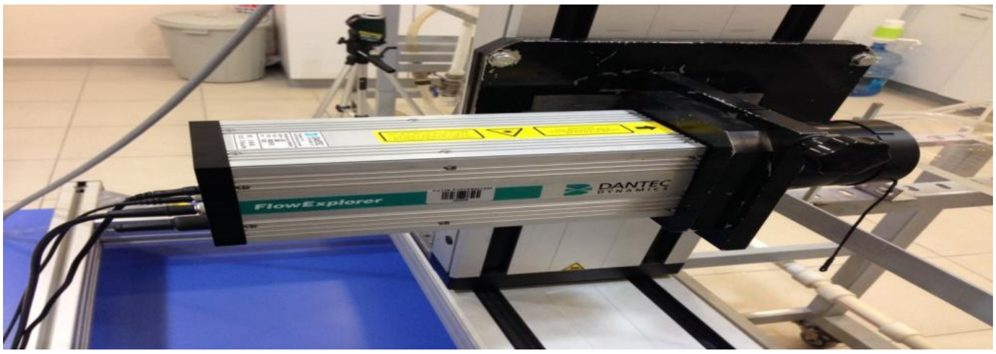


Figure 2.11 Laser Doppler Probe

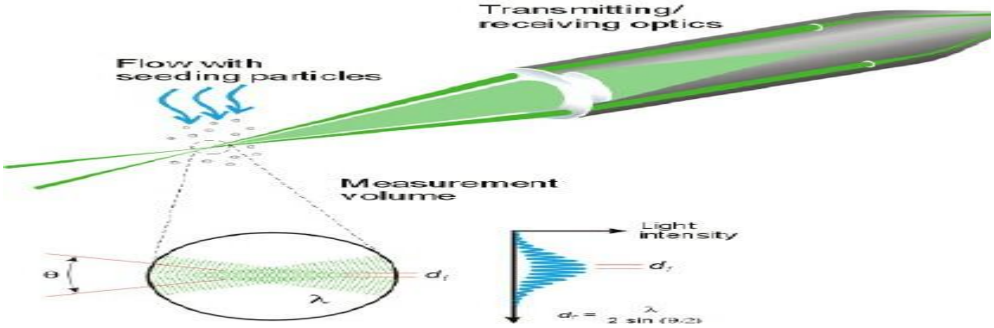


Figure 2.12 Working Principle of LDA

2.3.6 Polyamide Seeding Particles (PSP)

This is a tracer that is small enough to follow (trace) fluid motion and does not alter fluid or flow properties.

These are produced by polymerisation processes and therefore have a round but not exactly spherical shape.

They are microporous and strongly recommended for water flow applications [33].

1 liter of water mixed with 2 grams of PSP for preparing the blood like fluid mixture for using inside the tube.

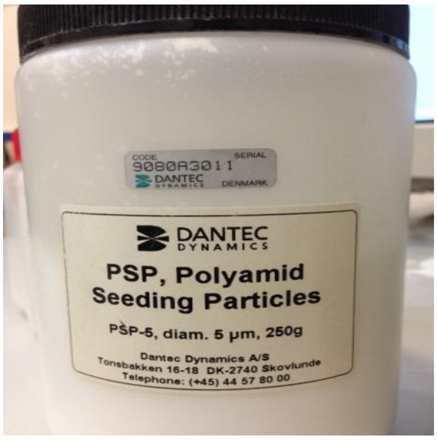


Figure 2.13 Polyamide Seeding Particles (PSP)

2.3.7 Traverse System

Traverse system used to move the laser light probe in vertical direction from top to down of the inner cross section area of the tube with predefind transition time for each point and positions by step size of the 1mm. After completing one cross section the traverse system moves 10mm toward the direction of the flow and BSA flow software starts to calculate the same process in new cross section. The system will continue to calculate the mean velocity till it reaches to the 10cm away from the beginning position. So we can get 10 velocity profiles in horizontal direction starting from the outlet position of the stent.

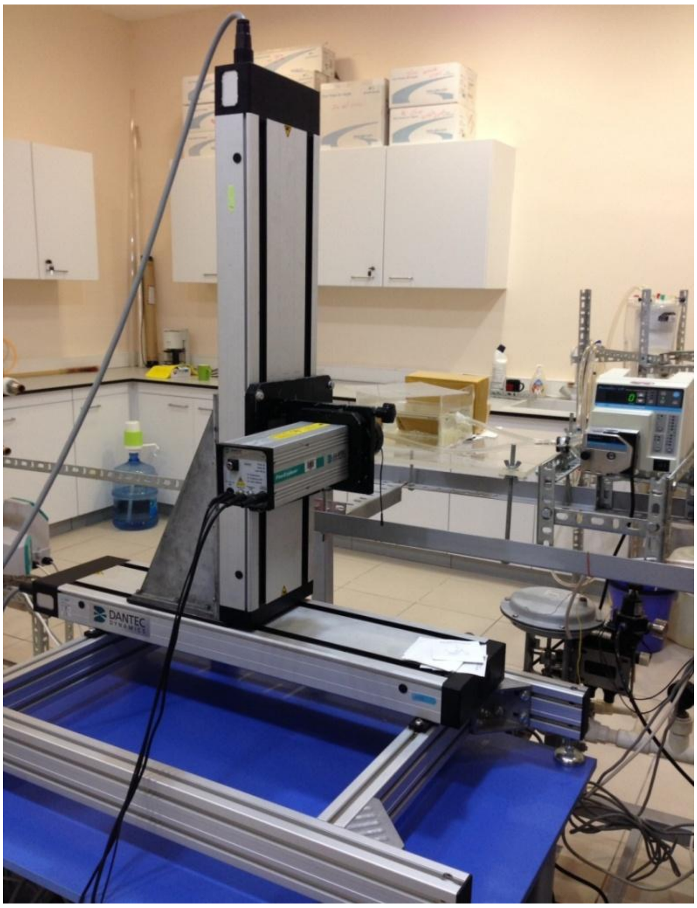


Figure 2.14 Traverse System Schematic

2.3.8 Dynamic Similarity Equations

Basic Reynold number formula: $R_e = \frac{\rho.U.D}{\mu}$

We keep the Reynold number constant for both the in vivo and in vitro conditions and make dynamic similarity:

$$\frac{\rho.U_m.D}{\mu} \tag{2.2}$$

$$Q = U_m.A \tag{2.3}$$

$$\frac{\rho.4.Q}{\pi.D.\mu} \tag{2.4}$$

Predefined informations:

$$\rho_{vivo} = 1060\ \frac{kg}{m^3}$$

$$\rho_{vitro} = 1000\ \frac{kg}{m^3}$$

$$Q_{vivo} = 225\ \frac{ml}{min} \Rightarrow 3{,}75\ .\ 10^{-6}\ \frac{m^3}{s}$$

$Q_{vivo\ =\ ?}$

$$D_{vivo} = 3{,}9\ mm \Rightarrow 3{,}9\ .\ 10^{-3}\ m$$

$$D_{vitro} = 7{,}5\ mm \Rightarrow 7{,}5\ .\ 10^{-3}\ m$$

$$\mu_{vivo} = 35(mp) \Rightarrow 357\ .\ 10^{-6}\ \frac{kg\ .s}{m^2}$$

$$\mu_{vitro} = 10(mp) \Rightarrow 102.\ 10^{-6}\ \frac{kg.s}{m^2}$$

$$\frac{\rho_{vivo}.\ 4.\ Q_{vivo}}{\pi.\ D_{vivo}.\ \mu_{vivo}} = \frac{\rho_{vitro}.\ 4.\ Q_{vitro}}{\pi.\ D_{vitro}.\ \mu_{vitro}}$$

$$\frac{\left(1060\,\frac{kg}{m^3}\right).\,(3{,}75.\,10^{-6}\,\frac{m^3}{s})}{(3{,}9.\,10^{-3}m).\,(357.\,10^{-6}\,\frac{kg.s}{m^2})}$$

$$\frac{\left(1000\,\frac{kg}{m^3}\right).\,(Q_{vitro}\,\frac{m^3}{s})}{(7{,}5.\,10^{-3}m).\,(102.\,10^{-6}\,\frac{kg.s}{m^2})}$$

$$Q_{vitro} = 2{,}2\,.\,10^{-6}\,\frac{m^3}{s} \Rightarrow 132{,}12\,\frac{ml}{min}$$

$$\frac{Q}{A} = U_m$$

$$\frac{130\ \frac{ml}{min}}{\pi\,.\,(7{,}5\ mm)^2} = \frac{2{,}17\,.\,10^{-6}\,\frac{m^3}{s}}{1{,}77\,.\,10^{-4}m^2}$$

Average velocity of flow in the tube in laminar flow conditions:

$$U_m = 0{,}0122\,\frac{m}{s}(2.3)$$

$$U = 0{,}0244\,\frac{m}{s}(2.5)$$

CHAPTER 3

RESULTS AND DISCUSSIONS

3.1 Steady Flow

In laminar flow the prestaltic pump itself produces a flow inside the tube and it sustain the produced flow rate at a constant magnitude by it's closed loop property, so by getting the back scattered information from the probe, the BSA flow software gives the mean velocity at each predefind vertical 5 point. By exporting the data to the Excel program, the graph of the flow at a specific cross section can be achieved and this process continue till measure mean velocity in each point in 10 cross section in downstream of the tube.

3.1.1 Velocity Profiles before Stent Implementation

By getting the datas from laser Doppler, the tables and graphs of velovity profiles inside the tube obtained by using the MS Offic Excel program. Starting from the position of x,y(0,0) in the tube by step sizes of 10mm and finished at the position of x,y(100,5), so 10 graphs and tables is obtained.

Unit of length in this research is in millimeters. In this section all the graphs are similar and datas on the tables are nearly same because there is not any obstacle inside the tube and flow is steady and the flow velocity profile in laminar flow could be seen. Due to the definition of the laminar flow, the velocity is maximum at the center of the tube and it decreasesas the flow approaches to the inner wall of the tube untill it reaches to zero at the walls.

Because of the similarity between graphs, here there is datas of flow obtained in beginning and end of the tube.

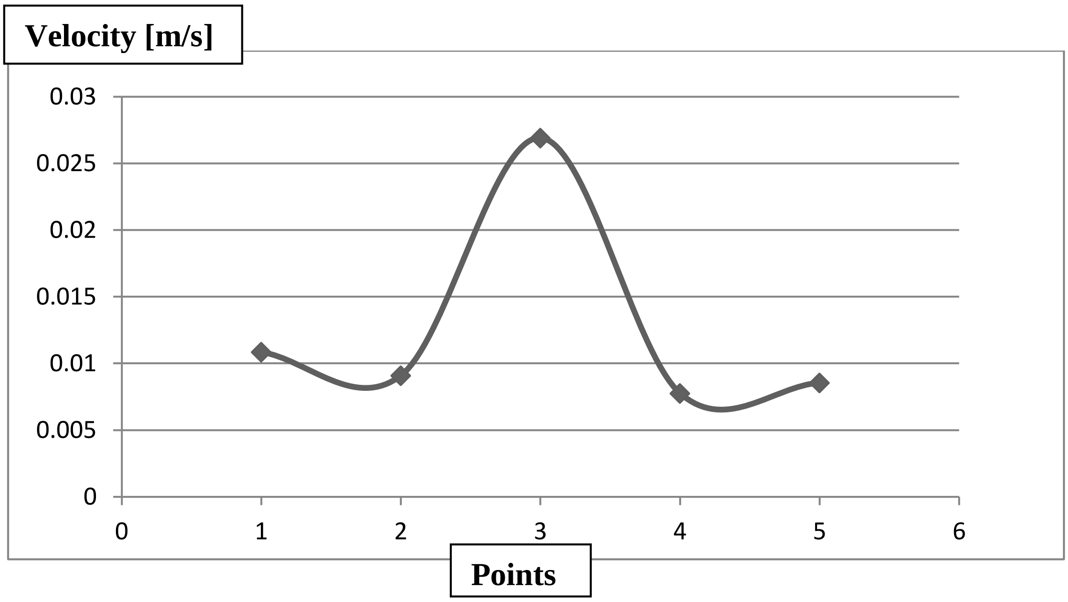


Figure 3.1 Stent Free Velocity Profile in Steady Flow at x=0mm

Table 3.1 Stent Free Velocity Datas in Steady Flow at x=0mm

X[mm]	Y[mm]	Z[mm]	Count{1}	LDA1-Mean [m/s]
0	1	0	194	0,0108535
0	2	0	243	0,0090888
0	3	0	27115	0,0269048
0	4	0	322	0,0077551
0	5	0	207	0,0085480

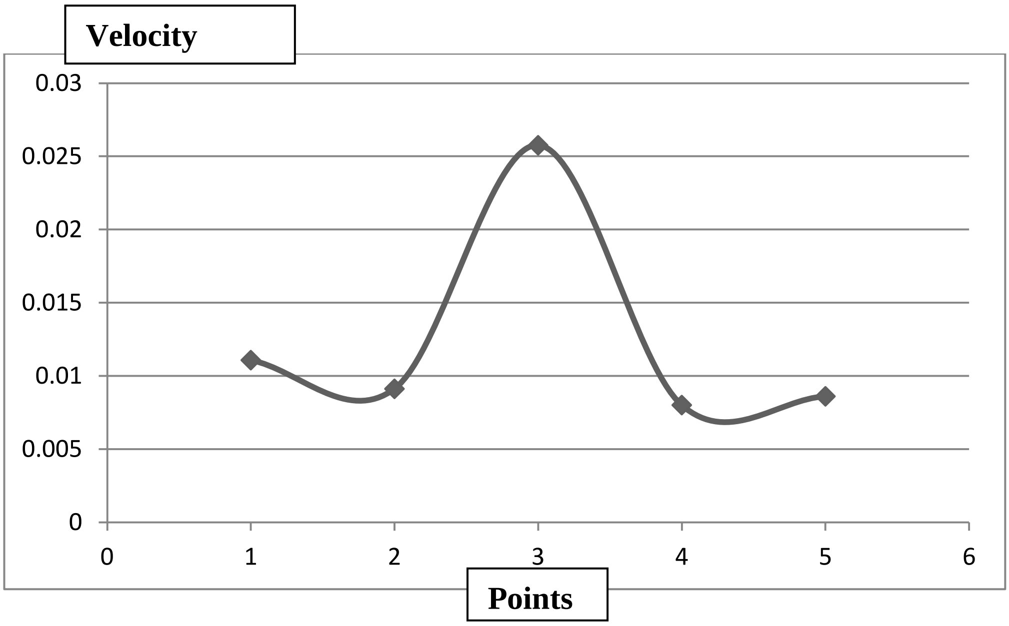


Figure 3.2 Stent Free Velocity Profile in Steady Flow at x=100mm

Table 3.2 Stent Free Velocity Datas in Steady Flow at x=100mm

X[mm]	Y[mm]	Z[mm]	Count{1}	LDA1-Mean [m/s]
-90	1	0	190	0,0110853
-90	2	0	301	0,0091267
-90	3	0	26503	0,0257649
-90	4	0	217	0,0080157
-90	5	0	191	0,0086125

The velocity at the center of the tube in the beginning position is 0,0269048[m/s] (see table 1) and in the end of the tube is 0,0257649[m/s]. By comparing these datas with the velocity achieved by the formula Eq. (2.5) for the tube that is 0,0244 [m/s], the accuracy of the system will appear.

The tube inside the system is not totally straight and it has curvature on it, so the velocity profiles near the wall contain some semi-Eddies flows because of the curvature.

An eddy is the swirling of a fluid and the reverse current created when the fluid flows in a curvature or past an obstacle.

This phenomena is the same in the human vessel and in the human arteries the eddies could be seen at the places near the wall of the artery.

3.1.2 Velocity Profiles after Stent Implementation

After implementation of stent datas obtained by using laser doppler starting from the outlet position of the stent x,y(0,0) in the tube by step sizes of 10mm and finished at the position of x,y(100,5).

10 graphs and tables achieved at this step. The flow disturbances started from first position and continue down stream of flow.

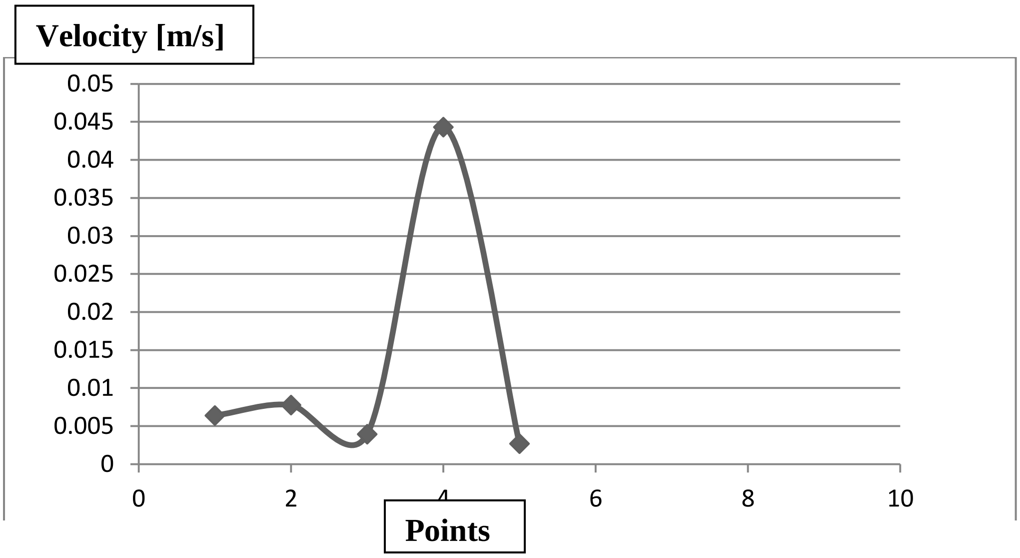


Figure 3.3 Stent Implanted Velocity Profile in Steady Flow at x=0mm

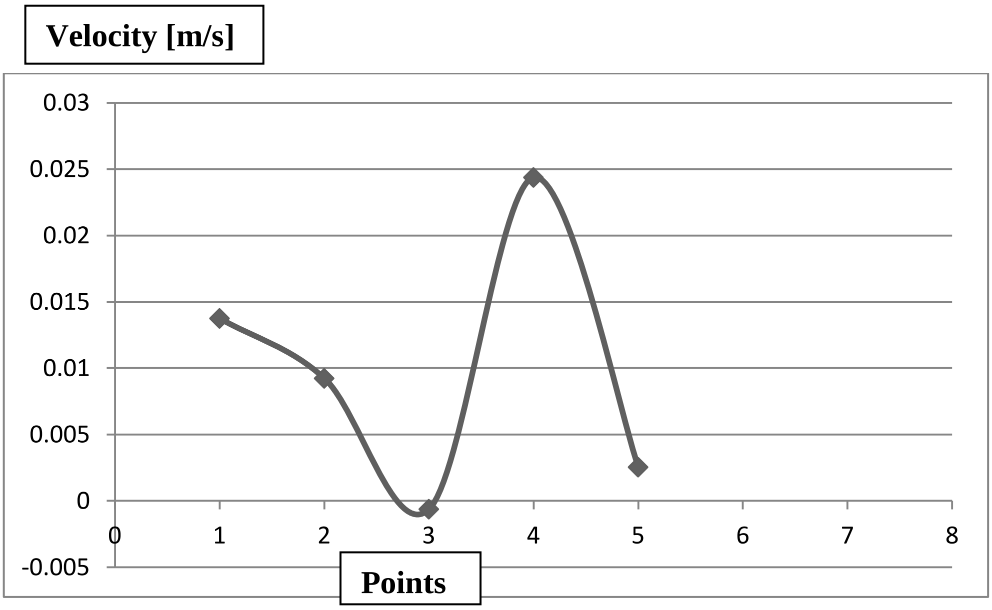


Figure 3.4 Stent Implanted Velocity Profile in Steady Flow at x=10mm

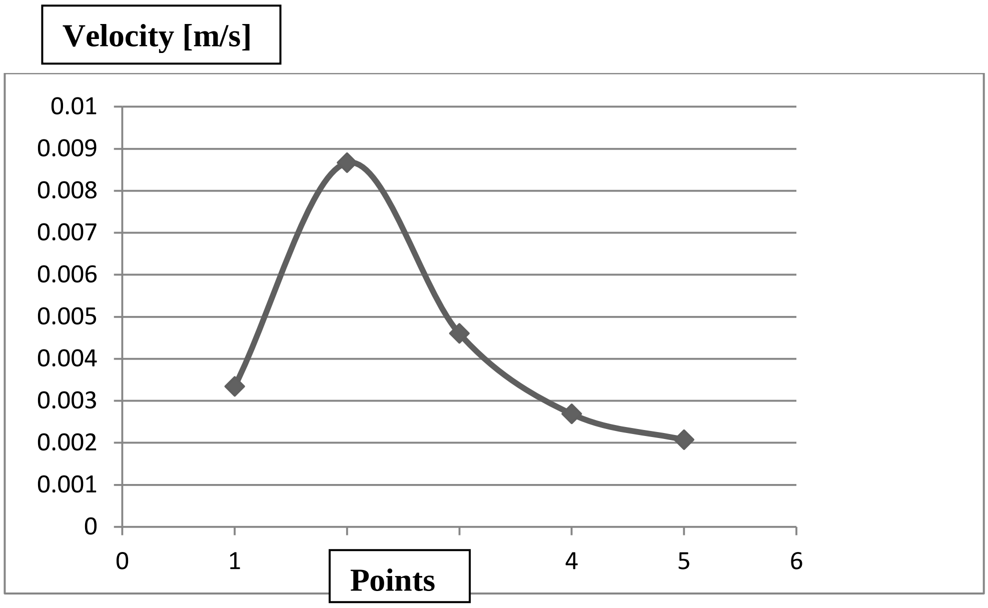


Figure 3.5 Stent Implanted Velocity Profile in Steady Flow at x=20mm

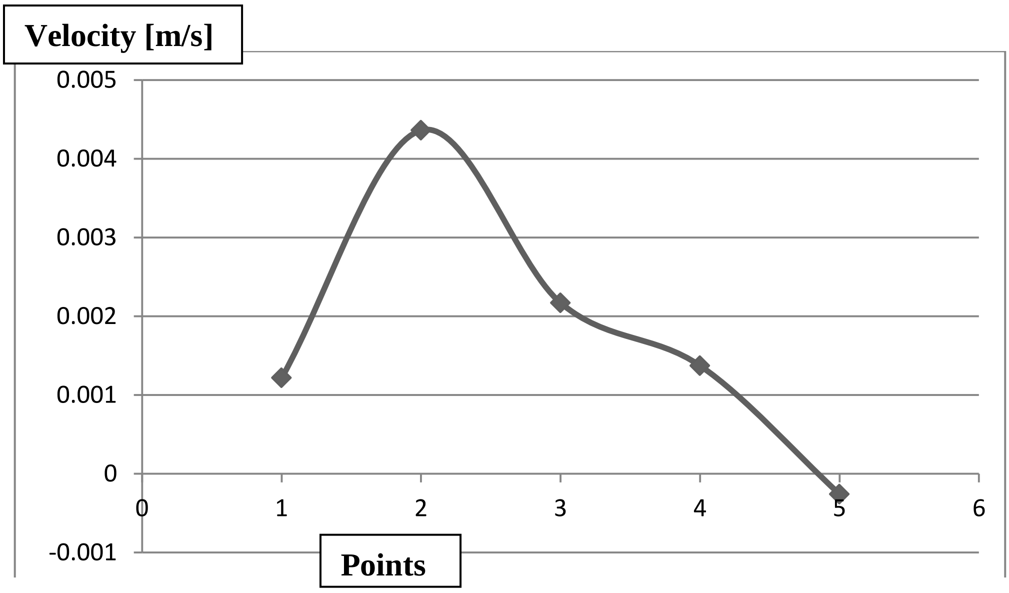


Figure 3.6 Stent Implanted Velocity Profile in Steady Flow at x=30mm

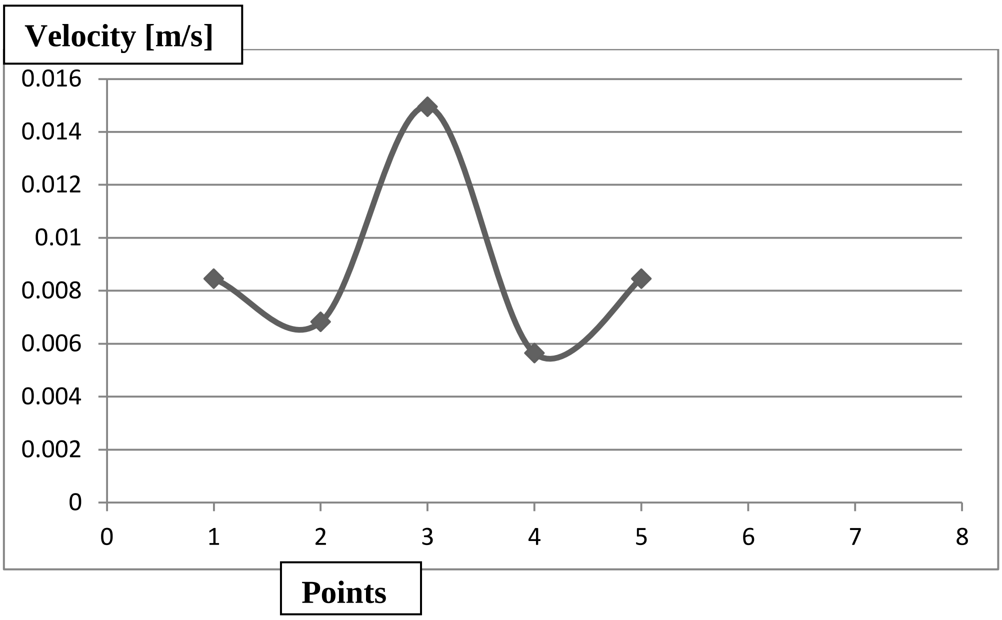


Figure 3.7 Stent Implanted Velocity Profile in Steady Flow at x=40mm

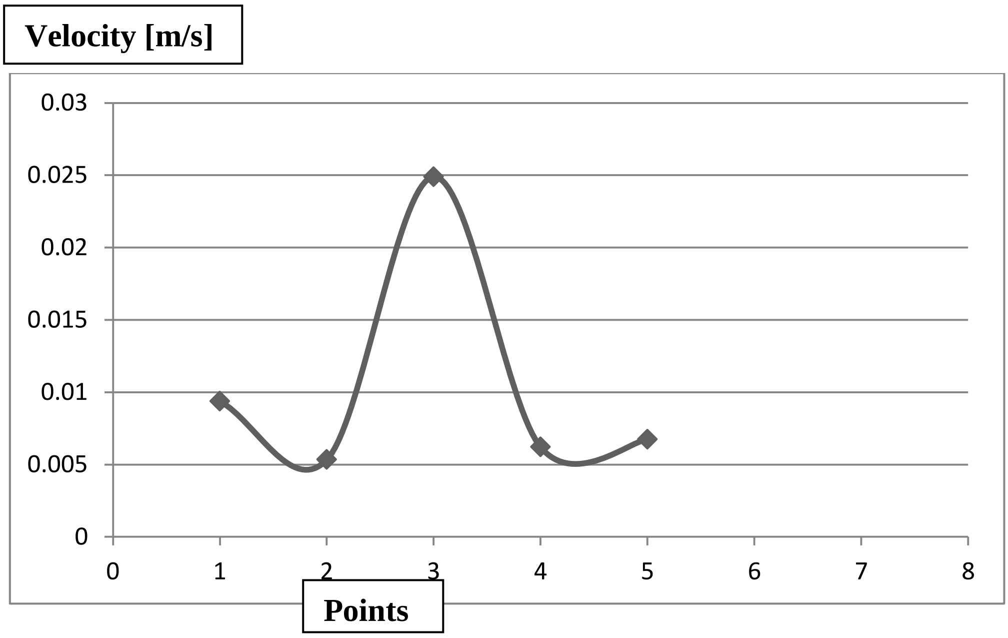


Figure 3.8 Stent Implanted Velocity Profile in Steady Flow at x=50mm

The effect of the stent is obvious in these figures. In laminar flow at the first position there is a increase in velocity in one point but rest are decreased and turbulances starts.

At second position the eddies are obvious and there is a negative velocity at some points that shows the turbulances and reverse direction of flow. This condition continues till the position 6.

The magnitude of the negative velocities are very small because the flow rate of the system is 132 ml/min and this magnitude is not enough to produce big turbulances also the flow is steady and it does not change by time and the pump pushes the flow at the same range.

Once the flow profile is constant and steady, the effect of stent on this flow with a small flow rate is not significant.

At the position 6 the velocity profile returns to its original situation and the effect of stent on blood flow disappears.

Whole figures and tables are included in appendix A.

3.2 Pulsatile Flow

After implantation of stent datas obtained by using laser doppler starting from the outlet position of the stent x,y(0,0) in the tube by step sizes of 10mm and finished at the position of x,y(100,5).

Because of the time dependant nature of the pulsatile flow, in the velocity calculation step, the generated signal from matlab transfer to the pump by the aid of humusoft DAQ card to command it to work as pulsatile.

Pulsatile flow produced by using Matlab program. Matlab takes real raw datas from cardiograghy and translate it to the codes and formulate it by using fourier transform series and find the coefficient of sines and cosines figure (see Figure 3.9.) then by using the simulink toolbox it generate the signals and with DAQ card and motor driver it sends the pulsatile signals to the pump and run it.

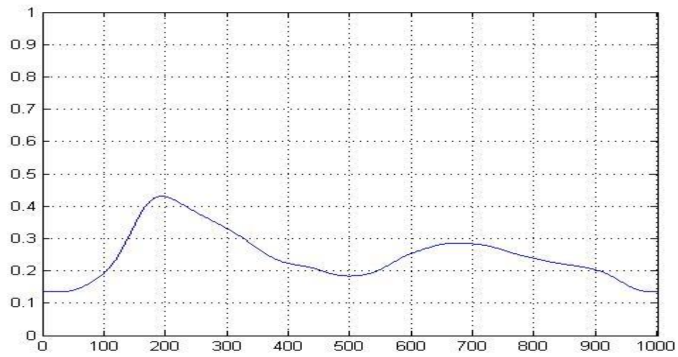


Figure 3.9 Matlab Generated Coronary Artery Signal

For each check point we measure the velocity profile in 5 vertical positions and by exporting the datas we obtain the velocity profile in a specific cross section for each check points. By continuing the process finally we will get five different velocity profiles for each cross section.

We measure 10 cross sections spaced 10mm to each other started from the outlet of the stent and continue down stream of the tube.

Finally we will get 10 different velocity profiles in 100 mm length of the tube and by the achieved datas we can compare the flow condition and profile in both stent implanted and stent free tube.

In the BSA flows software, the laser Doppler measures the particles velocity in each point in 200 second time domain, so 20 profiles is achieved. By comparing the profiles of the same point, the average data at each point at specific time of the period of the signal is achieved.

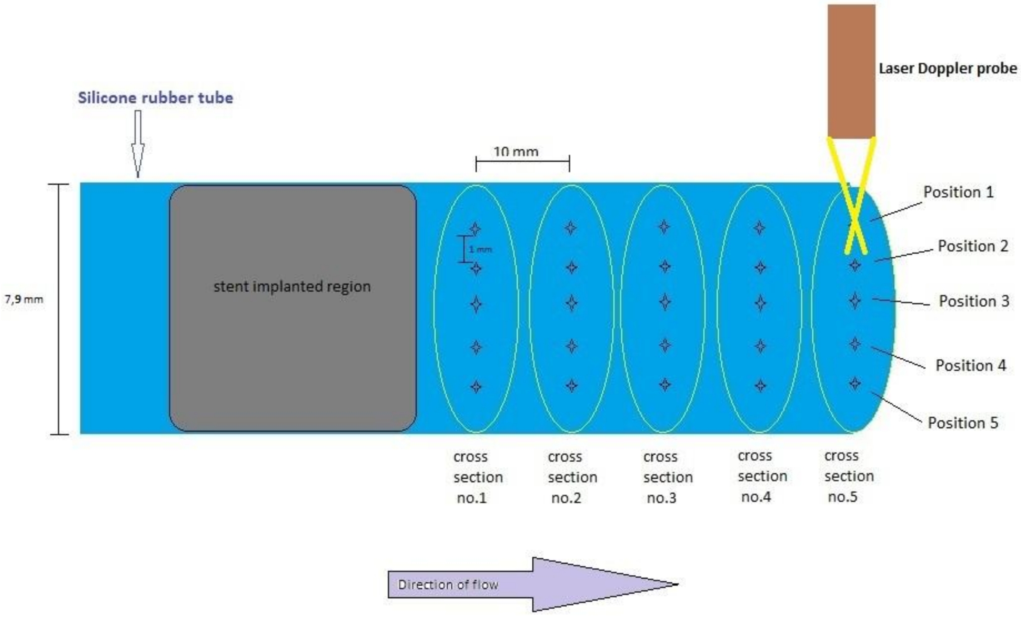


Figure 3.10 Measurement Procedures by LDA and Traverse System

By knowing this fact that the pulsatile flow is a time dependant flow and the magnitude of the velocity at each second is changing in a period time domain, so we set the period of the signal to be 10 second and we divide the period to 5 time intervals or 5 check points.

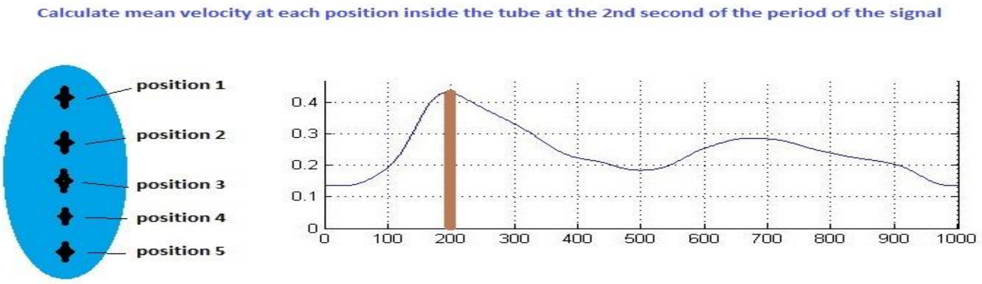


Figure 3.11 First Check point on Period of the Signal

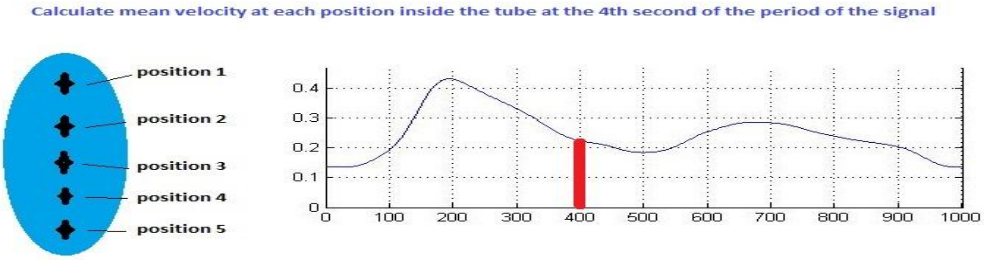


Figure 3.12 Second Check point on Period of the Signal

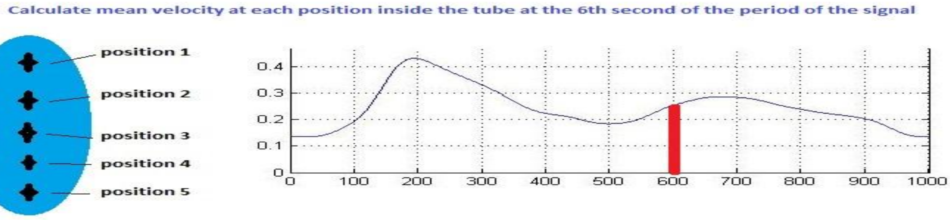


Figure 3.13 Third Check point on Period of the Signal

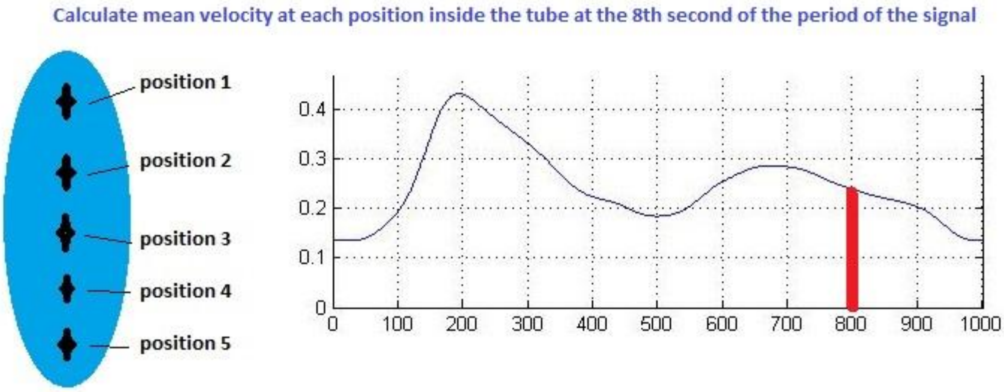


Figure 3.14 Forth Check point on Period of the Signal

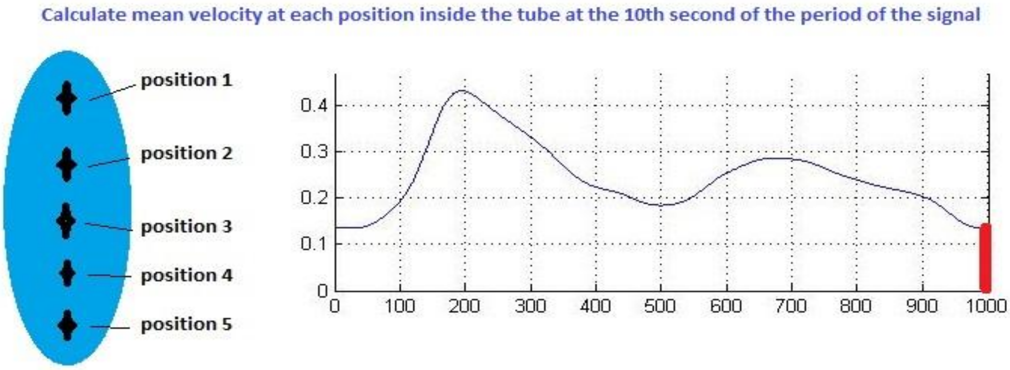


Figure 3.15 Fifth Check point on Period of the Signal

3.2.1 Velocity Profiles before Stent Implantation

The range of the pumping flow rate is between 0-132 ml/min that adjusted by the matlab software. The flow velocity profiles are shown below and because of the absence of stent in this step, the velocity profiles are nearly same at all 10 cross section areas on the tube. There is five different velocity profiles on these graphs. Each one is belong to a specific time of the period of the signal.

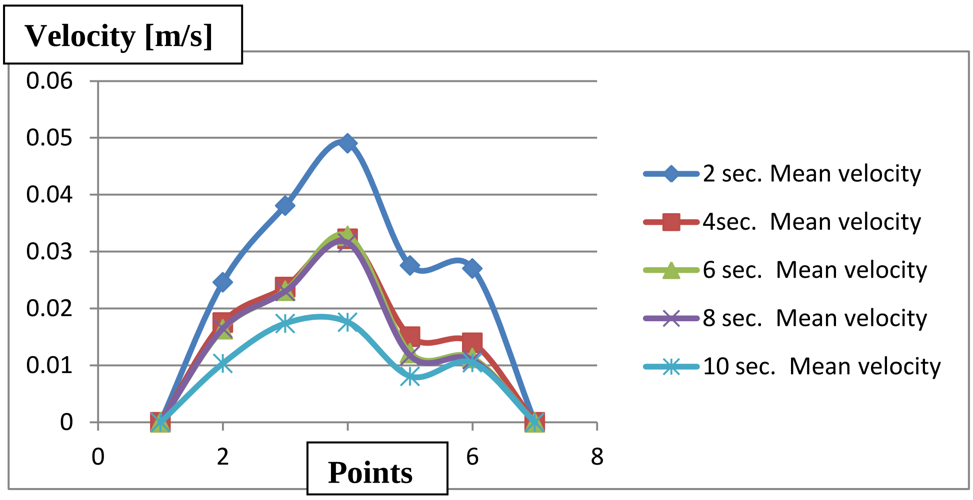


Figure 3.16 Stent Free Velocity Profile in Pulsatile Flow at x=0mm

Table 3.3 Stent Free Velocity Datas in Pulsatile Flow at x=0mm

	0 sec.	**2 sec. Mean velocity**	**4sec. Mean velocity**	**6 sec. Mean velocity**	**8 sec. Mean velocity**	**10 sec. Mean velocity**	**12 sec**
1st point	0	0,024616	0,017533	0,016367	0,016482	0,010352	0
2nd point	0	0,038084	0,023768	0,023127	0,023007	0,017365	0
3rd point	0	0,049046	0,0322559	0,032774	0,031532	0,017592	0
4th point	0	0,027563	0,0150496	0,012177	0,011692	0,008078	0
5th point	0	0,027039	0,013969	0,011307	0,010981	0,010468	0

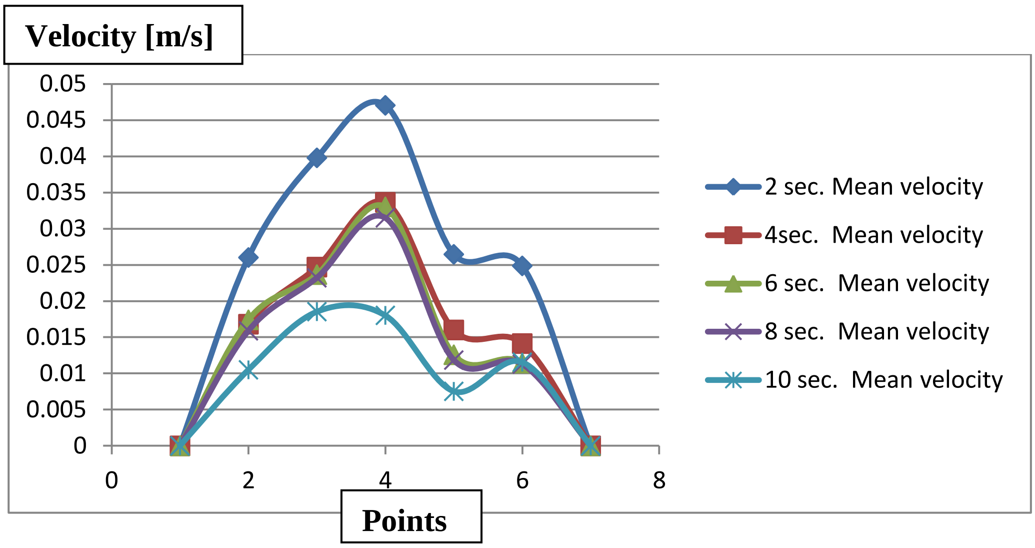


Figure 3.17 Stent Free Velocity Profile in Pulsatile Flow at x=100mm

Table 3.4 Stent Free Velocity Datas in Pulsatile Flow at x=100mm

	0 sec.	**2 sec. Mean velocity**	**4sec. Mean velocity**	**6 sec. Mean velocity**	**8 sec. Mean velocity**	**10 sec. Mean velocity**	**12 sec**
1st point	0	0,026017	0,016802	0,017410	0,015893	0,010505	0
2nd point	0	0,039785	0,024689	0,023658	0,023216	0,018541	0
3rd point	0	0,047035	0,033641	0,033014	0,031498	0,018029	0
4th point	0	0,026456	0,016012	0,012586	0,011852	0,007531	0
5th point	0	0,024860	0,014128	0,011436	0,011293	0,011567	0

The maximum velocity profile is related to the 2nd second of the period that is peak systolic pressure. Again the max. Velocity is related to the point at the center of the tube. In this step just the profiles at the beginning and the end of the tube are shown, because the rest are nearly same.

Whole figuress and tables are included in appendix B.

3.2.2 Velocity Profiles after Stent Implementation

The range of the pumping flow rate is between 0-132 ml/min that adjusted by the matlab software.

The stent implanted into the tube and laser doppler starting measurement from the outlet position of the stent x,y(0,0) in the tube by step sizes of 10mm and finished at the position of x,y(100,5).

10 graphs and tables achieved at this step. The flow disturbances started from first position and continue down stream of flow.

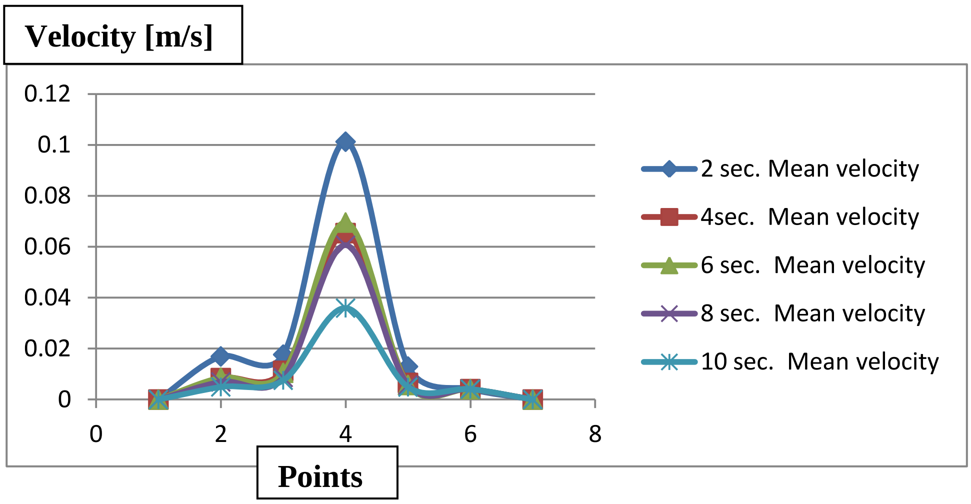


Figure 3.18 Stent Implanted Velocity Profile in Pulsatile Flow at x=0mm

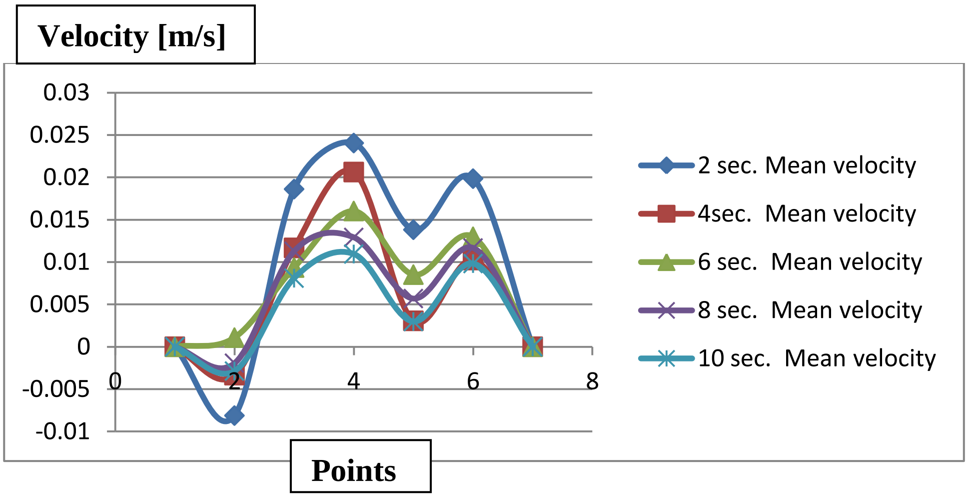


Figure 3.19 Stent Implanted Velocity Profile in Pulsatile Flow at x=10mm

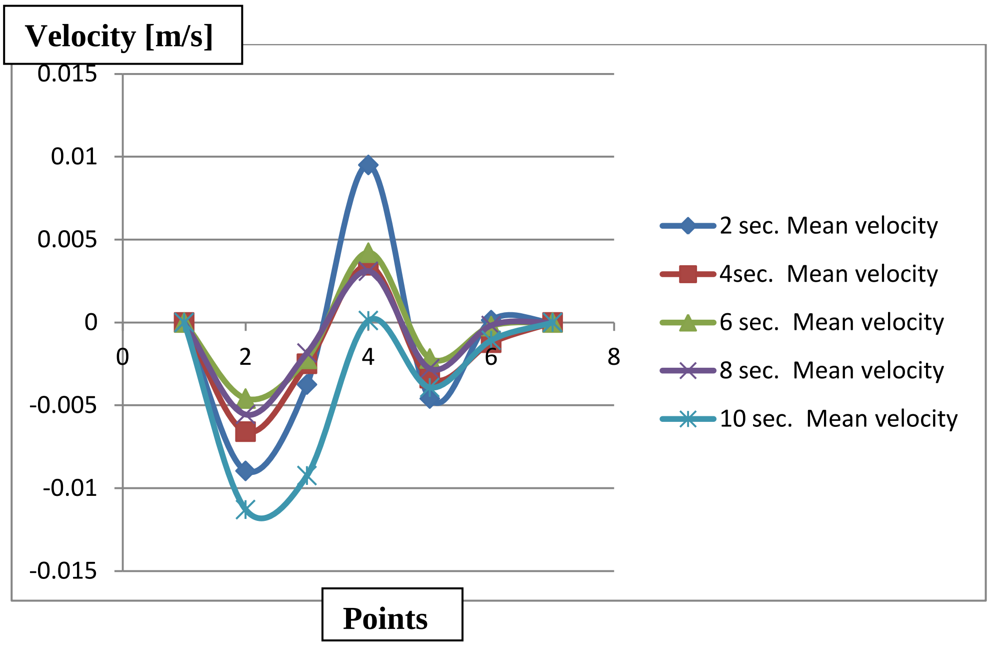


Figure 3.20 Stent Implanted Velocity Profile in Pulsatile Flow at x=20mm

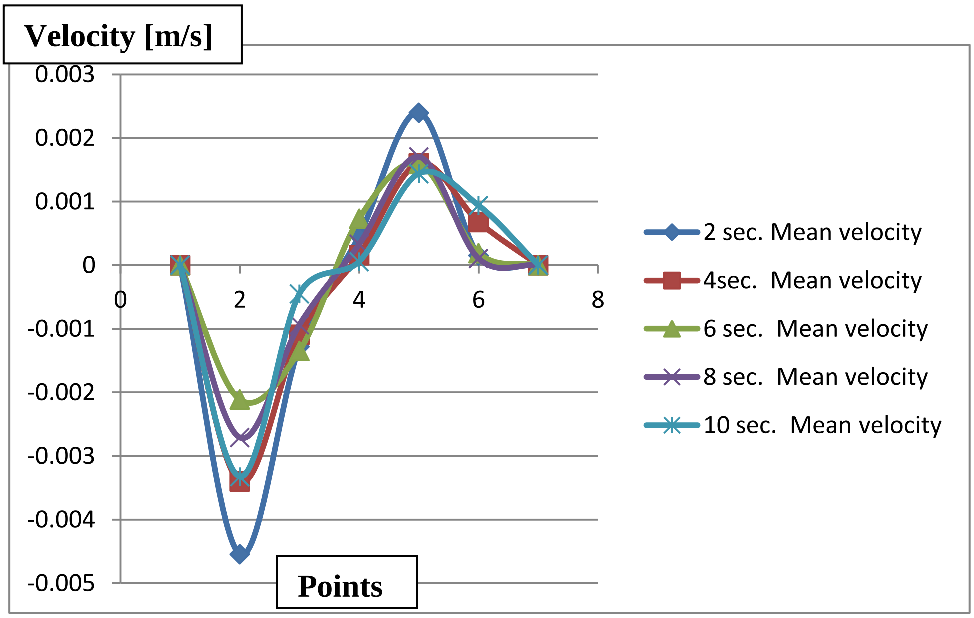


Figure 3.21 Stent Implanted Velocity Profile in Pulsatile Flow at x=30mm

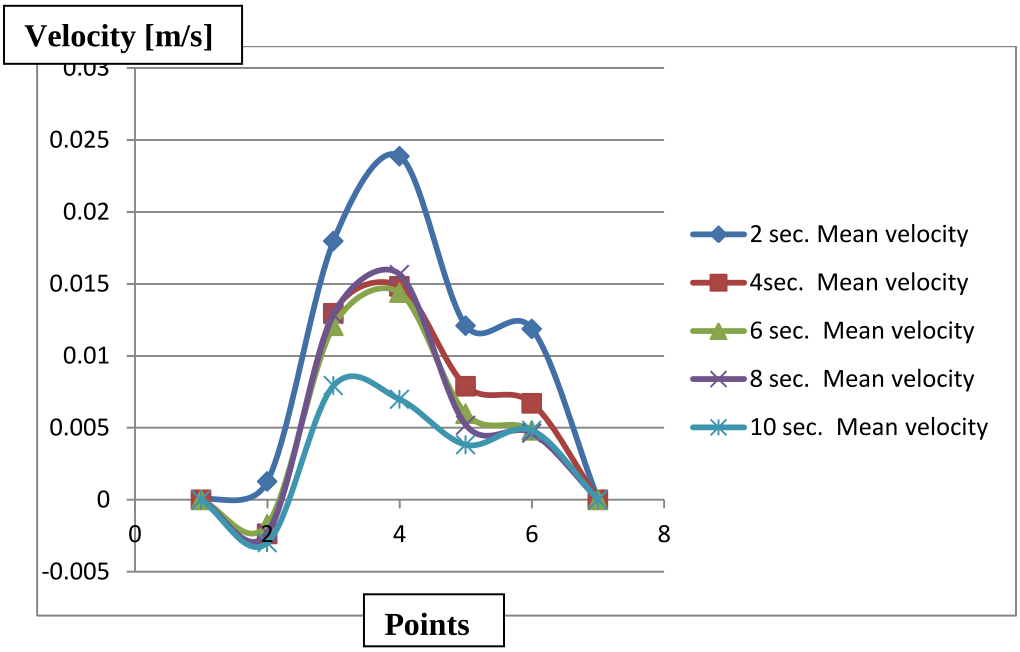


Figure 3.22 Stent Implanted Velocity Profile in Pulsatile Flow at x=40mm

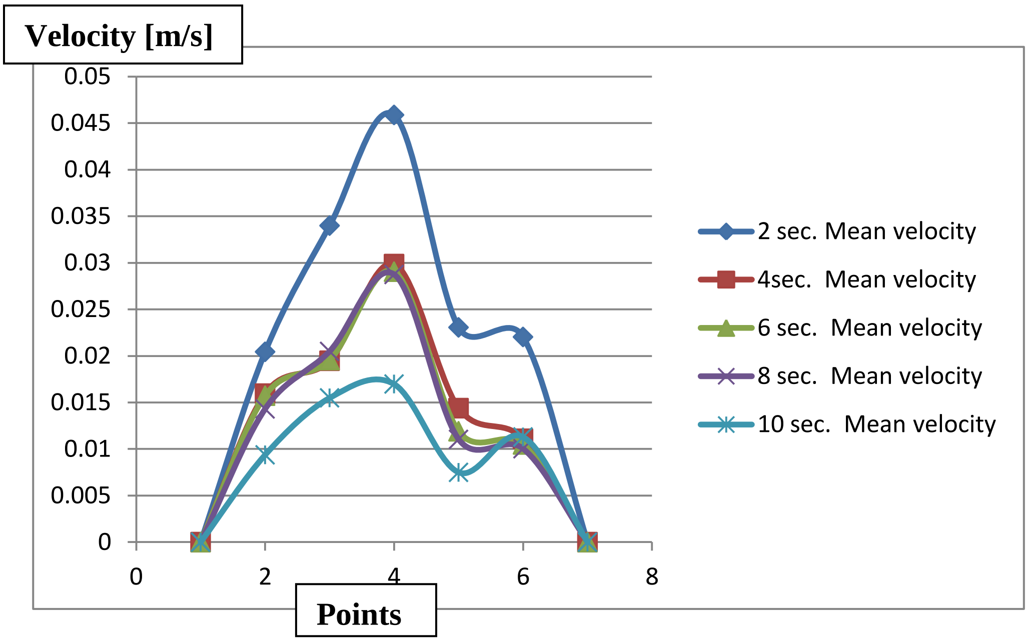


Figure 3.23 Stent Implanted Velocity Profile in Pulsatile Flow at x=50mm

The effect of the stent is obvious in these figures. Turbulences started from first position, velocity partially increase at the center but at the other points decreases, turbulences and eddies are increasing as the laser Doppler progress down stream.

Turbulences generally are at the positions near the wall and negativ velocity magnitudes are present near the wall that shows the turbulences.

Deformation of the velocity profile continues till the 5th cross section, at the 6th cross section the velocity profile returns to it normal profile and the effect of stent on flow disappears.Since turbulence causes eddies of flow perpendicular to the wall of the tube (see figure 3.23.), collision of the particles will increases at the positions near the wall.

Whole figuress and tables are included in appendix B.

CHAPTER 4

CONCLUSION

The main aim of this work was understanding the effect of stent implantation on blood flow velocity in LDA coronary artery of cardiovascular system.

To achieve the effects of stent implantation to blood flow velocity in steady and pulsatile conditions, firstly the simple model of the coronary artery was decided to be a silicone rubber tube because of it's properties. By using a stainless steel spring insteed of using stent the the artery with implemented stent prepared. Spring is used because for getting accurate datas from laser doppler, number of analysed points have to be at least 5 and it needed at least 7 or greater inner diameter of tube. by knowing this fact that any stent can not expand more than 4mm in coronary arteries [34], the spring has choosed.

Using the laser doppler anemometry the result obtained. Laser doppler is a appropreate and well established device for measuring and calculating velocity at each point.

The LDA results in the chapter 3 revealed significant differences in the flow velocity profiles before and after stent implantation.

The velocity profiles disturbed at the outlet position of the stent and increasing and decreasing of velocity in points on cross section areas has observed. Regarding to the curvature structure of tube, the profiles were not symmetrically disturbed.

The profile near the crest of the tube became disturbed but in positive direction on the other hand profiles near the bottom became turbulant in negative direction, it means there is eddies of flow and circulatory flow at that points.

The velocity change in artery caused adhesion of thrombies, the lawer turbulant velocity or eddies make adhesion faster in respect to the normal condition.

This is important that the geometry of stents effects blood flow and the major results of its mechanical and chemical actions. The number and design of the struts inside the stent can change the effects on blood flow. By optimizing the designs and biomaterials that used, the side effect of stent implantation could be reduce.

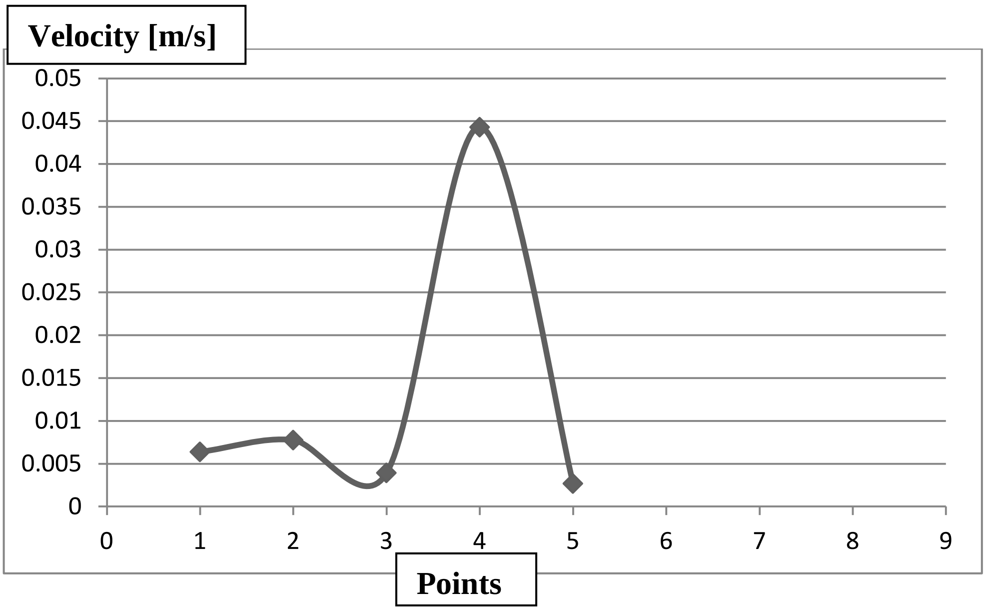
The effect of stent in both laminar and turbulant flow in a tube analysed in vitro to show and compare the great effect of any obstacle in human coronary artery.

In the future studies the effect of different stent designs can be analyse and the optimum design of stent meshes that reduce restenosis risk and thrombosis formation could be analysed also by passing flow through the flow kits the effect of the flow on the cell containing kits and finally the analysis in animal arteries could be done by diagnosing the post effects of different design of the stent.

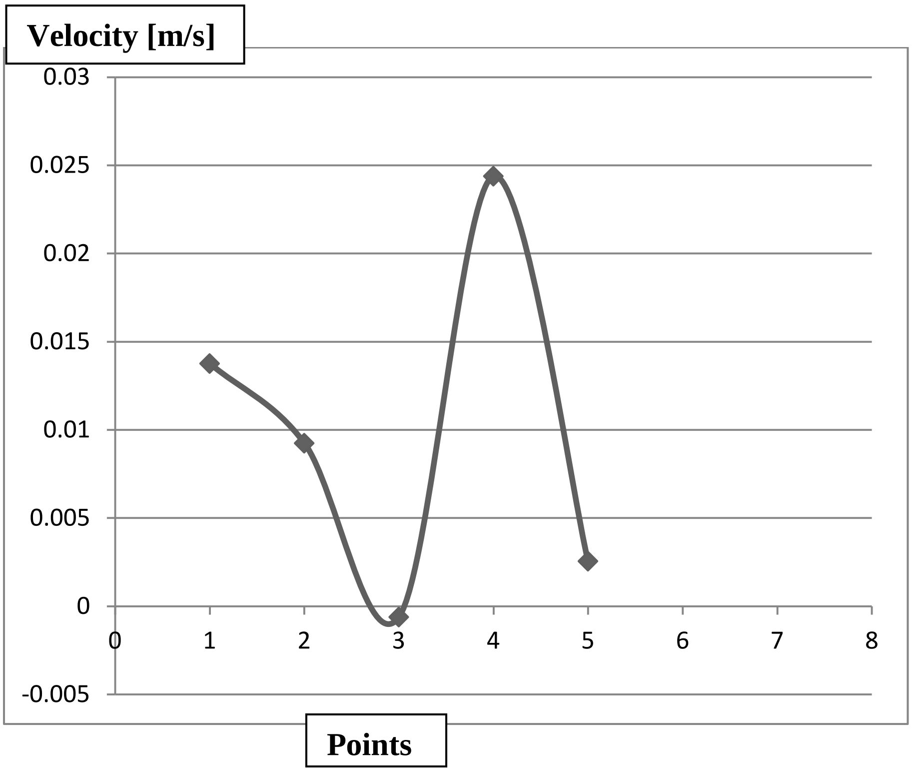
APPENDICES

APPENDIXA

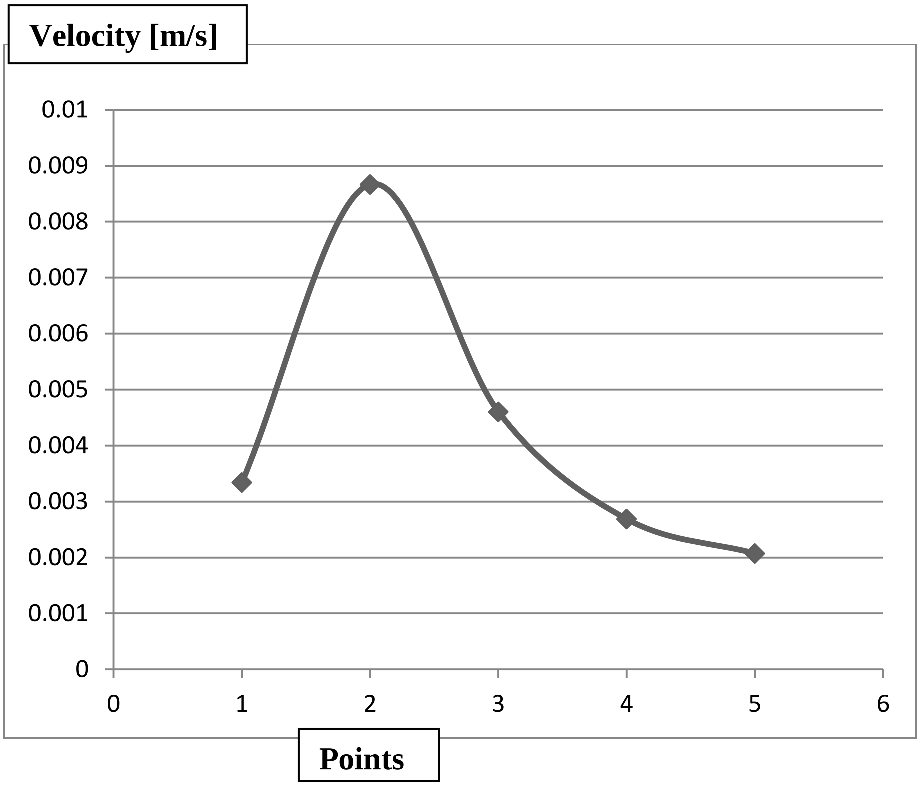
Velocity profile figures and tables after stent implantation in steady flow



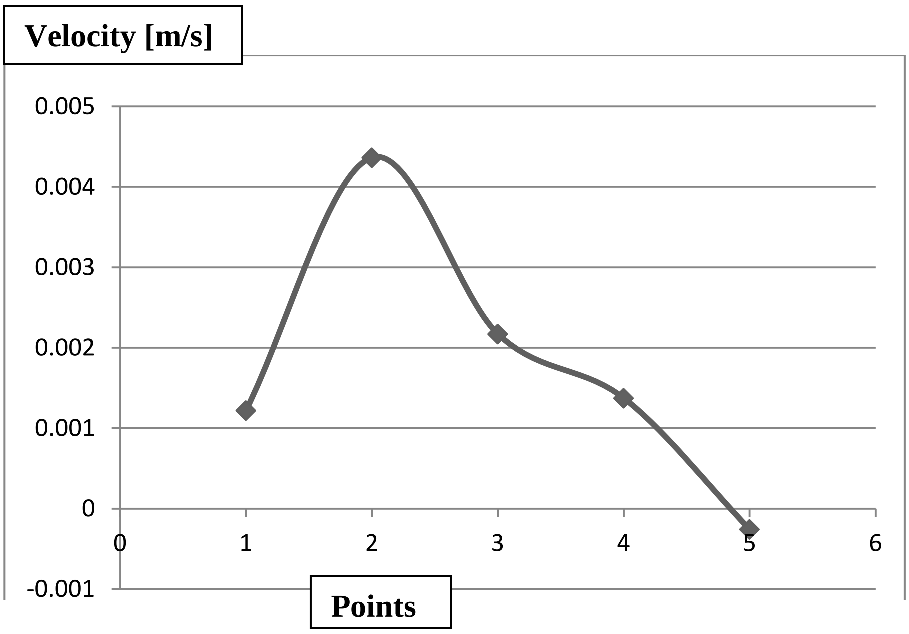
X[mm]	Y[mm]	Z[mm]	Count{1}	LDA1-Mean [m/s]
0	1	0	216	0,006388
0	2	0	36	0,007766
0	3	0	99	0,003935
0	4	0	15013	0,044304
0	5	0	105	0,002689



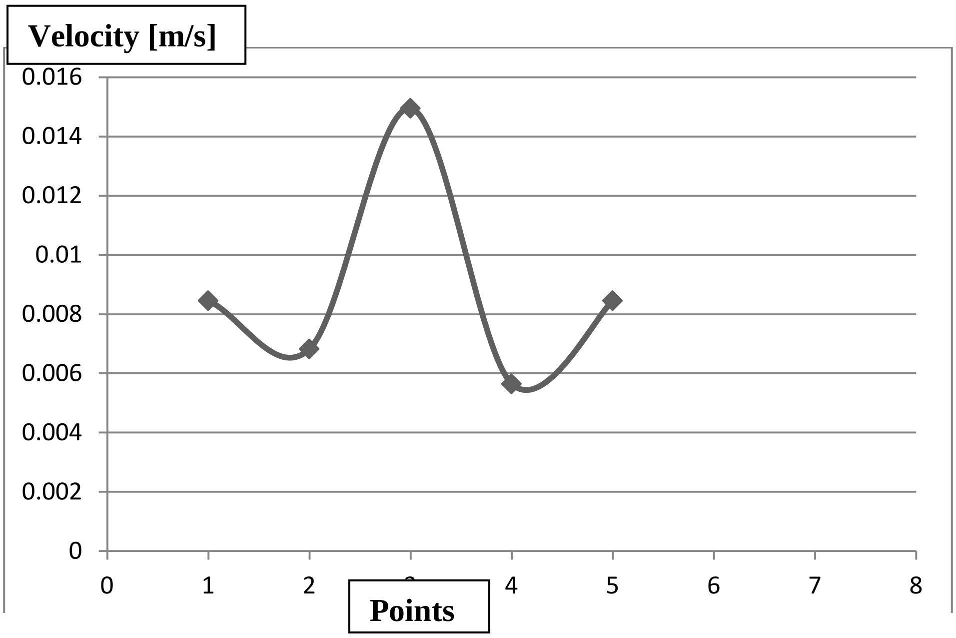
X[mm]	Y[mm]	Z[mm]	Count{1}	LDA1-Mean [m/s]
10	1	0	146	0,013757
10	2	0	73	0,009241
10	3	0	76	-0,00062
10	4	0	30346	0,02438
10	5	0	50	0,002551



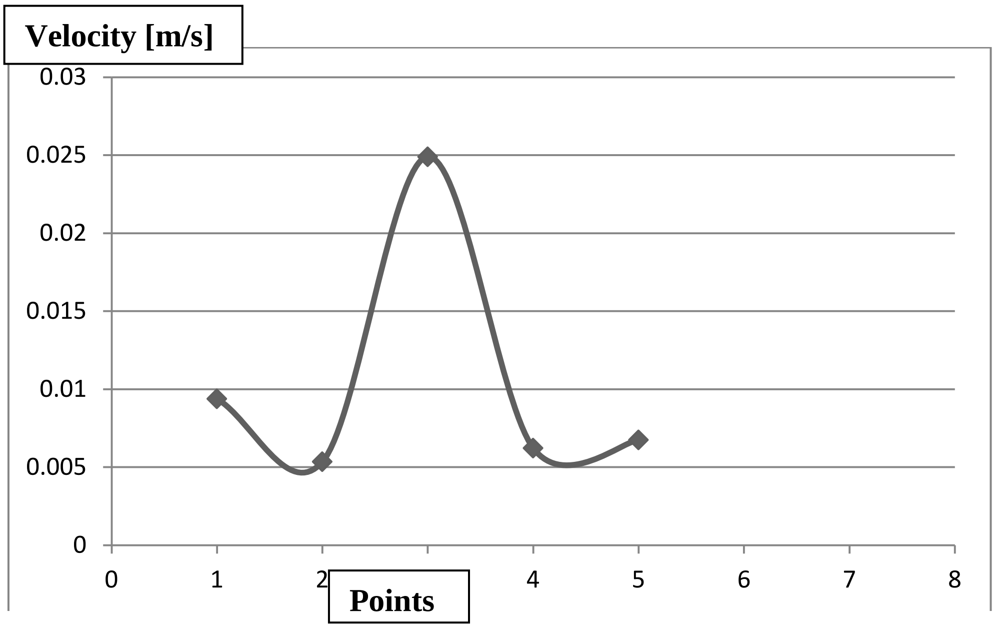
X[mm]	Y[mm]	Z[mm]	Count{1}	LDA1-Mean [m/s]
20	1	0	8461	0,00334
20	2	0	21090	0,008665
20	3	0	23912	0,004602
20	4	0	37815	0,002687
20	5	0	23187	0,002072



X[mm]	Y[mm]	Z[mm]	Count{1}	LDA1-Mean [m/
30	1	0	18656	0,001219
30	2	0	7137	0,004363
30	3	0	6457	0,002171
30	4	0	7464	0,001373
30	5	0	35702	-0,00026



X [mm]	Y [mm]	Z [mm]	Count{1}	LDA1-Mean [m/s]
40	-10	0	460	0,008455
40	-9	0	535	0,006826
40	-8	0	17028	0,014948
40	-7	0	1074	0,005646
40	-6	0	586	0,008455

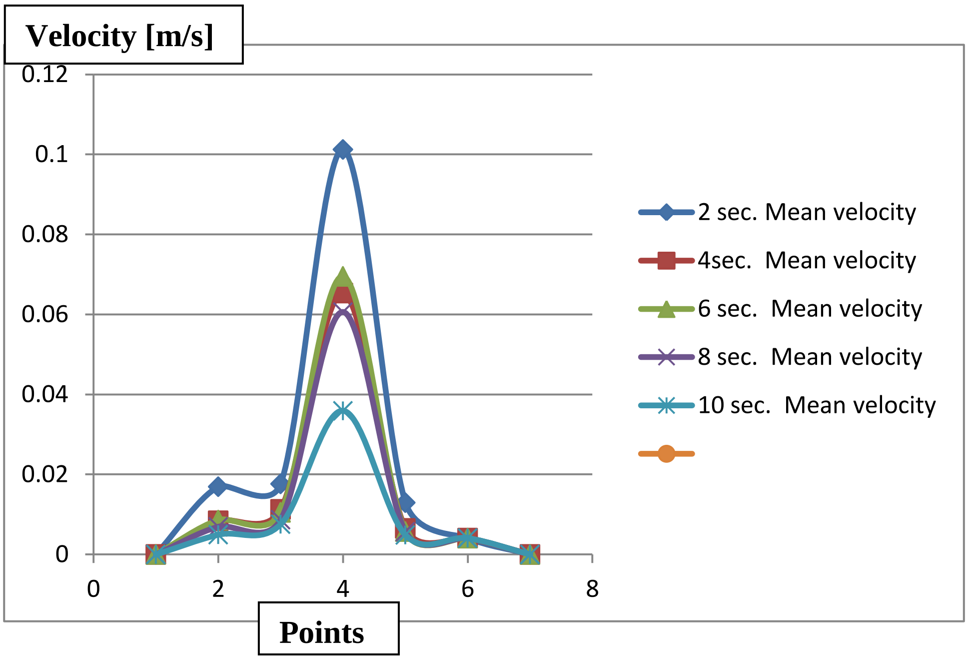


X [mm]	Y [mm]	Z [mm]	Count{1}	LDA1-Mean [m/s]
50	-10	0	209	0,00938
50	-9	0	387	0,00535
50	-8	0	19097	0,024893
50	-7	0	742	0,00622
50	-6	0	293	0,006746

APPENDIX B

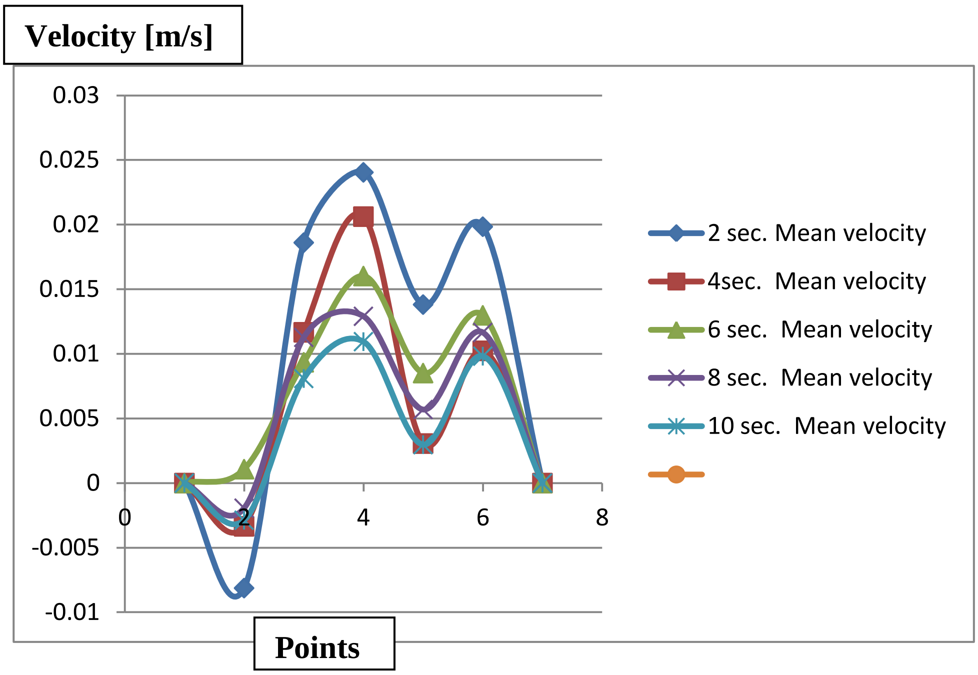
Velocity profile figures and tables after stent implantation in turbulent flow

At x=0mm.



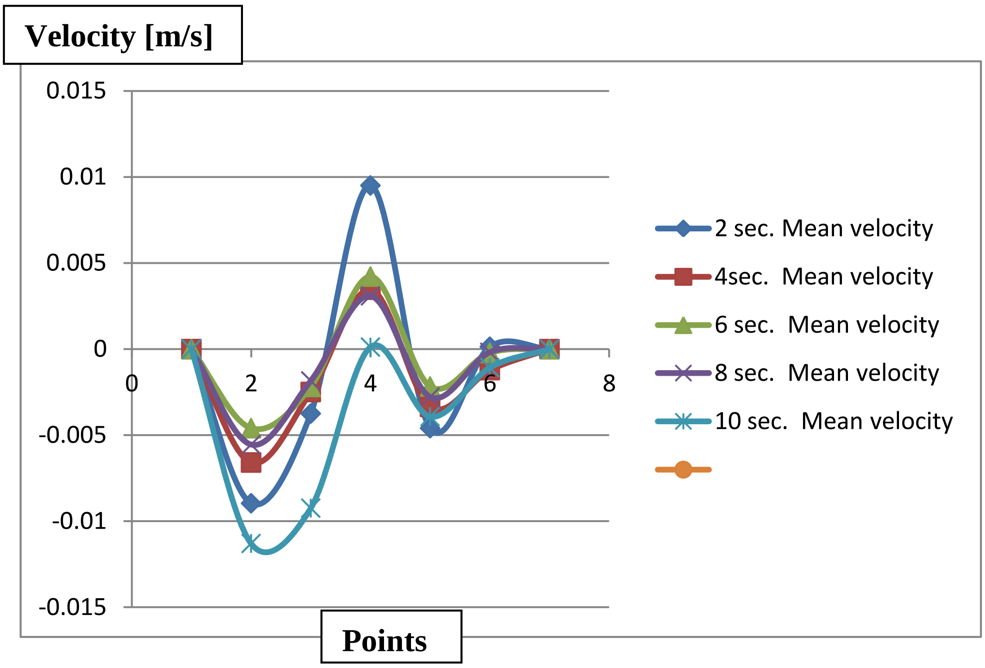
	0 sec.	2 sec. Mean velocity	4sec. Mean velocity	6 sec. Mean velocity	8 sec. Mean velocity	10 sec. Mean velocity	12 sec
1st point	0	0,016936	0,008413	0,008597	0,006912	0,004952	0
2nd point	0	0,017644	0,011268	0,010517	0,008687	0,0075695	0
3rd point	0	0,1012352	0,0653459	0,069514	0,060582	0,035902	0
4th point	0	0,012953	0,00651	0,005727	0,005682	0,004876	0
5th point	0	0,004088	0,004088	0,004088	0,004088	0,004088	0

At x= 10mm.



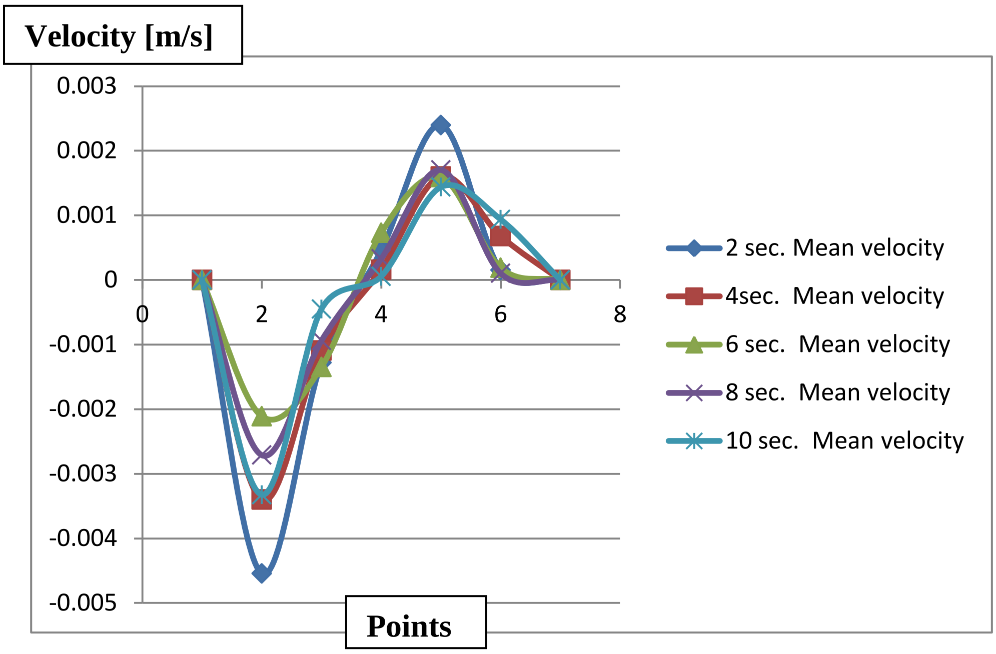
	0 sec.	**2 sec. Mean velocity**	**4sec. Mean velocity**	**6 sec. Mean velocity**	**8 sec. Mean velocity**	**10 sec. Mean velocity**	**12 sec**
1st point	0	-0,008126	-0,00334	0,001077	-0,001938	-0,00287	0
2nd point	0	0,018609	0,011668	0,009347	0,0112764	0,008094	0
3rd point	0	0,024046	0,020621	0,0160214	0,012908	0,010945	0
4th point	0	0,013813	0,003058	0,0085124	0,0056911	0,002974	0
5th point	0	0,019841	0,010234	0,012982	0,011658	0,009821	0

At x= 20mm.



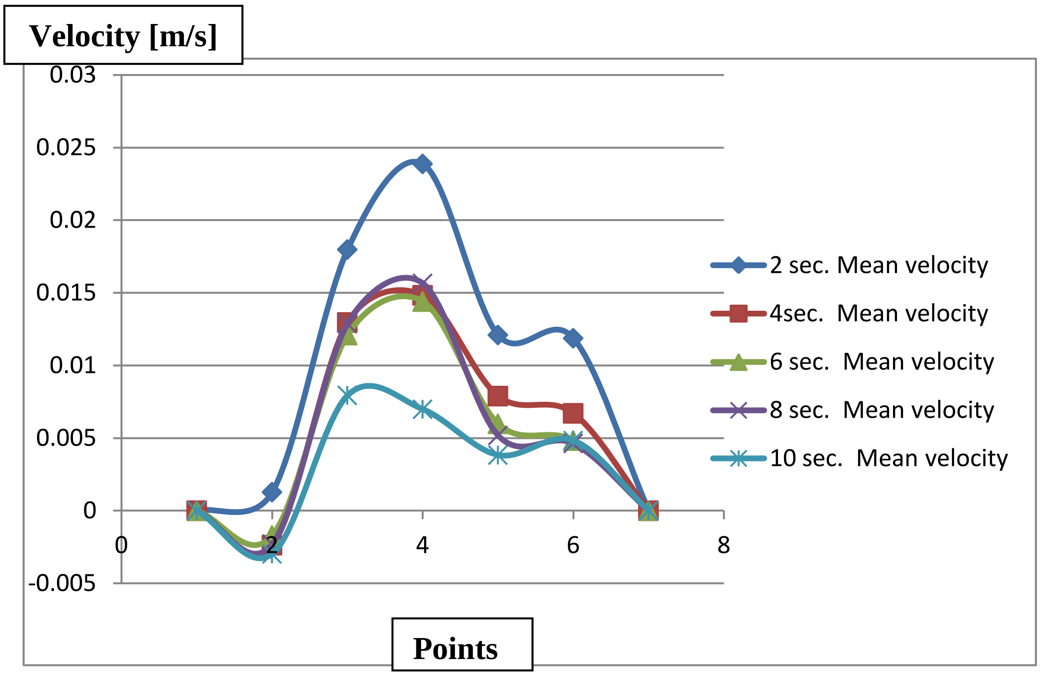
	0 sec.	**2 sec. Mean velocity**	**4sec. Mean velocity**	**6 sec. Mean velocity**	**8 sec. Mean velocity**	**10 sec. Mean velocity**	**12 sec**
1st point	0	-0,00895	-0,00658	-0,00459	-0,00554	-0,01129	0
2nd point	0	-0,00374	-0,00249	-0,00219	-0,00184	-0,00923	0
3rd point	0	0,009504	0,003452	0,004212	0,003092	0,000119	0
4th point	0	-0,00459	-0,00335	-0,00217	-0,00278	-0,00392	0
5th point	0	0,00013	-0,00121	-0,00021	-0,00018	-0,00107	0

At x= 30mm.



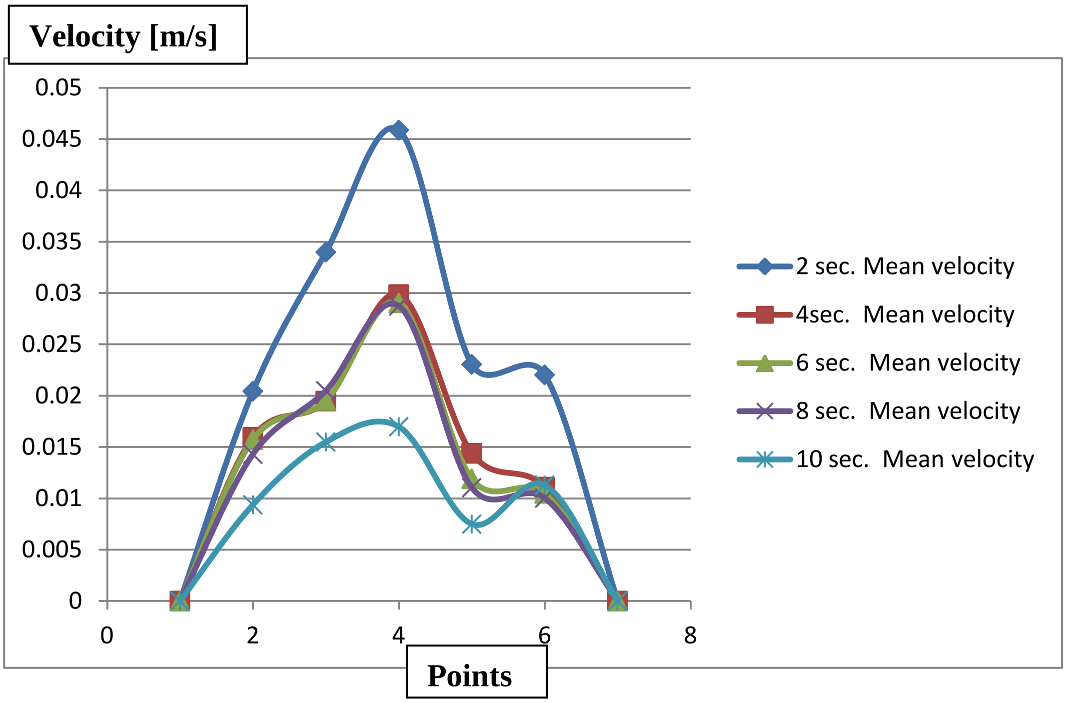
	0 sec.	**2 sec. Mean velocity**	**4sec. Mean velocity**	**6 sec. Mean velocity**	**8 sec. Mean velocity**	**10 sec. Mean velocity**	**12 sec**
1st point	0	-0,00454	-0,00339	-0,00210	-0,00270	-0,00332	0
2nd point	0	-0,00128	-0,00109	-0,00134	-0,00093	-0,00045	0
3rd point	0	0,00045	0,00015	0,00073	0,00032	0,000054	0
4th point	0	0,00239	0,00160	0,00159	0,00170	0,001439	0
5th point	0	0,00015	0,00067	0,00018	0,00010	0,000937	0

At x=40mm.



	0 sec.	2 sec. Mean velocity	4sec. Mean velocity	6 sec. Mean velocity	8 sec. Mean velocity	10 sec. Mean velocity	12 sec
1st point	0	0,001276	-0,00237	-0,00170	-0,00229	-0,0029	0
2nd point	0	0,01798	0,01295	0,01209	0,012873	0,00794	0
3rd point	0	0,02387	0,01483	0,01439	0,015653	0,00698	0
4th point	0	0,01209	0,00789	0,00598	0,00518	0,00382	0
5th point	0	0,01187	0,00670	0,00482	0,004628	0,00483	0

At x= 50mm.



	0 sec.	2 sec. Mean velocity	4sec. Mean velocity	6 sec. Mean velocity	8 sec. Mean velocity	10 sec. Mean velocity	12 sec
1st point	0	0,020436	0,015943	0,015726	0,014298	0,00937	0
2nd point	0	0,033984	0,019476	0,019540	0,020486	0,01549	0
3rd point	0	0,045871	0,029856	0,029043	0,028736	0,01698	0
4th point	0	0,023056	0,014386	0,011903	0,011038	0,00749	0
5th point	0	0,022031	0,011098	0,010487	0,010027	0,01129	0

APPENDIXC

Matlab Codes for Generating Pulsatile Flow

```
% clear all
% close all
% clc

delt=0.01;        % <= set sampling time interval
T=10;             % <= set signal period
fs=1/T;           % <= set frequency (sampling frequency)
t=[0:delt:T]';
% f = column vector of measured values
Qraw = dlmread('coronaryraw1.txt','\t');
f = Qraw(:,2);

N=length(f);
dt=T/N;
tv=[0:N-1]'*dt;

% remove negative values
%f=max(f,0);

c0=sum(f)*dt/T-1.55;

for k=1:14
   A(k)=2*sum(f.*cos(tv*k*2*pi/T)*dt)/T;
   B(k)=2*sum(f.*sin(tv*k*2*pi/T)*dt)/T;
end

%==============================
```

```
%Sinyal Genliğinin Değiştirilmesi
%==============================
singen=1*0.09;  %<= katsayıyı değiştirerek ayarla
A=singen*A;
B=singen*B;
%=============================
%=============================
% Raw datadan elde edilen katsayılar ile sinyal oluştur
for i=1:14
sc(i,:)=A(i)*cos(2*pi*fs*t*i);
ss(i,:)=B(i)*sin(2*pi*fs*t*i);
end
stt=c0+sum(sc)+sum(ss);
%================================================
%grafiğinin çizilmesi
%====================
figure
plot(stt);
grid
% xlabel('time (s)')   % label x-axis
% ylabel('Q (mL/s) ') %
axis([0 length(stt) 0 1])
%=======================
%simulink için arraylar workspace
A=A';
B=B';
```

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