Modelling of Blood Flow Through Human Carotid Artery

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Abstract

In the study, it has been aimed to model the blood flow through the carotid artery that is one of the most important vessels of the human circulatory system and to compare it with academic studies. In the study, it has been assumed that there is a constriction inside the carotid artery caused by cholesterol. The existence of constricted region delays the flow to become a fully-developed laminar flow and that is possible near the exit of the vessel, because the existence of contricted region prevents the flow that has just left the constricted region to tidy itself up suddenly. As the constant shear stresss values obtained on the wall as the flow has become fully-developed laminar near the artery exit have only 3% and 4% relative errors compared with the wall shear stresss value of the academic study, it shows that the results that have been found assuming the blood a Newtonien fluid in the study are reliable.

Keywords: Newtonien fluid, blood, carotid artery

1.Introduction

Some fluids such as water, air, benzene are Newtonien fluids. This means that shear stress-shear strain (rate) graphic that is drawn at a certain temperature has a constant slope regardless of shear shear strain. This slope is called “fluid viscosity”. All the gases are Newtonien fluids; whereas liquids that have small molecular weight and liquid solutions of molecules with small weight (such as the aqueous solutions of salt and sugar) are Newtonien fluids as well.

The fluids that don’t have such a relationship between shear stress and shear rate are called “non-Newtonien fluids”. Science of “Rheology” deals with the research of the behaviours of such fluids. Fluids with high molecular weight-among which polymer melts, polymer

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solutions, fluids inside which thin particles dissolve (such as mud, paste) exist-are usually non-Newtonien. In this situation, when shair strain of the shear stress-shear strain graphic drawn changes, slope of the curve won't remain constant. Fluids that their viscosities decrease with the increasing shear strain are called "shear-thinning fluids". On the contrary, namely, fluids that their viscosities increase with the increasing shear strain are called "shear-thickening fluids". Shear-thickening fluid behaviour is more common than shear-thinning fluid behaviour. Shear-thinning liquids are also called "pseudoplastic liquids".

Examples of shear-thinning liquids are these: Molten polyester, polymer solutions like aqueous solution of polythene oxide and some dyes. When shear stress is applied to dye using a brush, it can be observed that the dye flows easily and when the shear stress is removed the viscosity increases and the dye can't flow. Some muds and pastes, on the other hand, have an increasing viscosity with the increasing shear-strain. These are called "shear-thickening" or "dilatant" fluids. Wheat strach and clay mud are examples for such fluids. Most of the dilatant fluids show the shear-thickening behaviour at very small shear-strain values.

Another one of non-Newtonien fluids are "viscoplastic fluids". These are fluids that don't flow when only a small shear-stresss is applied on them. For these fluids to flow, there exists a critical value of shear stress that must be reached. Thus, viscoplastic fluids behave like a solid at shear stress values smaller than the critical shear stresss. Tootpaste is an example for such fluids. If a small shear stress is applied to the toothpaste in the box, the toothpaste don't leave the box; for the toothpaste to leave the box shear stress at a sufficient value must be applied. On the other hand, Bingham plastics are a special type of viscoplastic fluids and there is a linear relationship between shear stress and shear rate for these fluids. Examples for viscoplastic fluids are these: Nuclear fuel muds, mayonnaise, toothpaste, blood and some dyes.

The aim of this study is to model the blood flow through the carotid artery that is one of the most important vessels of human circulatory system and compare it with academic studies.

Density value that is used in the analysis and other values that define the viscosity are obtained using different sources.

Among these values, while calculating viscosity value for the assumption of Newtonien fluid, viscosity of water at 37^{o}C has been calculated at first using the equation below (Çengel ve Cimbala 2008).

$$\mu = a.10^{\frac{b}{T-c}} \tag{1.1}$$

(Here μ is fluid viscosity; T is the temperature value in Kelvin; a,b,c are constant values.)

Here, for water a=2,414. 10^{-5} Pa.s ; b=247,8K ; c=140K and these values are constant. The given equation has an error smaller than 2,5 per cent between 0^oC ve 370^oC temperature interval. In this situation, if the equation is solved using T=310K, viscosity value for water is calculated at 37^oC as below:

$$\mu = 0{,}0006962 \text{ Pa.s}$$

Here in order to calculate the viscosity of blood at the same temperature, it is necessary to know the relative viscosity of blood compared with water. Relative viscosity of blood compared with water(for any temperature value) changes between 3,5-5,4 (Gülen 2009-2010). If value of 4,5 at the middle is selected, viscosity of blood at 37^oC is found as below:

$$\mu = 0{,}0006962 \text{ Pa.s x 4,5}$$
$$\mu = 0{,}003133 Pa.s$$

Density value for blood, on the other hand, can be taken as $\rho = 1060 kg/m^3$ (Gülen 2009-2010).

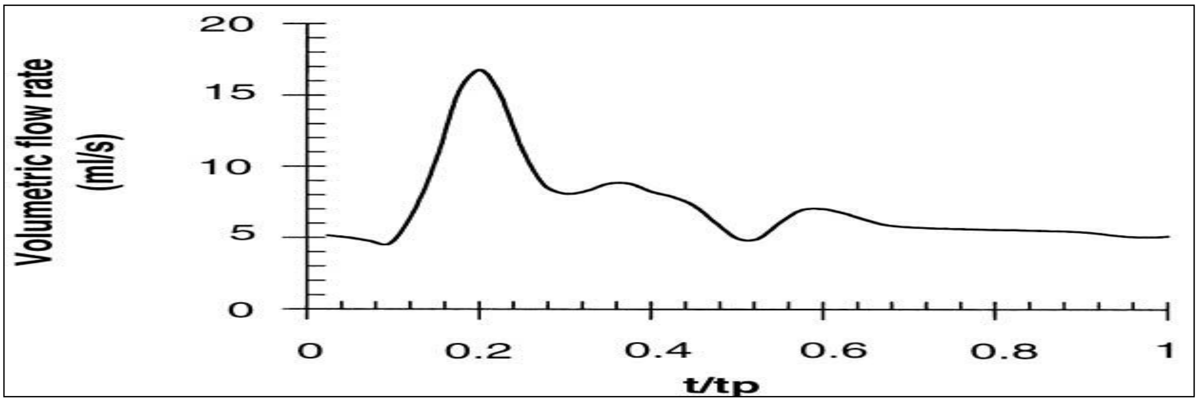

Figure 1. Volumetric flow rate-dimensionless time curve of blood flow through human carotid artery

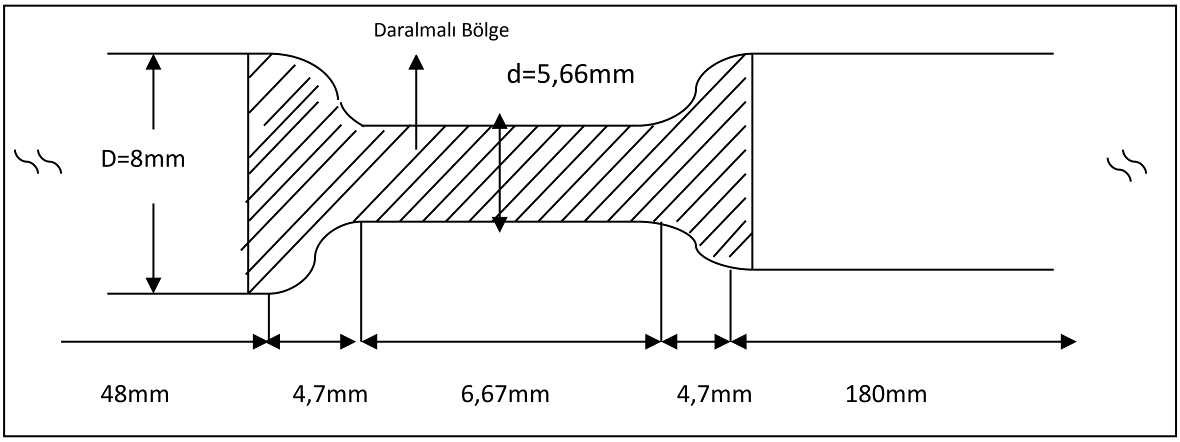

Figure 2. Dimesions of carotid artery constricted because of cholesterol

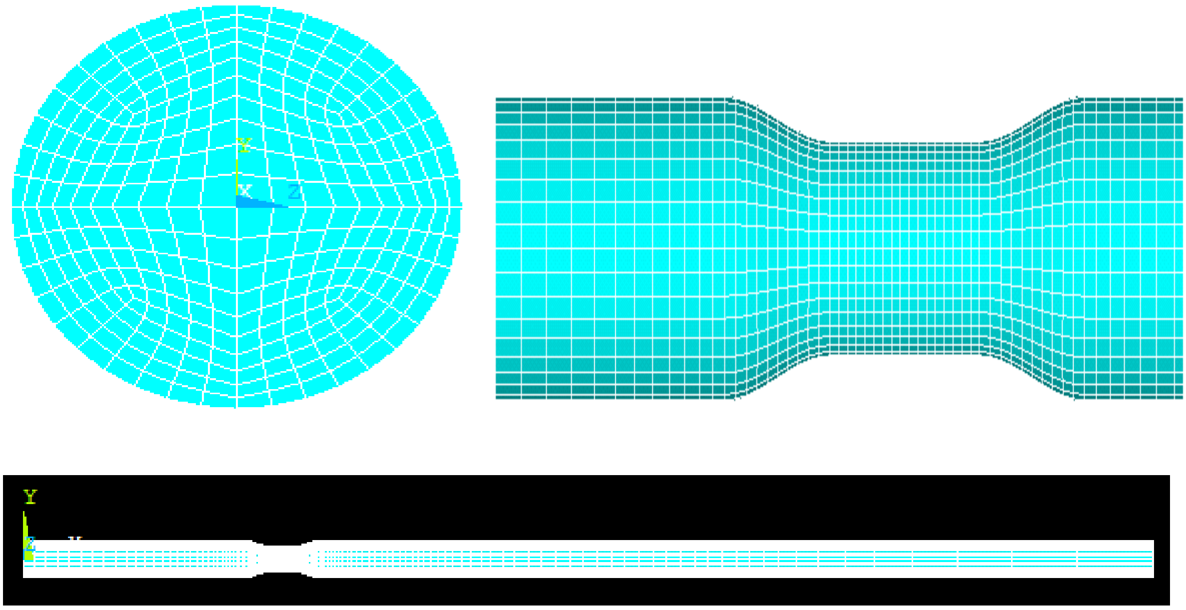

Figure 3. Web structures of constricted carotid artery at the inlet section and at the constricted region and artery's image along its length

2.Material and method

In this study, fluid analysis has been done using ANSYS programme and finite elements method. Density value that is used in the analysis and other values that define the viscosity are obtained using different sources.

3.Calculations

<u>Assumptions in the study:</u>

- The existence of a constriction inside the carotid artery caused by the cholesterol
- Cross-sectional area of the constricted region is 50% of the one in regions without constriction
- The blood is a Newtonien fluid

The blood is actually a non-Newtonien fluid. If the part where shear strain values that exist in the horizontal axis of the shear stress-shear strain graphic of blood are smaller than 100 s^{-1} will be regarded, necessessary thing to do is to model the blood as a non-Newtonien fluid or to be sure that shear-strain values at any points of the analysed model are bigger than 100 s^{-1}. However, as this is a very small part on all the graphic and then the graphic linear, selecting the fluid type as Newtonien hasn't caused any problem as will be seen from the analysis.

3.1.Outlet velocity profiles when inlet velocity profile is uniform and parabolic respectively

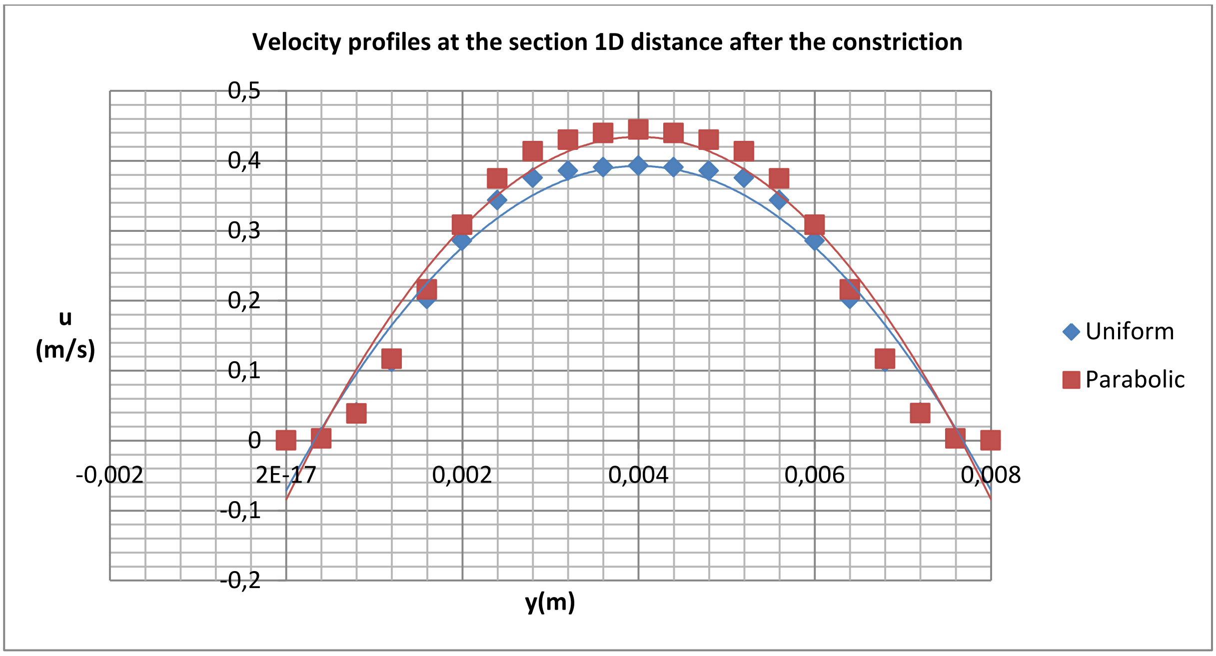

Figure 4. Velocity profiles at the section 1D distance after the constriction

When the inlet velocity profile is uniform, velocity profile after 1 diameter distance from the constriction has been parabolic, however, it hasn't been symmetrical according to the central axis yet. The flow is laminar in all the section, however, it is not fully-developed yet as it has just left the constricted region. Besides, as it will be fully-developed laminar flow after a certain distance, its velocity profile has started to be similar with that of the fully-developed laminar flow as well.

When the inlet velocity profile is parabolic, velocity profile after 1 diameter distance from the constriction has been parabolic, however, it hasn't been symmetrical according to the central axis yet. The flow is laminar in all the section, however, it is not fully-developed yet as it has just left the constricted region. Besides, as it will be fully-developed laminar flow after a certain distance, its velocity profile has started to be similar with that of the fully-developed laminar flow as well.

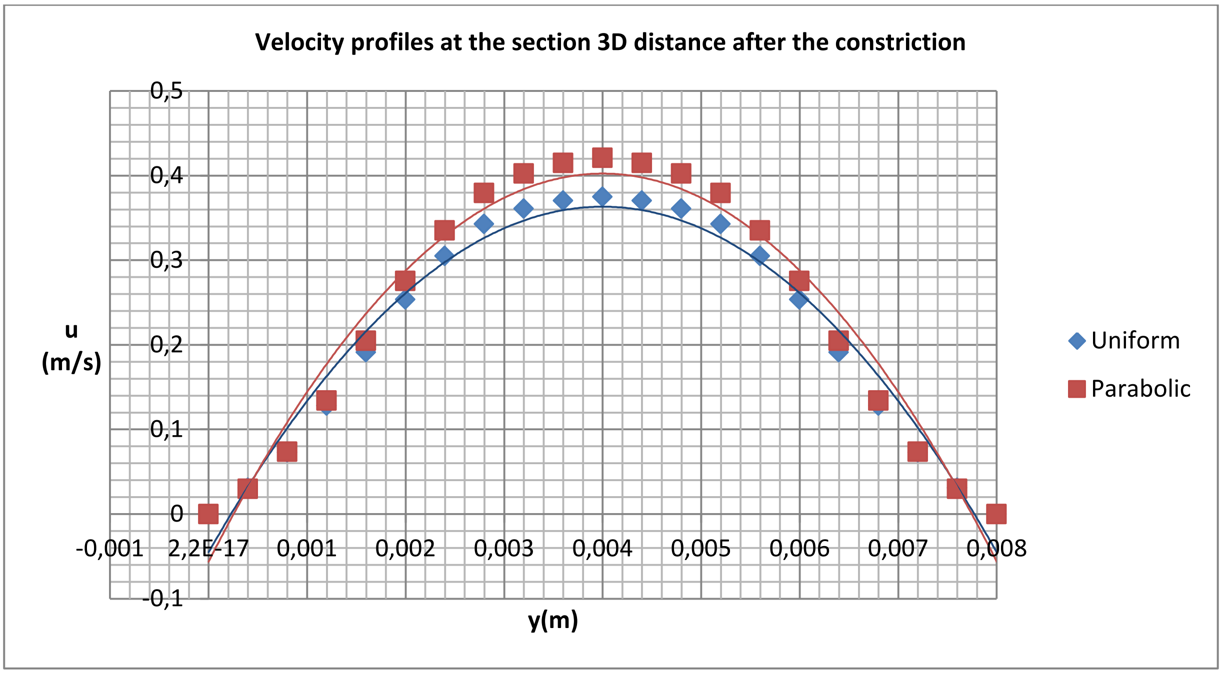

Figure 5. Velocity profiles at the section 3D distance after the constriction

When the inlet velocity profile is uniform, velocity profile after 3 diameters distance from the constriction has been parabolic, however, it hasn't been symmetrical according to the central axis yet. The flow is laminar in all the section, however, it is not fully-developed yet as it has just left the constricted region. Besides, as it will be fully-developed laminar flow after a certain distance, its velocity profile has started to be similar with that of the fully-developed laminar flow as well.

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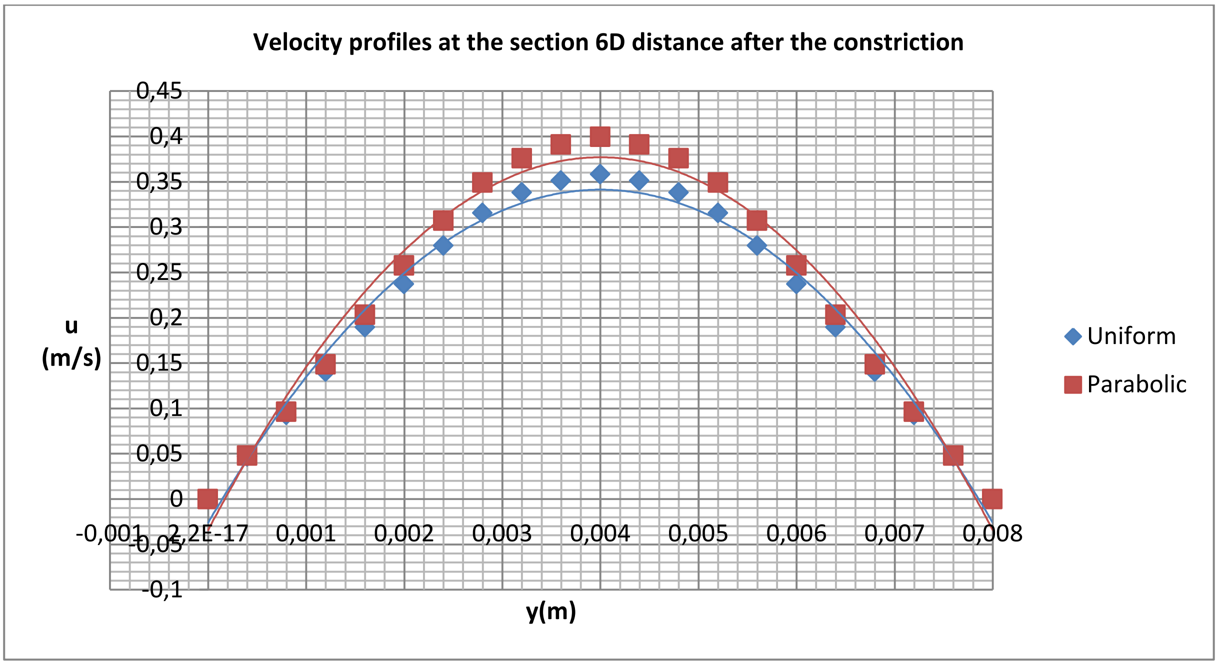

Figure 6. Velocity profiles at the section 6D distance after the constriction

When the inlet velocity profile is uniform, velocity profile after 6 diameters distance from the constriction has been parabolic, however, it hasn't been symmetrical according to the central axis yet. The flow is laminar in all the section, however, it is not fully-developed yet as it has just left the constricted region. Besides, as it will be fully-developed laminar flow after a certain distance, its velocity profile has started to be similar with that of the fully-developed laminar flow as well.

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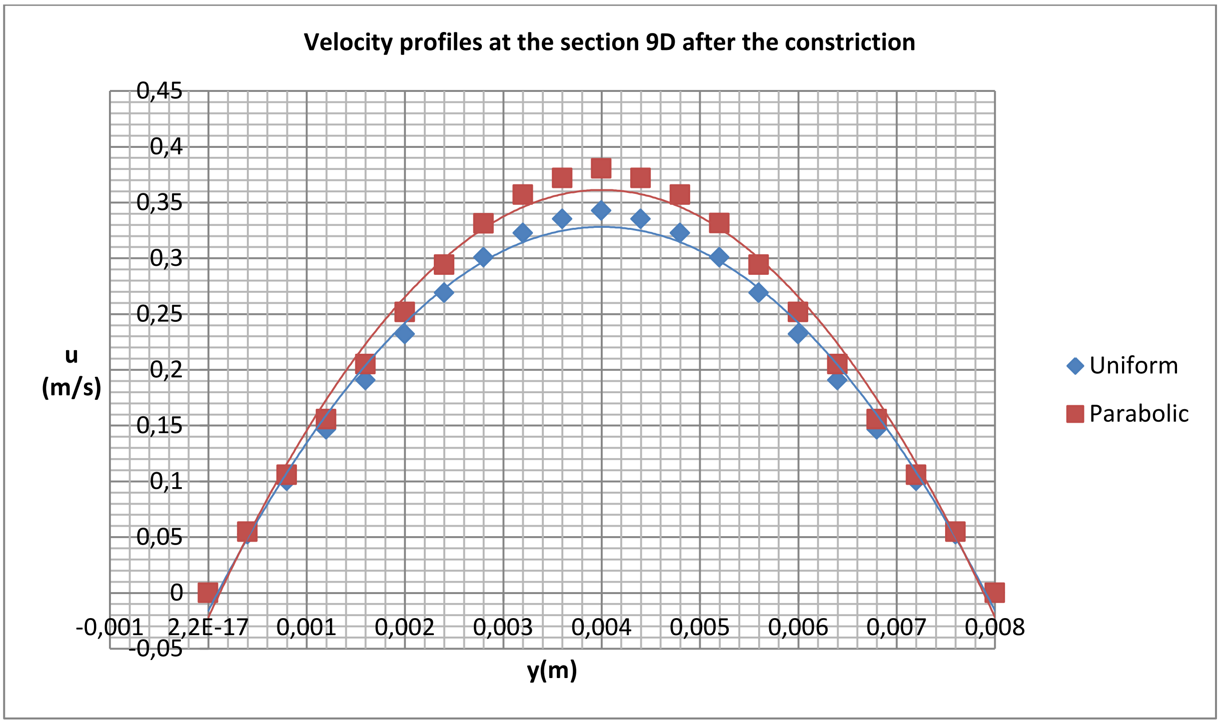

Figure 7. Velocity profiles at the section 9D distance after the constriction

When the inlet velocity profile is uniform, velocity profile after 9 diameters distance from the constriction has been parabolic, however, it hasn't been symmetrical according to the central axis yet. The flow is laminar in all the section, however, it is not fully-developed yet as it has just left the constricted region. Besides, as it will be fully-developed laminar flow after a certain distance, its velocity profile has started to be similar with that of the fully-developed laminar flow as well.

When the inlet velocity profile is parabolic, velocity profile after 9 diameters distance from the constriction has been parabolic, however, it hasn't been symmetrical according to the central axis yet. The flow is laminar in all the section, however, it is not fully-developed yet as it has just left the constricted region. Besides, as it will be fully-developed laminar flow after a certain distance, its velocity profile has started to be similar with that of the fully-developed laminar flow as well.

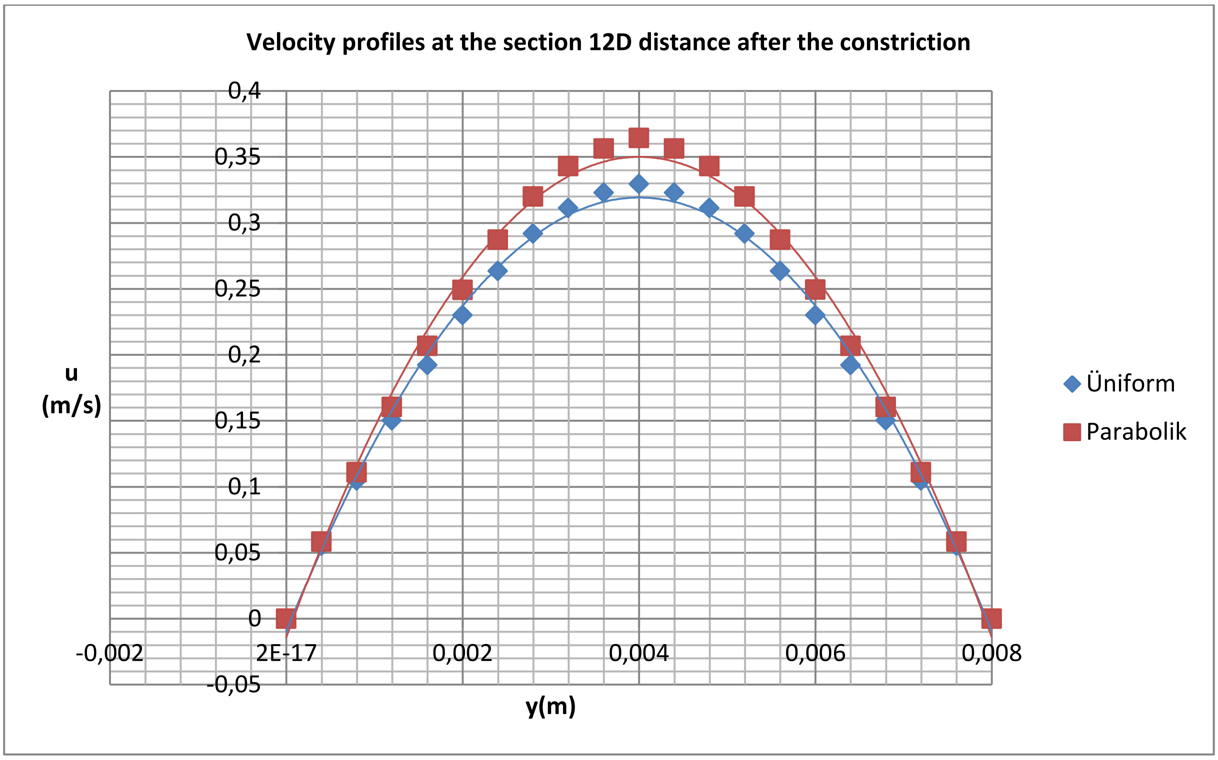

Figure 8. Velocity profiles at the section 12D distance after the constriction

When the inlet velocity profile is uniform, velocity profile after 12 diameters distance from the constriction has been parabolic, however, it hasn't been symmetrical according to the central axis yet. The flow is laminar in all the section, however, it is not fully-developed yet as it has just left the constricted region. Besides, as it will be fully-developed laminar flow after a certain distance, its velocity profile has started to be similar with that of the fully-developed laminar flow as well.

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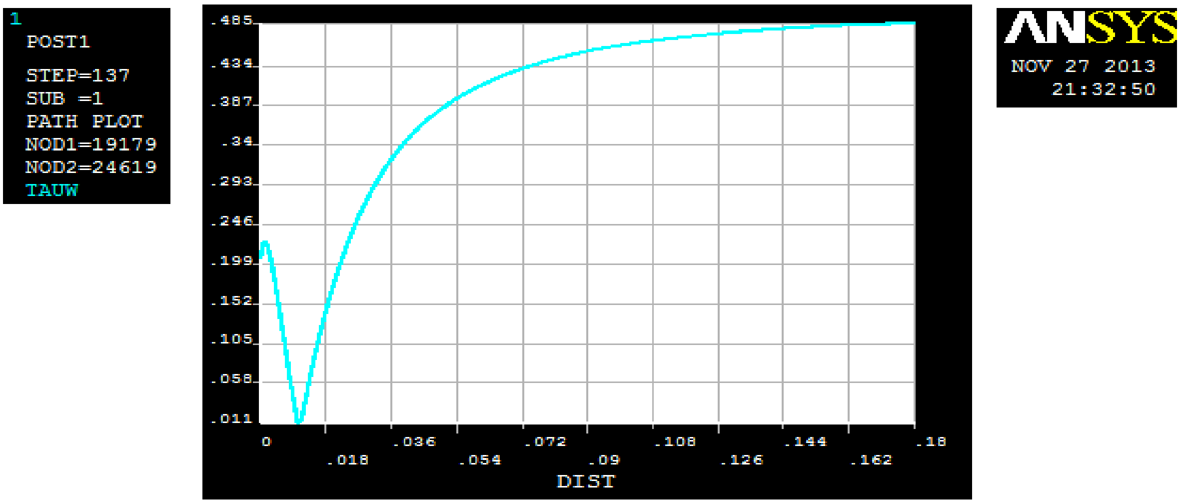
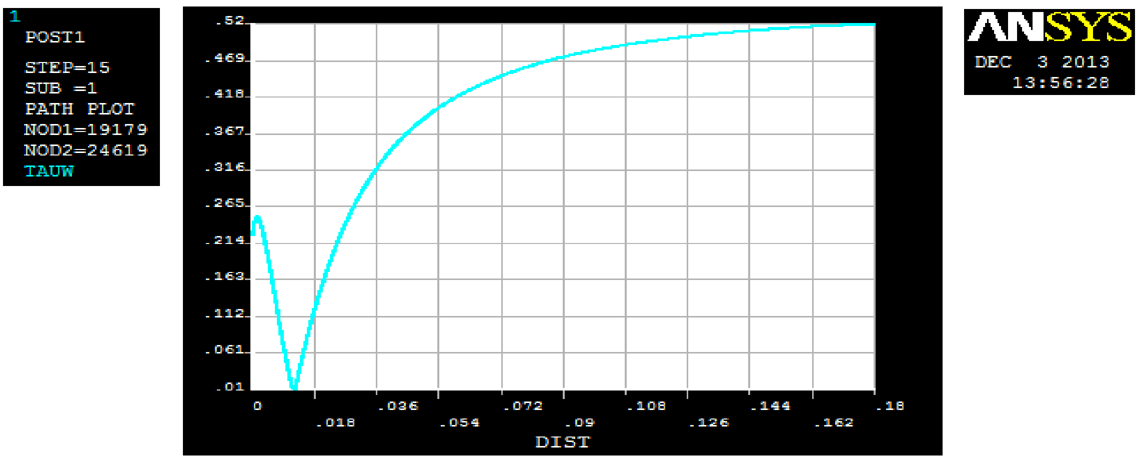
Besides, it is seen from the graphics that maximum velocity value decreases while moving away from the constricted region and thus the fluid decelerates. This situation is a result of that the constricted region has been left and fully-developed flow condition has been approached.

3.2.Giriş hız profili üniform ve parabolik iken daralma bitiminden damar sonuna kadarki kesit üzerindeki kesme gerilmesi



(a)



(b)

Figure 9. Shear stress on the section beginning from the end of the constriction until the artery outlet when inlet velocity profile is a)uniform and b)parabolic

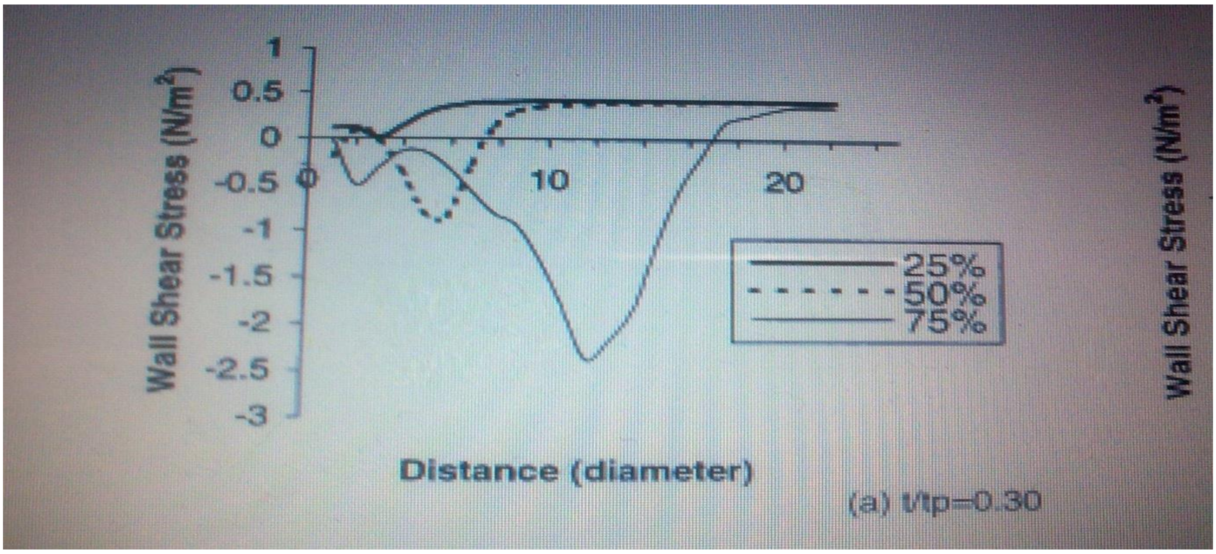


Figure 15. Wall shear stress of the academic study on the section beginning from the end of the constriction until the artery outlet [5]

In both of the shear stress graphics, a sudden drop at first and then approximation to a constant value are seen. As this is same in both of the graphics show that, changing the inlet velocity profile hasn't changed the general shape of the shear stress graphic. This sudden drop and following approximation in our graphics also exist in the shear stress graphic given in the academic study. Mentioned sudden drop is a behaviour of the fluid that it showed while leaving the constricted region and entering the region without constriction, because during this passing, the flow is not tidied up yet and thus it is not fully-developed; however as moving away from the constricted region the flow will be fully-developed after a certain distance and at this point its shear stress value will be a constant value as well. It is understood from our graphics that this happens near the artery outlet.

4.Discussion

Shear stress curve in the academic study and the curves obtained as a result of the analysis are very similar to each other. The curve in the academic study approximates to 0,5 N/m^2 value after an oscillation with a shape of hole at the beginning. In our study, when the inlet velocity profile is given parabolic the mentioned value approximates to 0,52 N/m^2; whereas it approximates to 0,485 N/m^2 when the inlet velocity profile is given uniform. Namely, selecting the inlet velocity profile as uniform has given a closer result. Actually, as parabolic velocity profile has been preferred in the academic study as well, parabolic inlet velocity profile must have given a closer result; however, as both of the results are very close to the value of the academic study, this situation is not important. Relative errors for these results found are 4% and 3% respectively.

5.Results and Suggestions

In the study, the blood flow through the carotid artery that is one of the most important vessels of the human circulatory system has been modelled and compared with an academic study. In the study, it has been assumed that there is a constriction inside the artery caused by cholesterol. According to the results, velocity profiles at the sections after the constricted region are parabolic; however the peaks of these paraboles don't exactly coincidence with the central axis. Besides, it is seen that velocity values decrease while moving away from the constriction and shear stressses on the wall approximate to constant values. The results obtained from here are these: After leaving the constricted region the flow approaches the fully-developed laminar flow condition step by step; however, as the flow hasn't tidied itself up near the constricted region yet, fully-developed laminar flow condition is possible near the artery outlet. Besides, the existence of 3% and 4% relative errors between the shear stress values obtained in our study and the shear stress value in the academic study shows that the results found assuming the blood as a Newtonien fluid are reliable.

6.References

[1]Burns M. Clinical Applications of Doppler Ultrasound 2. Hemodynamics P.N 1995.

[2]Çengel YA, Cimbala JM. Akışkanlar Mekaniği Temelleri ve Uygulamaları. Nevada Üniversitesi Makine Mühendisliği Bölümü; 2008, p. 49.

[3]Gülen Ş. Kan Fizyolojisi: Kanın Görevleri, Fiziksel ve Kimyasal Özellikleri. Başkent Üniversitesi Tıp Fakültesi, Ankara: 23-21. (http://www.baskent.edu.tr/~sebnem/05Kaningorevleri20092010.pdf)

[4]Güleren KM, Temel ÜN, Pınarbaşı A. Atardamar Daralmalarının Basınç Kaybına Olan Etkisi. IV. Ulusal Biyomekanik Kongresi. Erzurum. 16-17 Ekim 2008.

[5]Long Q, Ramnarine KV, Hoskins P. Numerical investigation of physiologically realistic pulsatile flow through arterial stenosis. Journal of Biomechanics 2001; 34: 1242-1129.

[6]Gürlek C, Pınarbaşı A. Düşük Re Sayısında Vasküler (Damarsal) Tüp Daralmalarında Gözlemlenen Akış Değişimlerinin Nümerik Analizi. DEÜ Mühendislik Fakültesi Fen ve Mühendislik Dergisi 2003; 5: 7-1.

[7]Chhabra RP. Non-Newtonian Fluids: An Introduction.

(http://www.physics.iitm.ac.in/~compflu/Lect-notes/chhabra.pdf)

[8]Subramanian RS. Non-Newtonian Flows.
(http://web2.clarkson.edu/projects/subramanian/ch330/notes/Non-Newtonian%20Flows.pdf)

[9]Li Z, Kleinstreuer C. Blood flow and structure interactions in a stented abdominal aortic aneurysm model. Medical Engineering and Physics 2004; 27: 382-369.

[10]Chan WY, Ding Y, Tu JY. Modeling of non-Newtonian blood flow through a stenosed artery incorporating fluid-structure interaction. Anziam Journal 2006; 47: 523-507.