Modeling Vessel Stenosis

Abstract:

Coronary heart disease is the dominant cause of death in the United States. The buildup of plaque in the heart's blood vessels causes the vessels to decrease in diameter and significantly decreases blood flow to important organs("Heart Disease Facts & Statistics."). Build up can occur in other parts of the body such as the spine, brain, kidneys, and limbs, which could possibly lead to death("Peripheral Artery Disease (PAD)."). Modeling stenosis in blood vessels is important in understanding how much blood is not delivered to the proper location and the proper biomedical solutions needed to treat the condition. An ANSYS Fluent model of a regular blood vessel was compared with a blood vessel with a shrink in diameter at the center of the vessel. Another regular vessel with a bifurcation was modeled in ANSYS Fluent and compared to a bifurcating vessel with stenosis. The results showed that the blood vessel with stenosis had 51.17% less blood delivered than the healthy blood vessel. Also, the bifurcating blood vessel with stenosis had 99.8% & 99.98% less blood delivered to the healthy branch and branch with stenosis, respectively. These models can help doctors create a personal treatment plan for patients by knowing the severity of the build up(Liu et al, 2010).

Motivation:

Stenosis, the blocking of blood flow in pathways, is one of the most prevalent biomedical issues as it often leads to death. Vessel stenosis in the heart occurs from atherosclerosis, the buildup of plaque in the heart vessels("Coronary Artery Disease: Causes, Diagnosis & Prevention."). Similarly, stenosis can occur in the brain and in the kidneys, leading to complications, such as stroke, hypertension, and kidney damage("Peripheral Artery Disease (PAD)."). Modeling vessel stenosis in patients gives doctors a good tool to determine a treatment plan. As modeling of vessel flow improves, this technique can be used to detect early vessel stenosis sooner and prevent extreme complications. Additionally, simulations of blood flow can help in the development of biomedical instrumentation(Pralhad and Shultz, 2004).

Problem Formulation:

The following are assumptions made in this ANSYS Fluent model and calculations: only laminar flow is present in all parts of the blood vessels modeled, blood has a constant viscosity in all parts of the model, blood is an incompressible fluid with constant density in all parts of the model, the length and radius of the blood vessel are set, all blood vessels are perfect cylinders, and there is a constant temperature in all blood vessels modeled.

However, some of these assumptions are questionable. The carotid artery leading from the heart to the brain inside the neck is often the site of arterial stenosis. This bifurcating artery can have plaque build up and cause turbulent flow and create eddys in the artery, which our model does not account for. Inside the body, blood vessels have curves, splits, and varying radiuses, this model only accounts for straight, ideal cylinders.

The important variables used in hand calculations was the initial pressure, final pressure, radius, viscosity, and length. These variables were used in Poiseuille's Law for Laminar Flow which allows calculations for the volume flow rate. Poiseuille's Law is defined as:

$$Q = \frac{(P_2 - P_1)\pi r^4}{8\eta l}.$$

Solution Method:

Vessel 1:

Similar to the first tutorial, we modeled a rectangle that was then mirrored about the x axis and converted to 3D. Approximately 6000 divisions were made during the meshing process. The inlet velocity was 0.315m/s, the density was 1060 kg/m^3, and the pressure was 13332 Pa. These reference values were taken from the second tutorial from Dr. Baskaran. The vessel was 60mm long with a 4mm diameter. 200 iterations were recorded to see where the drag coefficient converged.

Vessel 2:

This vessel was similar to the first vessel in that it was created 2D and then mirrored about the x axis. The vessel was 60mm long with a 4mm diameter. The stenosis was modeled by creating a bend 20mm in from the edge. It was 10mm long with a 75% decrease in diameter. The narrowest region had a 1 mm diameter. The reference values were the same as the previous vessel. Around 6000 divisions were made on this vessel with the divisions being extra concentrated around the stenosis. 100 iterations were recorded to see where the drag coefficient converged.

Vessel 3:

This vessel was created by connecting three 3D cylinders in DesignModeler. This created a "Y" shape. The inlet was 40mm long with a diameter of 4mm. The two outlets were 30mm long with a diameter of 4mm. The same reference values were used. About 400,000 divisions were made with a sphere of influence around the intersection of the bifurcation. 100 iterations were recorded for this vessel's drag coefficient.

Vessel 4:

This vessel was created like the one before but an ellipse was added to combine with one of the outlets and then subtracted creating a divot 10mm long and 10mm from intersection of the bifurcation. The stenosis was a 75% decrease in diameter, making the narrowest region 1mm in diameter. Over 400,000 divisions were made for this vessel as well. A sphere of influence was made around the intersection of the bifurcation and the divot that was made. 50 iterations were recorded for the drag coefficient.

Results:

In comparing vessel #1 and vessel #2, figures 1A and 2A show that in vessel #1 the velocity grew exponentially while the velocity in vessel #2 increased significantly after the stenosis divot. To calculate the volume flow rate we used Poiseuille's Law. For an accurate comparison, we calculated the length from the inlet to the center of the divot (where the stenosis was more extreme), we then used that length in reference to calculate the pressure drop and radius of the vessel. We found that there was 51.17% less blood delivered because of the stenosis.

In comparing vessel #3 and vessel #4, figures 3A and 4A show that in vessel #3 the velocity decreased exponentially in the stem (inlet) and continued to decrease exponentially in the branch (outlet) while in vessel #4 the velocity decreased almost linearly and in the regular branch it increased and then decreased while in the branch with stenosis it spiked and then went almost to zero. For this example, we used 3 lines (line 1= stem, line 2= healthy branch, line 3= branch with stenosis) to collect data as we figured it was the best way to compare the two models. To calculate the volume flow rate we used Poiseuille's Law. For an accurate comparison, we calculated the length from the center of the bifurcation to the center of the divot, we then used this length in reference to calculate the pressure drop and radius of the vessel of the branches. We found that the healthy branch had 99.8% of blood delivered while the vessel with stenosis had 99.98% less blood delivered.

Sample calculations:

$$Q = \frac{(\Delta P)\pi(r^4)}{8\eta L}$$

$$Q = \frac{(32Pa)\pi(.002m^4)}{8(.0035Pa*s)(.025m)} = 2.298 \bullet 10^{-6}\ \frac{m^3}{s} \qquad Q = \frac{(4000Pa)\pi(.0005m^4)}{8(.0035Pa*s)(.025m)} = 1.122 \bullet 10^{-6}\ \frac{m^3}{s}$$

$$\frac{\textit{Regular volume flow rate}}{\textit{Stenosis volume flow rate}} = \frac{2.298 \bullet 10^{-6}\frac{m^3}{s} - 1.122 \bullet 10^{-6}\frac{m^3}{s}}{2.298 \bullet 10^{-6}\frac{m^3}{s}} \bullet 100 = 51.17\% \text{ less blood delivered}$$

Conclusions:

From the results, our assumptions were correct in that we knew the blood volume flow rate would decrease in the vessels with stenosis, however, we did not expect such a decrease as shown above. We were unsure about how exactly the pressure contours would look through out the vessel. We understood there would be a pressure drop from the inlet to the outlet, but we did not expect a rapid change in pressure after the stenosis in vessel #2. We also did not expect the pressure contour of vessel #4. We expected more pressure build up right before the stenosis in the outlet.

These models are a good starting block on the way to fully modeling real blood vessels in patients with plaque build up in blood vessels. A more accurate model should include blood vessels of varying radius as well as longer vessels. These more complex geometries are more common in the body. Turbulent flow inside the vessels is also a very possible situation that should be accounted for. Another improvement would be to model different stages of stenosis, such as 30% decrease in diameter and 50% decrease in diameter. We also could have improved our data collection on the wall shear in vessel #2 (figure 2C) as there is no data where we would expect the wall shear to be the highest.

Ethical Issues:

When doctors are tasked with treating patients with life threatening conditions, they must ensure they are making the best decision possible with the information presented. Jonathan Butcher, a Cornell professor with research focused on cardiovascular developmental mechanobiology, states “The opportunity for simulation is to improve decision making. And that improvement in decision making helps spread limited resources around to where they are most needed.” Modeling a specific patient’s vessels can help determine what treatment is most useful and worth the cost and risks. Before modeling a patient’s vessels, he or she must give the doctors and scientists consent to use their anatomy. During the modeling process, the scientist is presented with the patient’s data in a deidentified way.

Contributions Section:

Jonathan Pierre modeled in Ansys, made graphs, analyzed results, made powerpoint. Anna Ashford modeled in Ansys, wrote paper, made powerpoint. Akugbe Imudia modeled in Ansys, 3D printed a model.

References:

Butcher, Jonathan. Personal interview. 4 October 2019.

"Coronary Artery Disease: Causes, Diagnosis & Prevention." *Centers for Disease Control and Prevention*. Centers for Disease Control and Prevention, 16 Sept. 2019. Web. 20 Oct. 2019.

"Heart Disease Facts & Statistics." *Centers for Disease Control and Prevention*. Centers for Disease Control and Prevention, 28 Nov. 2017. Web. 01 Nov. 2019.

Liu, Xuemei, Huan Liu, Aimin Hao, and Qinping Zhao. "Simulation of Blood Vessels for Surgery Simulators." *2010 International Conference on Machine Vision and Human-machine Interface* (2010): n. pag. *IEEE Xplore*. Institute of Electrical and Electronics Engineers, 29 July 2010. Web.

"Peripheral Artery Disease (PAD)." *Mayo Clinic*. Mayo Foundation for Medical Education and Research, 17 July 2018. Web. 20 Oct. 2019.

Pinto, S.I.S., E. Doutel, J.B.L.M. Campos, and J.M. Miranda. "Blood Analog Fluid Flow in Vessels with Stenosis: Development of an Openfoam Code to Simulate Pulsatile Flow and Elasticity of the Fluid." *International Conference on Biomedical Engineering and Technology* (n.d.): n. pag. *ScienceDirect*. Elselvier, 19 May 2019. Web. Sept. 2019.

Pralhad, R.N., and D.H. Shultz. "Modeling of Arterial Stenosis and Its Applications to Blood Diseases." *Mathematical Biosciences* 190.2 (204): 203-20. *ScienceDirect*. Elsevier, Aug. 2004. Web. 31 Oct. 2019.

Figures:

Regular Vessel:

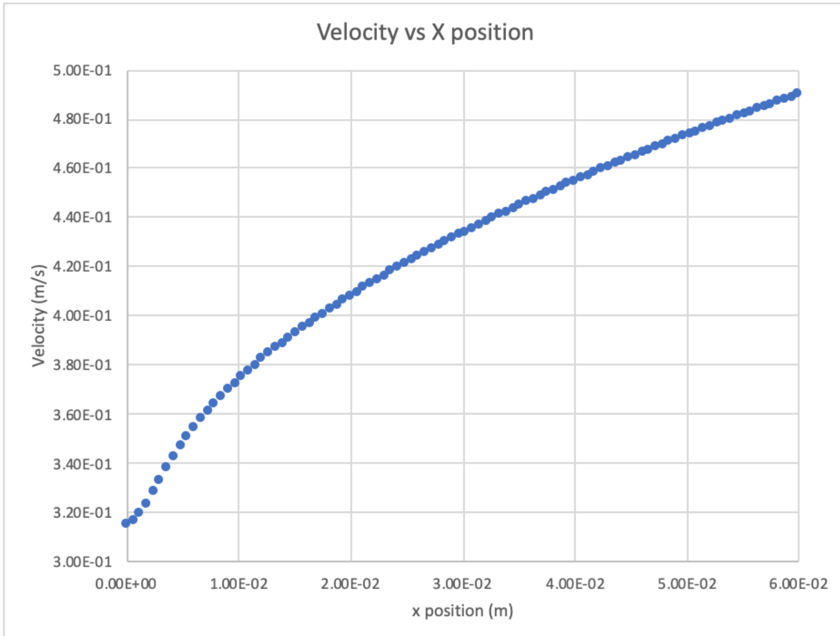

Figure 1A: Velocity of the blood through a regular vessel on the centerline as a function of the x position.

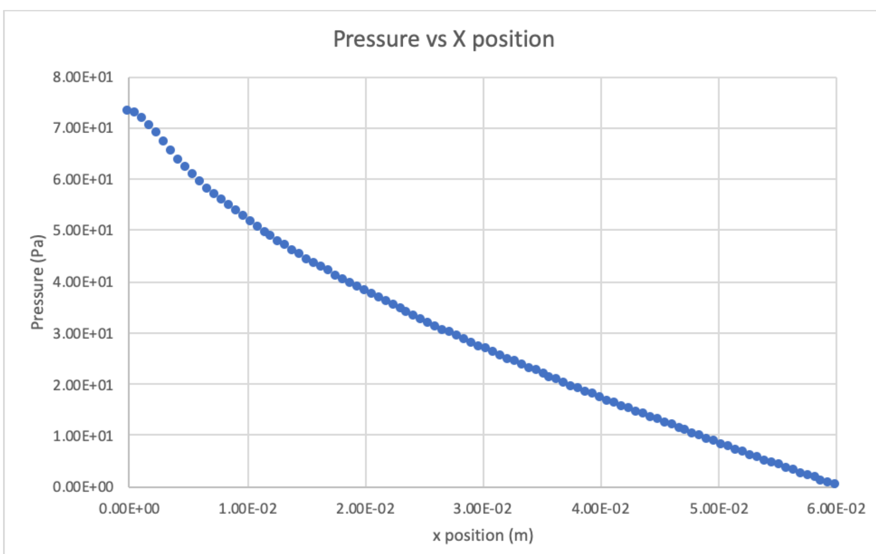

Figure 1B: Pressure from the blood flow through a regular vessel on the centerline as a function of the x position.

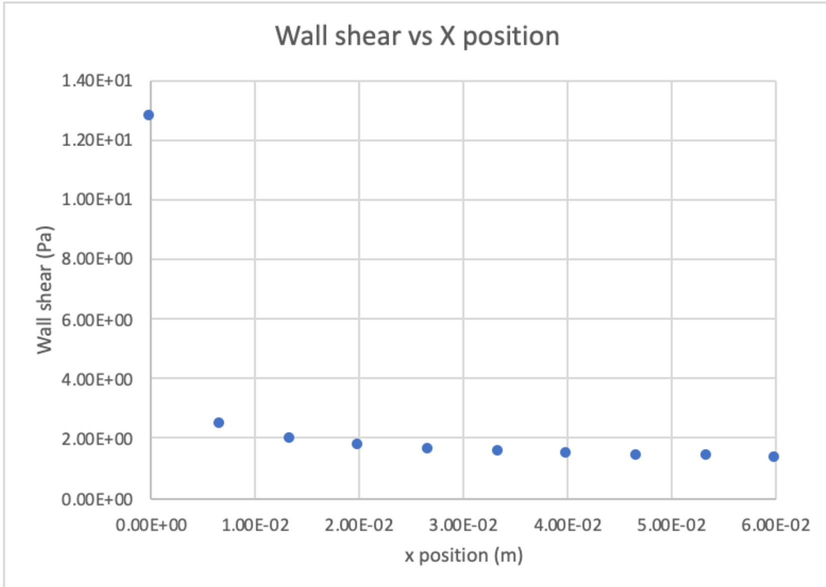

Figure 1C: Wall shear from the blood flow through a regular vessel on the vessel wall as a function of the x position

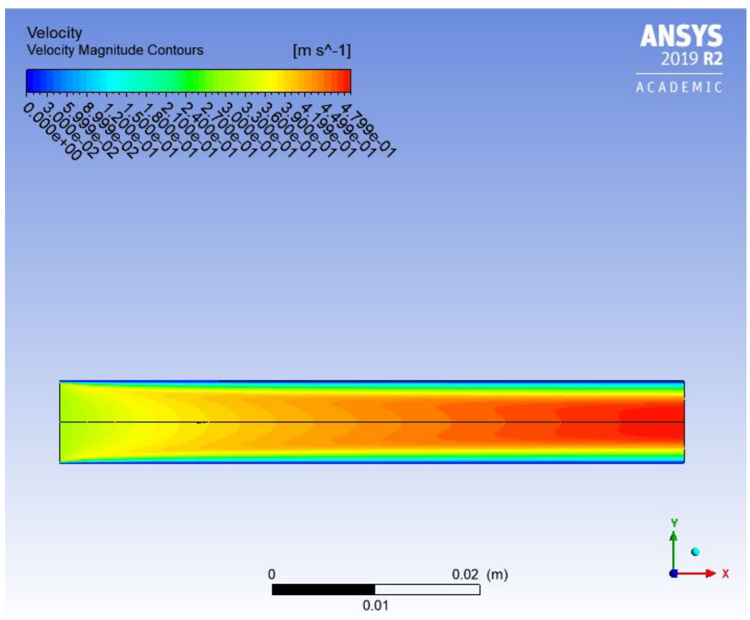

Figure 1D: Image of the velocity magnitude contours of blood flow through a regular vessel

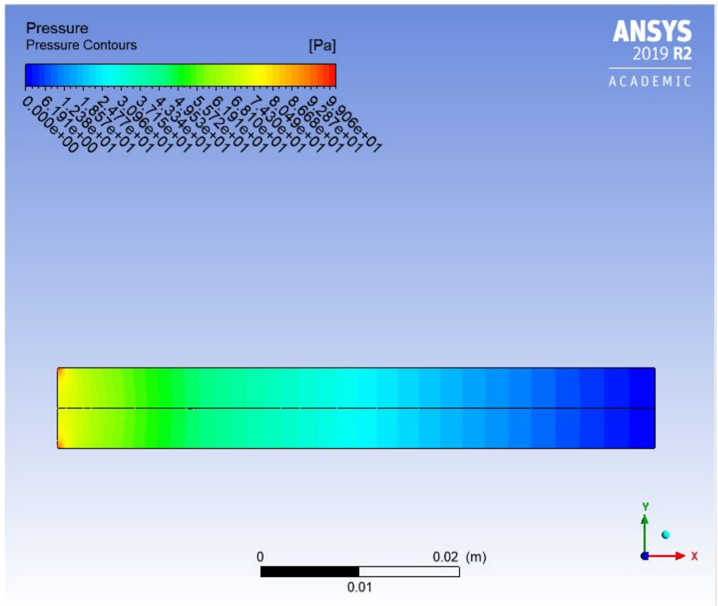

Figure 1E: Image of the pressure magnitude contours of blood flow through a regular vessel

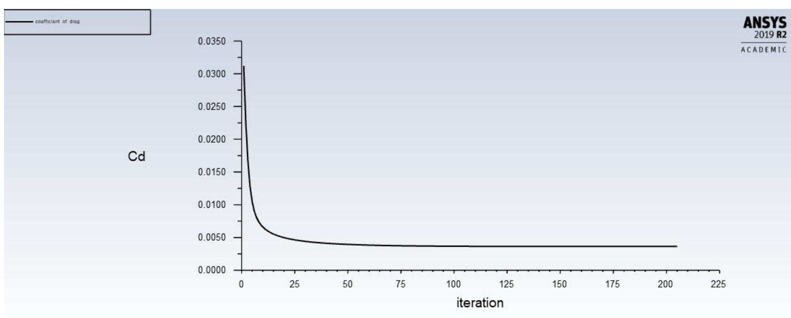

Figure 1F: Image of the coefficient of drag graph of blood flow through a regular vessel

Vessel with stenosis:

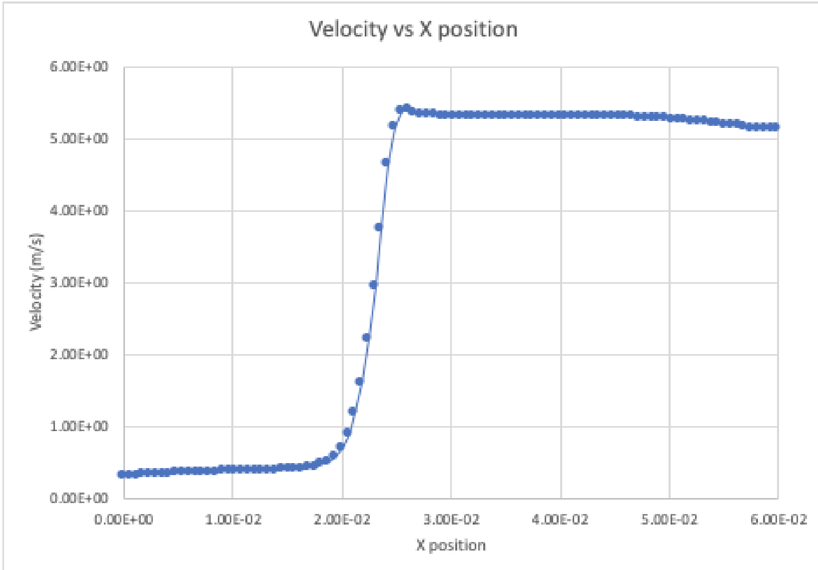

Figure 2A: Velocity of the blood flow through a vessel with stenosis on the centerline as a function of the x position.

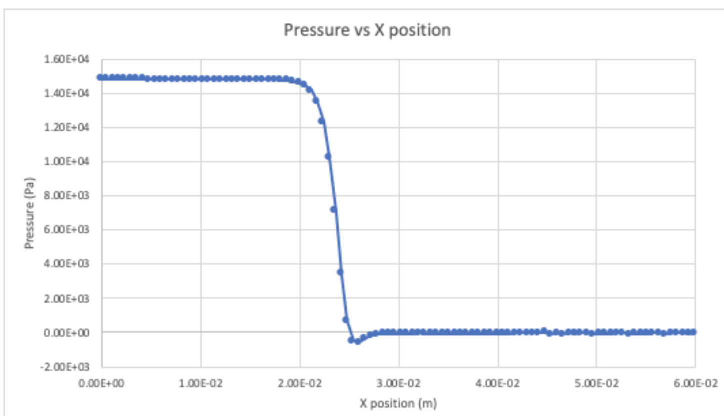

Figure 2B: Pressure from the blood flow through a vessel with stenosis on the centerline as a function of the x position

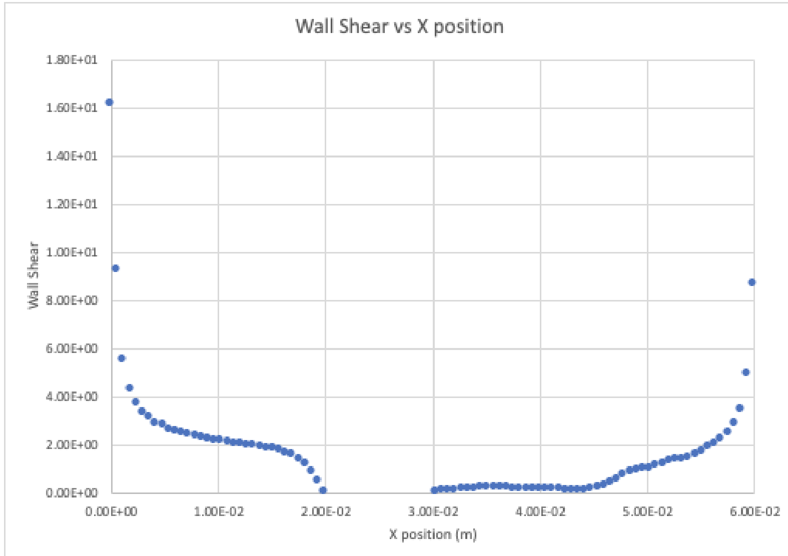

Figure 2C: Wall shear from the blood flow through a vessel with stenosis on the vessel wall as a function of the x position

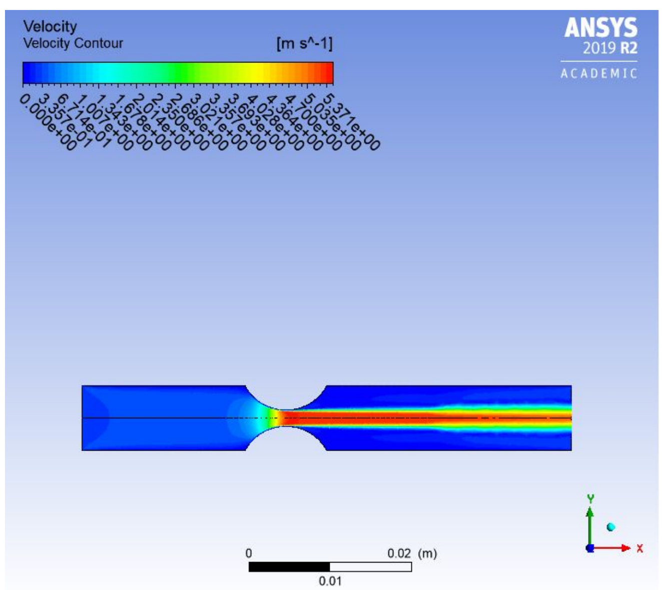

Figure 2D: Image of the velocity magnitude contours of blood flow through a vessel with stenosis

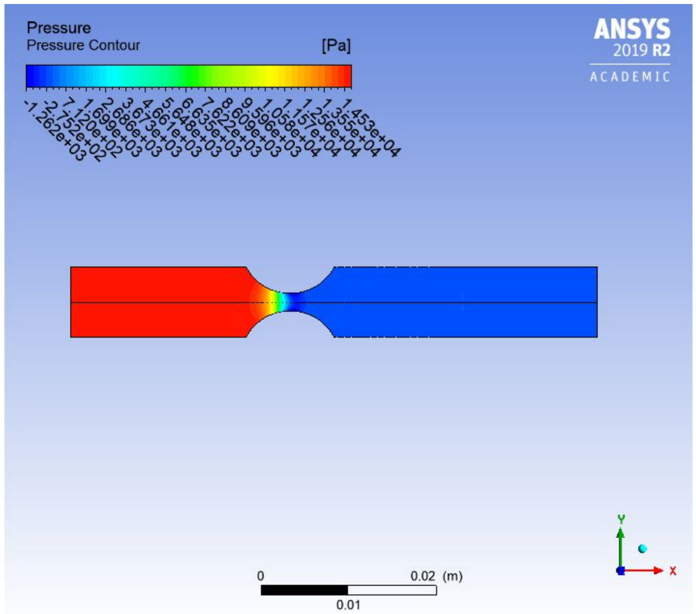

Figure 2E: Image of the pressure magnitude contours of blood flow through a vessel with stenosis

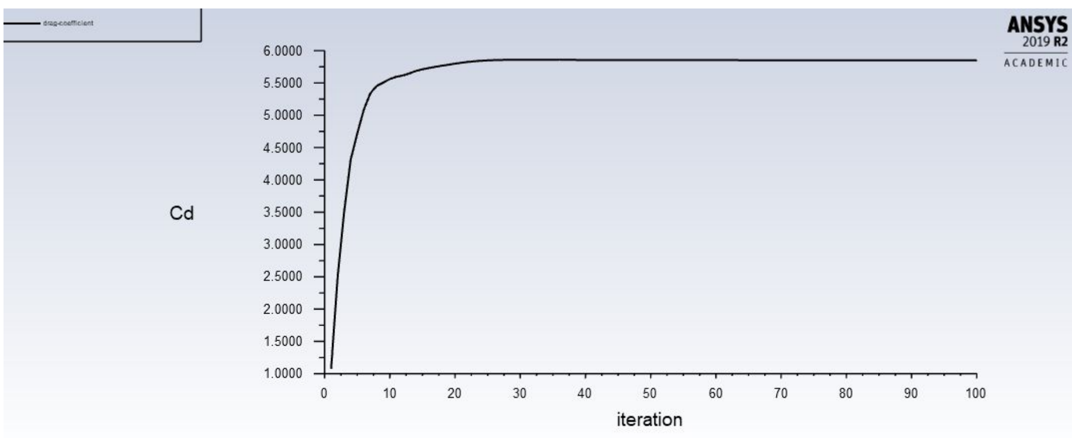

Figure 2F: Image of the coefficient of drag graph of blood flow through a vessel with stenosis

Regular Bifurcation:

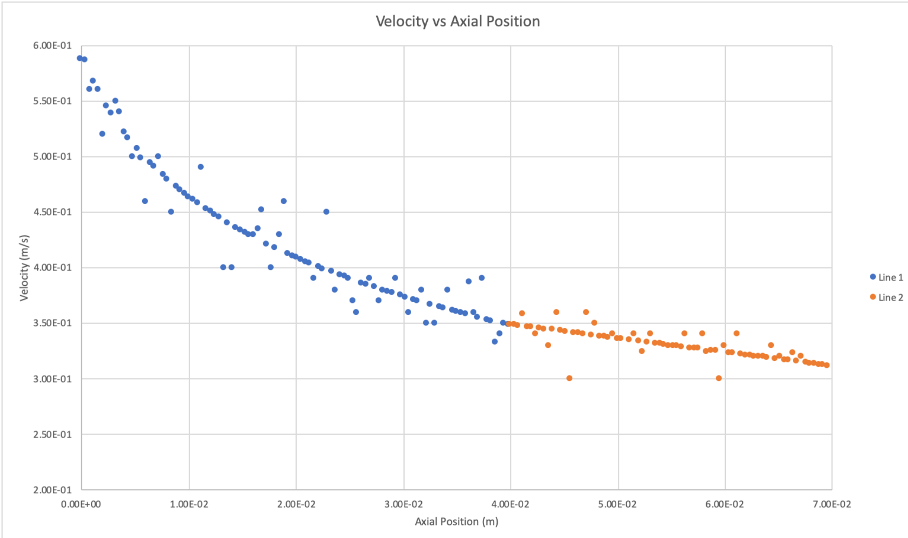

Figure 3A: Velocity of blood flow through a bifurcating vessel as a function of the axial position. Line 1 indicates the stem of the vessel (inlet) and Line 2 indicates a branch (outlet). We only included 1 branch as they are assumed to be the same.

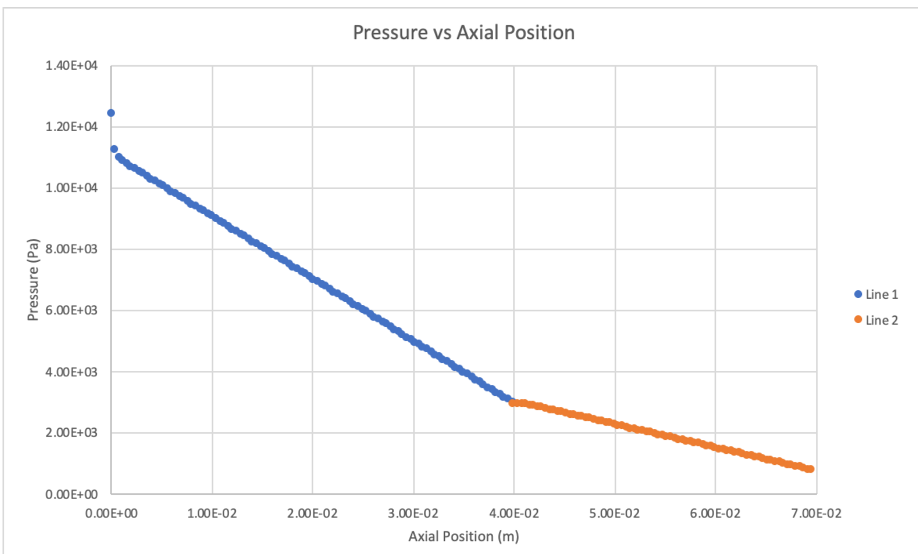

Figure 3B: Pressure from blood flow through a bifurcating vessel as a function of the axial position. Line 1 indicates the stem of the vessel (inlet) and Line 2 indicates a branch (outlet). We only included 1 branch as they are assumed to be the same.

Figure 3C: Wall shear from blood flow through a bifurcating vessel as a function of the axial position. Line 1 indicates the stem of the vessel (inlet) and Line 2 indicates a branch (outlet). We only included 1 branch as they are assumed to be the same.

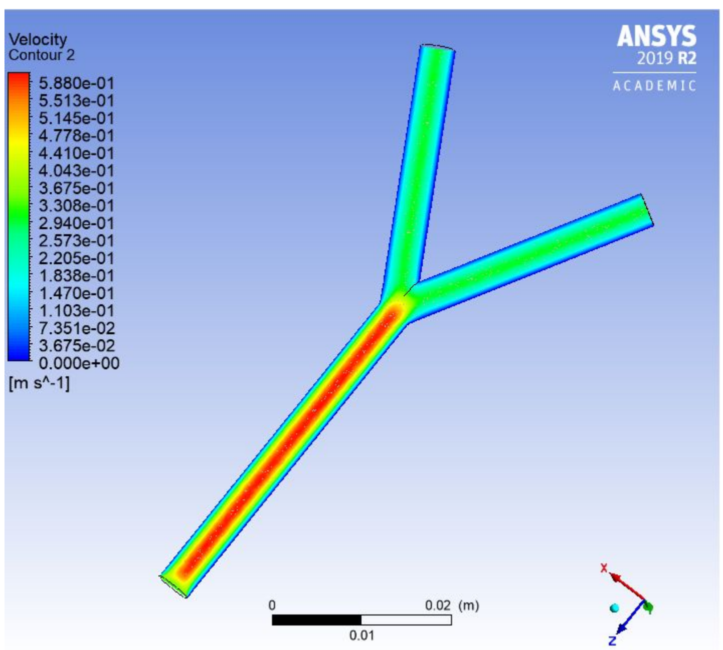

Figure 3D: Image of the velocity magnitude contours of blood flow through a bifurcating vessel

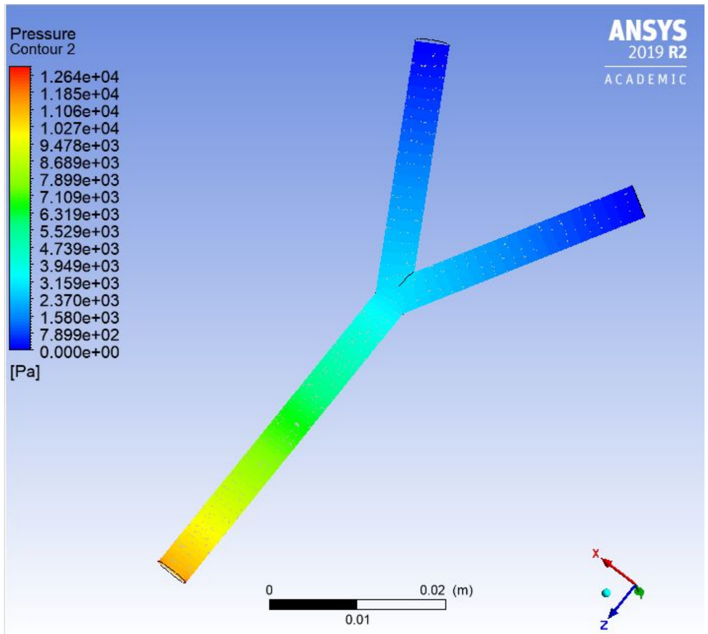

Figure 3E: Image of the pressure magnitude contours of blood flow through a bifurcating vessel

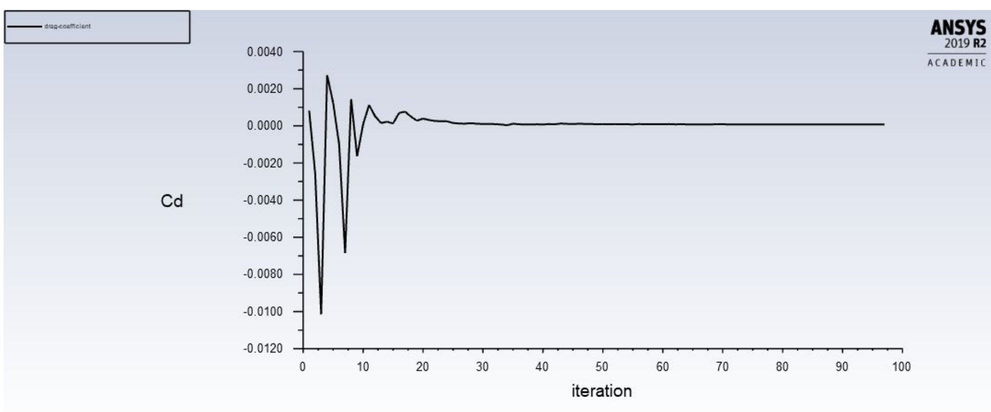

Figure 3F: Image of the coefficient of drag graph of blood flow through a bifurcating vessel

Bifurcation with stenosis:

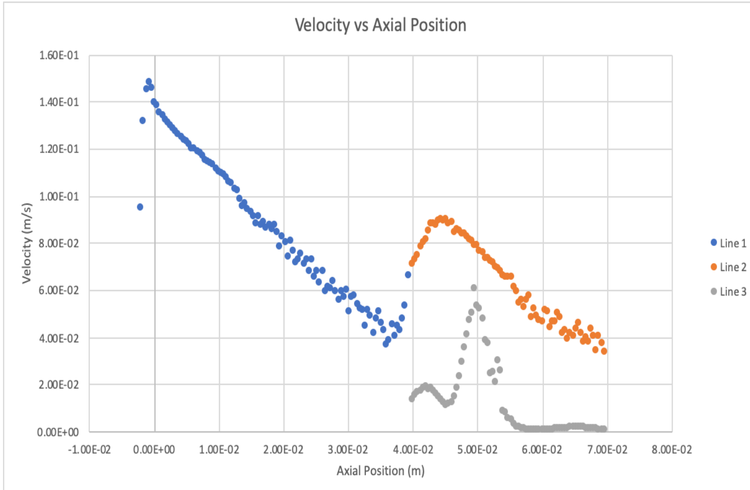

Figure 4A: Velocity of blood flow through a bifurcating vessel with stenosis as a function of the axial position. Line 1 indicates the stem of the vessel (inlet), Line 2 indicates the regular branch (outlet) and Line 3 indicates the branch with stenosis (outlet).

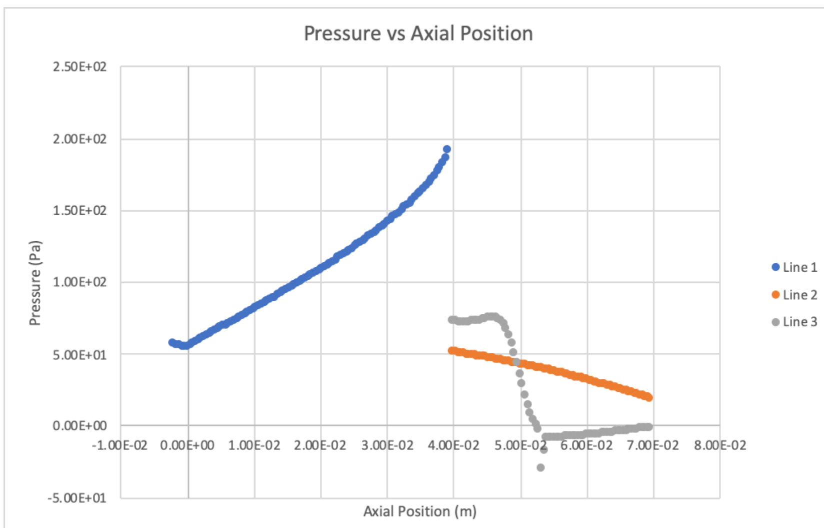

Figure 4B: Pressure from the blood flow through a bifurcating vessel with stenosis as a function of the axial position. Line 1 indicates the stem of the vessel (inlet), Line 2 indicates the regular branch (outlet) and Line 3 indicates the branch with stenosis (outlet).

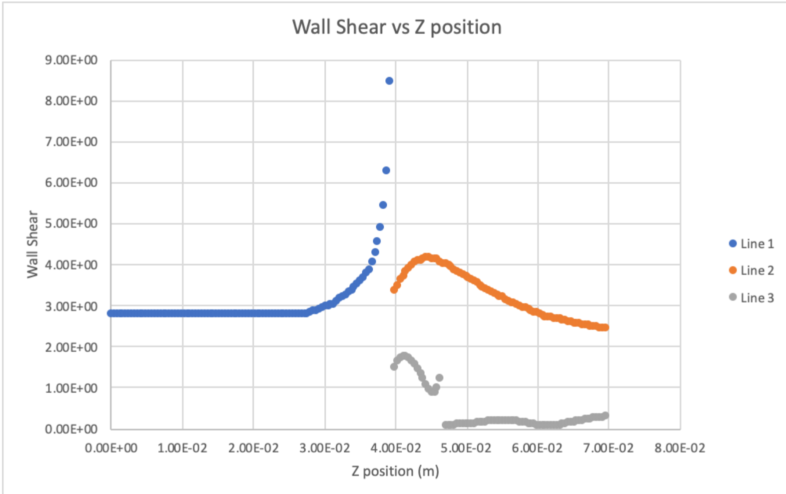

Figure 4C: Wall shear from the blood flow through a bifurcating vessel with stenosis as a function of the axial position. Line 1 indicates the stem of the vessel (inlet), Line 2 indicates the regular branch (outlet) and Line 3 indicates the branch with stenosis (outlet).

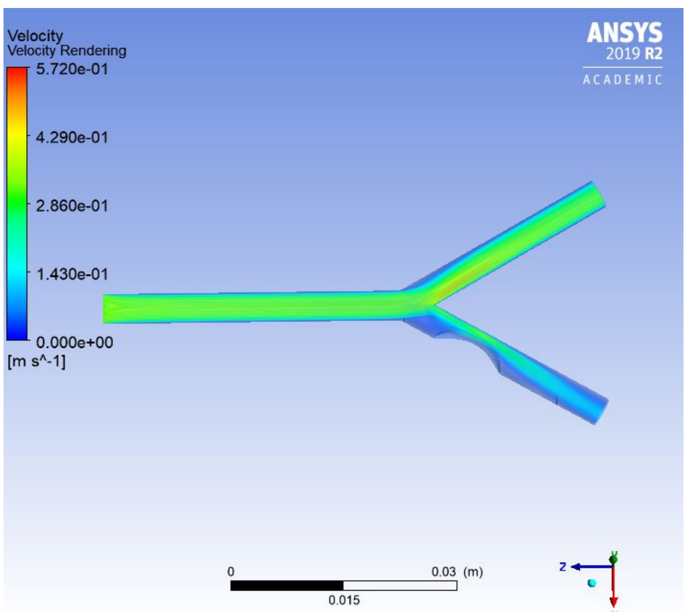

Figure 4D: Image of the velocity magnitude contours of blood flow through a bifurcating vessel with stenosis

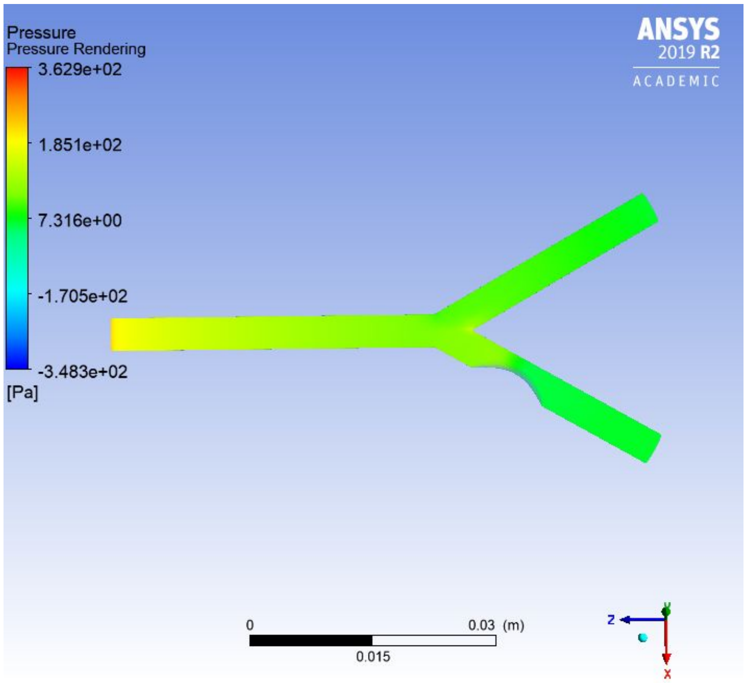

Figure 4E: Image of the pressure magnitude contours of blood flow through a bifurcating bvessel with stenosis

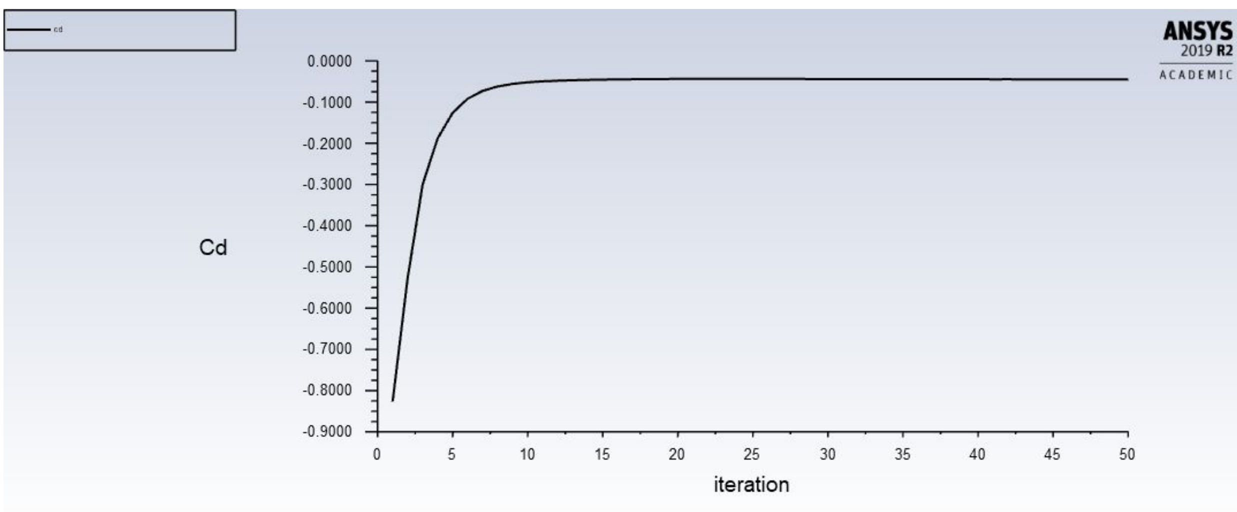

Figure 4F: Image of the coefficient of drag graph of blood flow through a bifurcating vessel with stenosis.