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# NUMERICAL ANALYSIS IN ARTERIAL STENOSIS AFFECTED BY ISCHEMIC HEART DISEASE USING FINITE VOLUME METHOD

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*ABSTRACT*

*Atherosclerosis is the narrowing of blood vessels caused by the buildup of cholesterol plaque on the walls of the arteries. Excessive buildup of cholesterol plaque disrupts the circulatory system, affecting blood flow speed and pressure. In the long term, atherosclerosis can cause ischemic heart disease. This study aims to analyze the influence of stenosis, initial velocity, and diameter on the velocity and pressure of blood flow in narrowed arteries that cause ischemic heart disease. This research built a Navier Stoke mathematical equation model, which was solved using the finite volume method with SIMPLE discretization (Semi Implicit Method for Pressure Equations). Finite volume methods are used to analyze unstructured objects such as blood flow. SIMPLE discretization is implemented simply in two and three dimensions with equations containing fluid motion. Matlab and Fluent are software used for process simulations, Matlab for visualizing graphs of numerical calculation results, and Fluent for visualizing blood flow. Based on the simulation results, it can be concluded that the smaller the diameter, the greater the stenosis, and the greater the initial velocity, the greater the blood flow velocity. On the contrary, the diameter gets smaller, the stenosis gets bigger, and the initial velocity gets bigger so that the pressure on the blood flow gets smaller. Blood flow simulation has the potential to contain ischemic heart disease if the maximum speed produced is greater than the maximum normal blood speed, namely 0.45 m/s.*

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## 1. INTRODUCTION

Mathematics is a branch of science that is the basis for developing science and technology. Mathematics plays an important role in the development of other fields of science, one of which is medicine [1]. Medical science studies comprehensive knowledge about the human body, such as the body's working systems, body balance, factors that interfere with body functions, and how to maintain and restore the balance of normal body functions. One of the things studied in medical science is the human circulatory system, which consists of the heart, blood vessels, and lymph channels [2]. The cardiovascular system consists of the heart and blood vessels, which accommodate blood through the blood vessels (arteries, veins, capillaries) and distribute blood containing oxygen (O2), nutrients, and other substances throughout the body. [3]. Atherosclerosis is a disorder of the cardiovascular system.

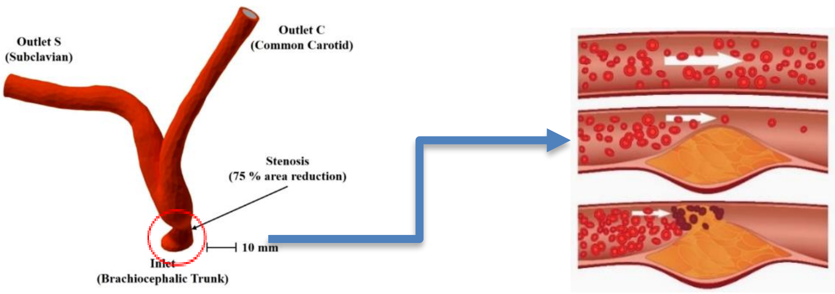
Atherosclerosis is a chronic inflammatory disease characterized by thickening of the artery walls due to the formation of cholesterol plaques [4]. Plaque formation in the lumen of blood vessels causes an abnormal increase in cholesterol levels. Cholesterol plaques can narrow the lumen in the arteries, decrease blood flow to the heart muscle, and cause ischemic heart disease. In advanced atherosclerosis, the shortening of blood vessel size can significantly reduce blood supply to vital organs, thus triggering ischemic heart disease [5]. Ischemic Heart Disease is a disease caused by narrowing or blockage of the coronary arteries, resulting in a lack of blood supply to the heart muscle [6].

World Health Organization (WHO) data for 2020 shows that ischemic heart is the first cause of death worldwide at 16%, and stroke is 11%, which is the second cause of death after ischemic heart [7]. The United States in 2020 has a growth rate of death from ischemic heart disease and stroke of 4.83% and 6.03% [7]. Numerical method is a technique used to formulate or describe mathematical, financial, or engineering problems so that they can be solved using calculation operations [8]. The numerical solutions are obtained by performing certain iterative procedures so that each result is more accurate than the previous estimate. There are many methods of solving mathematical models in numerical methods, one of which is the finite volume method. The mathematical model equation is built with a continuous, discrete point using the finite volume method [9]. The finite volume method is applied to solve fluid flow and aerodynamic problems that have irregular shapes, such as air, water, and blood flows. The finite volume method is considered an excellent discretization method used for numerical simulations because it has a very high accuracy value. The finite volume method computation time is significantly shorter than the finite element method [10]. In this study, the finite volume method was used to complete the numerical analysis of the narrowing of the arteries that causes ischemic heart disease.

Based on the description above, a numerical analysis study was carried out on the narrowing of blood vessels to determine the effect of velocity and pressure on narrowing. The research was carried out by modeling fluid flow in narrowed blood vessels, which was solved using the finite volume method. The mathematical model is a translation of mathematical ideas or ideas from a real problem that is generated [11]. Research conducted by Loppes et al., with the title "Analysis of finite element and finite volume methods for fluid-structure interaction simulation of blood flow in a real stenosed artery" simulates blood vessel flow in arteries that experience stenosis (narrowing) with two methods namely finite element method and finite volume method. The results obtained in the study of Lopes et al., with the title “Analysis of finite element and finite volume methods for fluid-structure interaction simulation of blood flow in a real stenosed artery” are that the finite volume method is more effective in completing the numerical analysis.

## 2. RESEARCH METHODS

The type of research carried out is a type of simulation research. Simulation is a model with a set of variables that display the main features of living systems [12]. Simulation Research has the goal of knowing the description through a simple system (model) which is carried out by way of simulation to get an effect close to the actual situation.




(a) (b)

**Figure 1. Arterial Stenosed (a) Blood Vessel Model; (b) Atherosclerosis**

**Figure 1** (a) is a blood vessel model taken from **[7]**, **Figure 1** (a) experiences 75% stenosis, in this research it was developed by simulating blood vessels that experience 20%, 35%, 50% stenosis, and 80%. **Figure 1** (b) shows how blood vessels experience atherosclerosis. The data obtained from **[7][13]**, then analyse using the finite volume method with SIMPLE discretization. The mathematical model used in this study is as follows **[7][13]**.

The continuity equation:

$$\rho\nabla.\vec{V} = 0 \tag{1}$$

The momentum equation:

$$\frac{\partial\vec{V}}{\partial t} + \rho(\vec{V}.\nabla)\vec{V} = -(\nabla p) + (\nabla\bar{\tau}) \tag{2}$$

Newtonian Quemada and Casson models for dynamic viscosity functions:

$$\mu(\|\dot{\gamma}\|) = \frac{{\mu_\infty}^2}{\|\dot{\gamma}\|} + \frac{2\mu_\infty N_\infty}{\sqrt{\|\dot{\gamma}\|}} + {N^2}_\infty \tag{3}$$

$\rho$ is the density of blood, $\vec{V}$ is the velocity field, is time, $p$ is pressure, $\bar{\tau}$ is stress tensor, $\mu(\|\dot{\gamma}\|)$ blood viscosity, $\mu_\infty$ is infinite shear rate viscosity, $\|\dot{\gamma}\|$ is rate of strain tensor, and $N_\infty$ constant.

The mathematical model of blood flow in this study was formed from the differential results of the mass continuity equation and the momentum equation. Mathematically, the continuity equation is used to calculate changes in blood flow velocity along blood vessels, and the momentum equation is used to calculate blood pressure. This study aims to determine the effect of blood flow speed and pressure on the narrowing of blood vessels, which causes ischemic heart disease.

The obtained mathematical model is solved using the finite volume method with SIMPLE discretization (Semi Implicit Method for Pressure Linked Equations). The SIMPLE algorithm is a semi-implicit iterative algorithm that is proven to be stable for Courant numbers much higher than one **[14]**. SIMPLE discretization relates pressure and blood flow velocity through the momentum equation and continuity equation. The SIMPLE algorithm solves these two equations iteratively to obtain a solution to the influence of pressure and velocity on the flow of blood vessels affected by atherosclerosis.

Fluid model analysis uses special techniques based on volume control by integrating volume control. The SIMPLE method differential difference is converted into a linear equation with the volume control method, which divides the calculation domain into small areas (control volume) and the center point as a node that represents the properties of the area **[15]**. The SIMPLE algorithm is an iterative pressure field algorithm that is obtained by iterating the initial guess on the actual value. Initial guesses of the velocity and pressure fields are used to solve the momentum equation. The pressure correction equation is solved by the mass continuity equation, after which the calculated pressure and velocity values are updated iteratively (under-relaxation) until the iteration reaches convergence **[7]**. Choosing the right under-relaxation value will produce a good iteration process. The iteration process will stop if the residue meets convergent criteria. The Finite Volume Method with the SIMPLE Algorithm has the following solution steps:

a. Initial guess $p^*, u^*, v^*$
b. STEP 1: Solve discretized momentum equations

$$a_{i,J}u^*_{i,J} = \sum a_{nb}u^*_{nb} + \left(p^*_{I-1,J} - p^*_{I,J}\right)A_{i,J} + b_{i,J} \quad (4)$$

$$a_{I,j}v^*_{I,j} = \sum a_{nb}v^*_{nb} + \left(p^*_{I,J-1} - p^*_{I,J}\right)A_{I,j} + b_{I,j} \quad (5)$$

c. STEP 2: Solve pressure correction equation

$$a_{I,J}p'_{I,J} = a_{I+1,J}p'_{I+1,J} + a_{I-1,J}p'_{I-1,J} + a_{I,J+1}p'_{I,J+1} + a_{I,J-1}p'_{I,J-1} + b'_{I,J} \quad (6)$$

d. STEP 3: Correct pressure dan velocities

$$u_{i,J} = u^*_{i,J} + d_{i,J}\left(p'_{I-1,J} - p'_{I,J}\right) \quad (7)$$

$$v_{I,j} = v^*_{I,j} + d_{I,j}\left(p'_{I,J-1} - p'_{I,J}\right) \quad (8)$$

$$p_{I,J} = p^*_{I,J} + p'_{I,J} \quad (9)$$

e. STEP 4: Solve all other discretized transport equations

$$a_{I,J}p'_{I,J} = a_{I+1,J}p'_{I+1,J} + a_{I-1,J}p'_{I-1,J} + a_{I,J+1}p'_{I,J+1} + a_{I,J-1}p'_{I,J-1} + b'_{I,J} \quad (10)$$

f. Convergence, if it doesn't converge then go back to step 1 by changing the initial guess.

The SIMPLE algorithm is a numerical procedure that is widely used in Computational Fluid Dynamics (CFD) to solve the basic equations governing fluid mechanics using a guessing procedure for calculating pressure on a staggered grid **[15]**. The mathematical model is simulated with the parameters of the thickness of the grease accumulation thickness of 80%, 65%, 50%, 35%, and 20% and the initial velocity of 0.2 m/s, 0.3 m/s, and 0.4 m/s in diameters of 9.343 mm, 7,862 mm, and 6.381 mm. The simulation is completed with the help of Matlab and Fluent software.

## 3. RESULTS AND DISCUSSION

Numerical analysis of blood flow in narrowed arteries causing ischemic heart disease was carried out by analyzing the results of mathematical model simulations with Matlab and Fluent. Based on the results of the literature study, the parameter variable data was obtained from the results of the journal study **[6]**. The variable data obtained is used to complete the SIMPLE method.

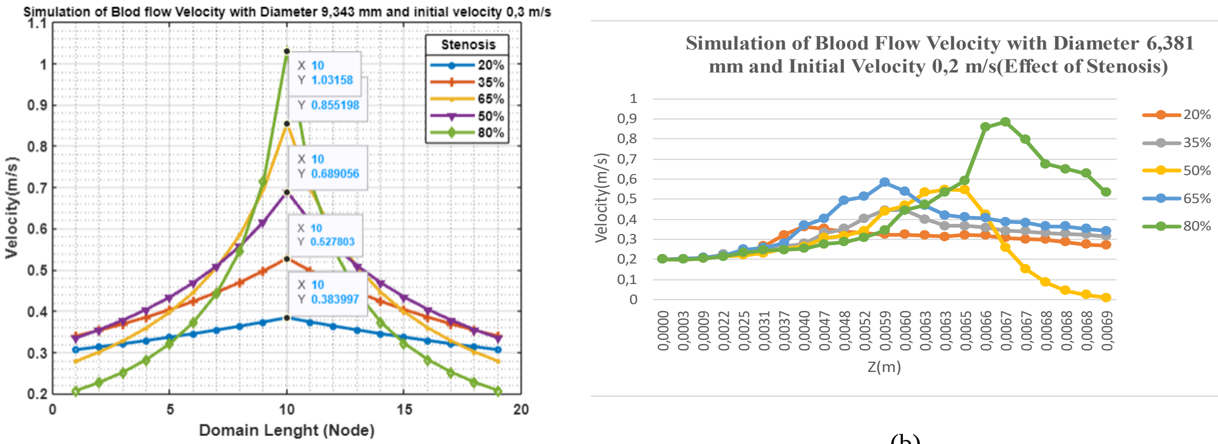
**Table 1. Data Parameter SIMPLE Method**

| Variable | Value | Description |
|---|---|---|
| $\rho$ | $1060\ kg/m^3$ | Blood density |
| $A_A$ | $6{,}856 \times 10^{-5} m^2$<br>$4{,}852 \times 10^{-5} m^2$<br>$3{,}1975 \times 10^{-5} m^2$ | Cross-sectional area at the inlet boundary for diameter 9.343 mm, 7,862 mm, and 6.381 mm |
| $A_J$ | $5{,}485 \times 10^{-5} m^2 - 7{,}994 \times 10^{-6} m^2$ | Cross-sectional area for stenosis 20%,35%,50%, 65%, 80% in diameter 9.343 mm, 7,862 mm, and 6.381 mm |
| $A_T$ | $6{,}856 \times 10^{-5} m^2$<br>$4{,}852 \times 10^{-5} m^2$<br>$3{,}1975 \times 10^{-5} m^2$ | Cross-sectional area at the outlet boundary for diameter 9.343 mm, 7,862 mm, and 6.381 mm |
| $p_0$ | 12300 Pa | Initial pressure |
| $m$ | $0{,}02\ kg/s - 0{,}03\ kg/s$ | mass flow |
| $\mu(\|\dot{\gamma}\|)$ | $0{,}003145\ Pa.s$ | Blood viscosity |

The problem studied is the analysis of the effect of diameter, stenosis, and initial velocity on velocity and pressure in the narrowing of blood vessels. The diameters used in this study were 9.343 mm, 7,862 mm, and 6.381 mm. The size of the narrowing or stenosis studied is 80%, 65%, 50%, 35%, and 20% of normal blood vessels. The higher the percentage of stenosis, the more severe the atherosclerosis. The initial velocity used is 0.2 m/s, 0.3 m/s, and 0.4 m/s.

### 3.1 Analysis of Velocity Simulation Results

#### a. Graph of the Effects of Stenosis

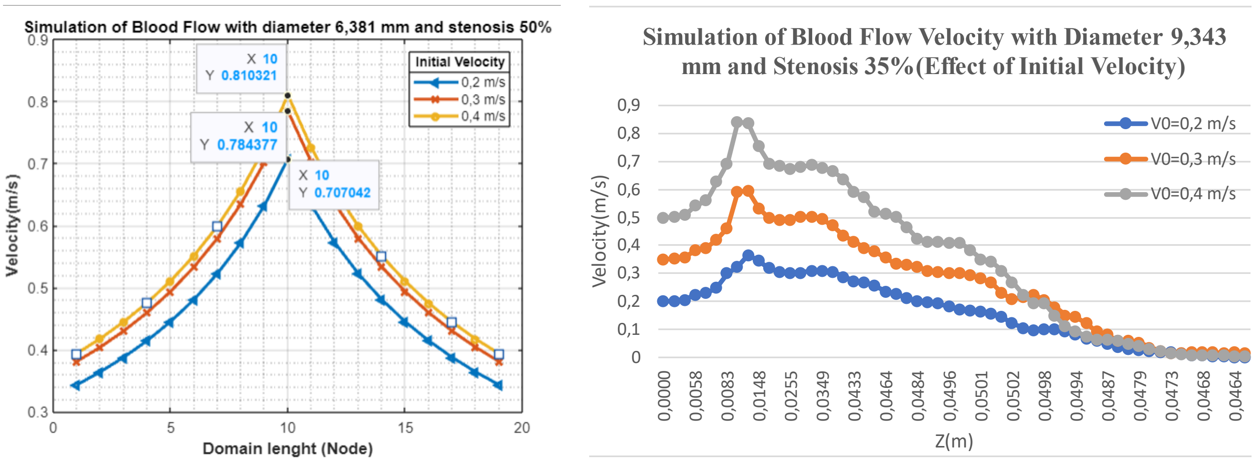



(a) (b)

**Figure 2. Graph of the effect of stenosis (20%,35%,50%,65%,80%) with $(a)\ d = 9,343\ mm\ and\ v_0 = 0,3\ m/s\ \ (b)\ d = 6,381\ mm\ and\ v_0 = 0,2\ m/s$**

**Figure 2** is the result of a simulation of the effect of blood flow velocity on the size of the stenosis. The graph in **Figure 2** experiences an increase when heading for the narrowing area and decreases again after passing through the narrowing area. The top of the chart is at the midpoint which is the center of narrowing. **Figure 2** (a) shows that the highest blood flow velocity is at node 10, with the highest blood flow velocity at 80% stenosis. The highest velocitys of 20%, 35%, 50%, 65% and 80% stenosis were 0.383997 m/s, 0.527803 m/s, 0.689056 m/s, 0.855194 m/s, 1.03158 m/s. **Figure 2** (b) shows a graph with 80% stenosis having a higher point so it can be said that the greater the narrowing of the blood vessels, the greater the flow velocity results.

#### b. Graph of the Effects of Initial Velocity




(a) (b)

**Figure 3. Graph of the Effects of Initial Velocity (0,2 $m/s$; 0,3; 0,4 $m/s$) with $(a)\ d = 6,381\ mm$ and stenosis 50% (b) $d = 9,343\ mm$ and stenosis 35%**

**Figure 3** is the result of a simulation of the effect of blood flow velocity on the initial velocity. Simulations were performed on different diameters and stenosis with two initial velocities, namely 0.2 m/s, 0.3 m/s, and 0.4 m/s. The initial velocity simulation results from **Figure 3** (a) show that the velocity of blood flow with an initial velocity of 0.4 m/s has a greater flow velocity than the graph with an initial velocity of 0.2 m/s and 0.3 m/s. the highest velocity values for each initial velocity are 0.707042 m/s, 0.784377 m/s, and 0.810321 m/s. **Figure 3** (b) shows a graph with an initial velocity of 0.4 m/s which has the highest value, so it can be concluded that the greater the initial velocity, the greater the resulting flow velocity.

### c. Graph of the Effects of Diameter

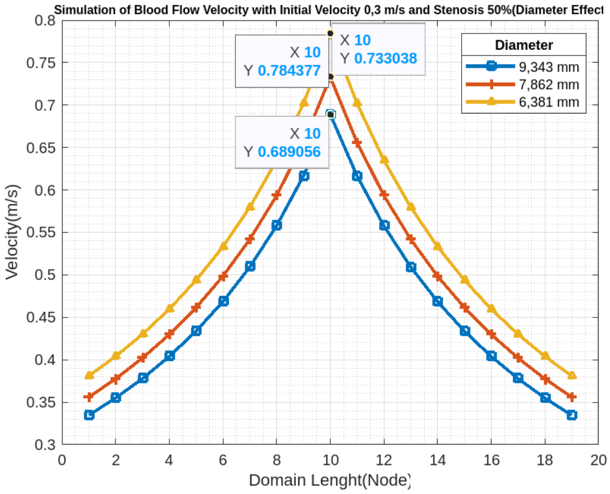
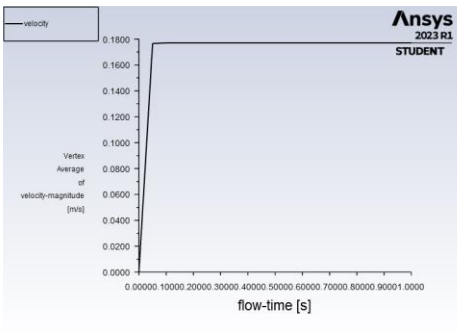
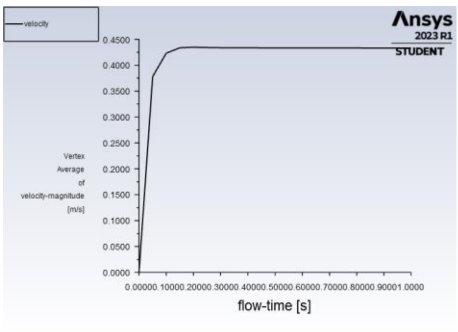



**Figure 4. Graph of the Effects of Diameter ($9,343\ mm$;7,862 $mm$; $6,381\ mm$) with Stenosis 50% and $v_0 = 0,3\ m/s$**

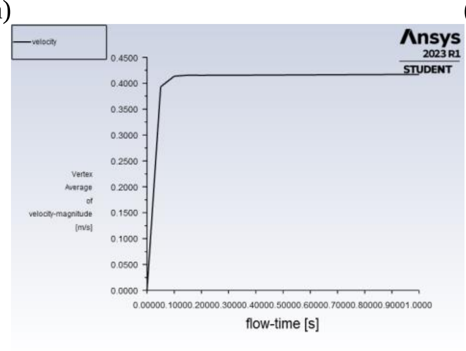
**Figure 4** shows a graph of the effect of blood flow velocity on diameter. The simulation was carried out at different initial velocities and stenosis with three diameters, namely 9,343 mm, 7,862 mm, and 6,381 mm. The results of the analysis in **Figure 4** show that the blood flow velocity chart with a diameter of 6,381 mm has a greater flow velocity than the graph with a diameter of 9,343 mm, and 7,862 mm. The highest velocity value for each diameter is 0.689056 m/s, 0.733038 m/s, 0.784377 m/s, so it can be concluded that the smaller the diameter, the greater the resulting flow velocity.




(a)




(b)



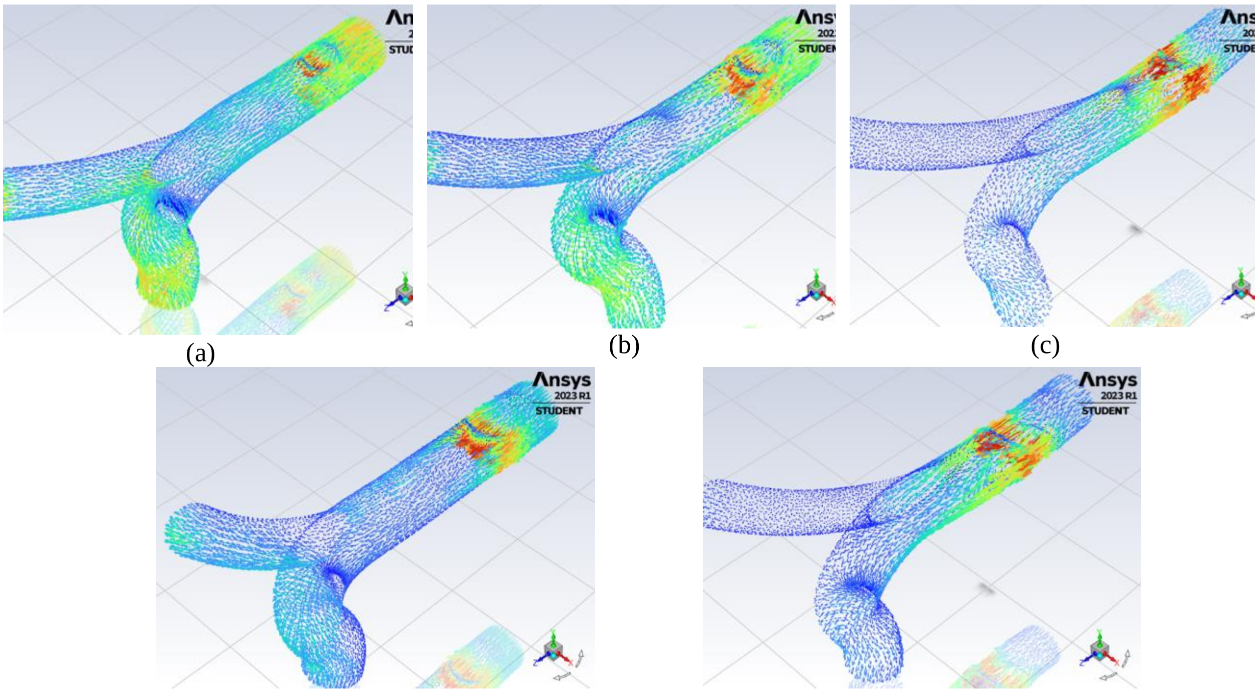

(c)

**Figure 5. Blood Flow Velocity Simulation with Stenosis 50% and Initial Velocity 0,3 m/s to (a) $d = 9,343\ mm$ (b) $d = 7,862\ mm$ (c) $d = 6,381\ mm$**

**Figure 5** is the result of a simulation of the effect of velocity on time, the results show that there is a change in flow velocity when heading for narrowing, for a diameter of 9.343 mm, 7.862 mm, and 6.381 flow velocity going up or towards narrowing at 0.1 s.

## d. Fluent Simulation

### 1) Simulation of Blood Flow Velocity to Determine the Effect of Stenosis

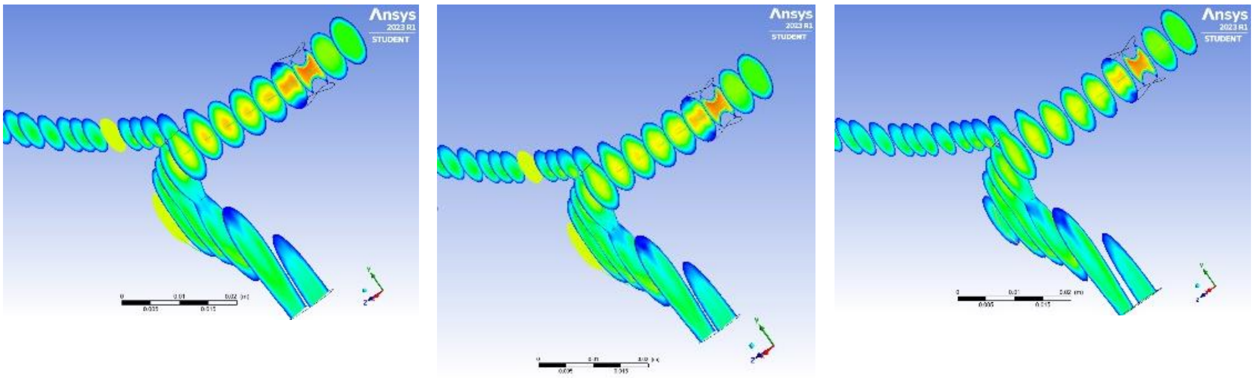


(a) (b) (c) (d) (e)

**Figure 6. Blood Flow Velocity Simulation with $d = 9,343\ mm\ and\ v_0 = 0,4m/s$ to (a) Stenosis 20% (b) Stenosis 35% (c) Stenosis 50% (d) Stenosis 65% (e) Stenosis 80%**

**Figure 6** is the result of a simulation of blood flow velocity at a diameter of 9.343 mm, an initial velocity of 0.4 m/s with three stenosis namely 20%,35%, 50%, 65%, and 80%. The five simulations show a change in the color contour of the stenosis area. The color contour resulting from stenosis of 20%,35%,50%, 65%, and 80% higher or more is dominated by red, with the red contour representing the highest velocity value. Based on the highest velocity value, the highest velocity results were obtained from 20%,35%,50%, 65%, and 80% stenosis, namely 0.4282 m/s, 0.5381 m/s, 0.7286 m/s, 0.9096 m/s, 1.1157 m/s. The simulation that produces the greatest blood flow velocity is the simulation with 80% stenosis as shown in **Figure 6** (c). It can be concluded that the greater the stenosis or narrowing in diameter, the greater the resulting blood flow velocity.

### 2) Simulation of Blood Flow Velocity to Determine the Effect of Initial Velocity

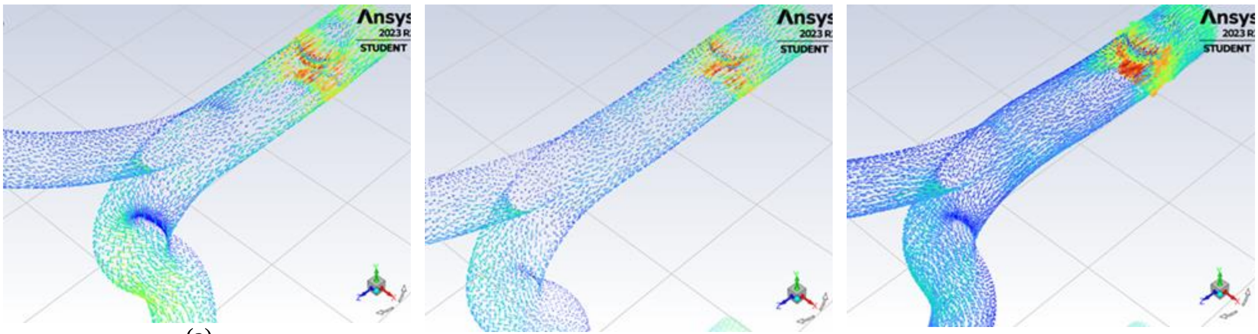


(a) (b) (c)

**Figure 7. Blood Flow Velocity Simulation with $d = 9,343\ mm$ and Stenosis 35% to (a) $v_0 = 0,2\ m/s$ (b) $v_0 = 0,3$ (c) $v_0 = 0,4\ m/s$**

**Figure 7** is a simulation of the velocity of blood flow at a diameter of 9.343 mm and 35% stenosis with three initial velocities, namely 0.2 m/s, 0.3 m/s, and 0.4 m/s. The highest velocity value of each different initial velocity, namely 0.2 m/s, 0.3 m/s, and 0.4 m/s is 0.4666 m/s, 0.5278 m/s, 0.5381 m/s. Simulation with an initial velocity of 0.4 m/s has a greater flow velocity compared to simulations with an initial velocity of 0.2 m/s and 0.3m/s, so it can be concluded that the greater the initial velocity, the greater the blood flow.

### 3) Simulation of Blood Flow Velocity to Determine the Effect of Diameter




(a) (b) (c)

**Figure 8** **Blood Flow Velocity Simulation with Stenosis 35% and $v_0 = 0,3m/s$ to (a) $d = 9,343\ mm$ (b) $d = 7,862\ mm$ (c) $d = 6,381\ mm$**

**Figure 8** is the result of a simulation of blood flow velocity at 35% stenosis and an initial velocity of 0.3 m/s with three different diameters, namely 9,343 mm, 7,862 mm, and 6,381 mm. The highest velocity values for each diameter of 9.343 mm, 7.862 mm, and 6.381 mm are 0.5278 m/s, 0.5506 m/s, and 0.5758 m/s. The simulation with a diameter of 6,381 mm has a greater flow velocity compared to the simulation with a diameter of 9,343 mm and 7,862 mm, so it can be concluded that the smaller the diameter, the greater the velocity of blood flow.

## 3.2 Analysis of Pressure Simulation Results

### a. Graph of the Effects of Stenosis

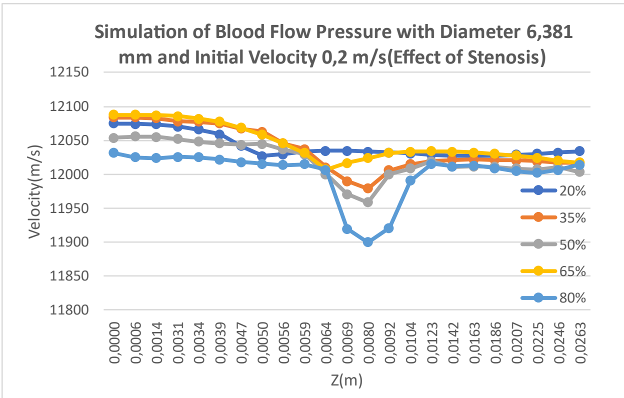



**Figure 9** **Simulation of Blood Flow Pressure with Diameter 6,381 mm and Initial Velocity 0,2 m/s (Effect of Stenosis)**

**Figure 9** shows a graph of the effect of blood flow pressure on stenosis. The simulation was carried out at different stenosis, namely 20%, 35%, 50%, 65%, and 80%. The results of the analysis in **Figure 9** show that the graph with decreased blood flow pressure and 80% stenosis has a smaller flow pressure than the graph with 65%, 50%, 35%, and 20% stenosis. The lowest pressure values for each stenosis are 11999 Pa, 11978 Pa, 11958 Pa, 11984 Pa, and 11899 Pa, so it can be concluded that the greater the stenosis, the smaller the resulting flow pressure.

**b. Graph of the Effects of Initial Velocity**

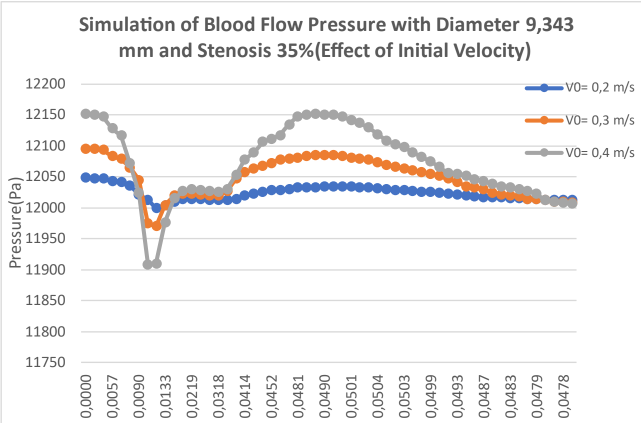



**Figure 10 Simulation of Blood Flow Pressure with Diameter 9,343 mm and Stenosis 35% (Effect of Initial Velocity)**

**Figure 10** shows a graph of the effect of blood flow pressure on initial velocity. The simulation was carried out at different initial velocities, namely 0.2 m/s, 0.3 m/s, and 0.4 m/s. The results of the analysis in **Figure 10** show that the graph of decreasing blood flow pressure and initial velocity of 0.4 m/s has a lower flow pressure than the graph with initial velocity of 0.3 m/s and 0.2 m/s. The lowest pressure values for each stenosis are 11999 Pa, 11970 Pa, and 11909 Pa, so it can be concluded that the greater the initial velocity, the smaller the resulting flow pressure.

**c. Graph of the Effects of Diameter**

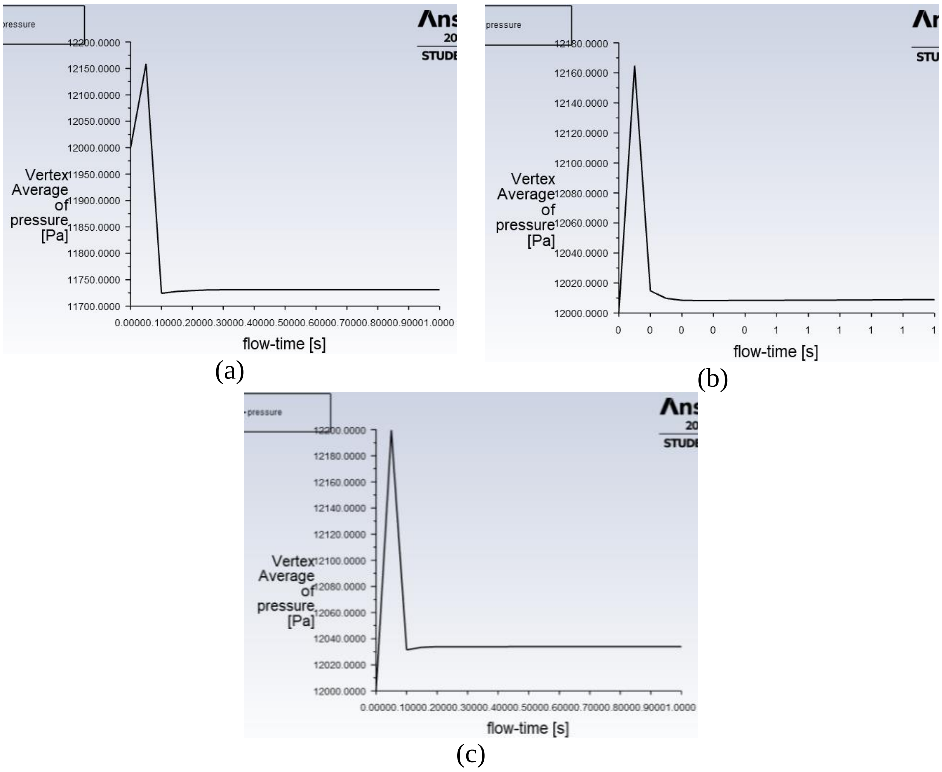
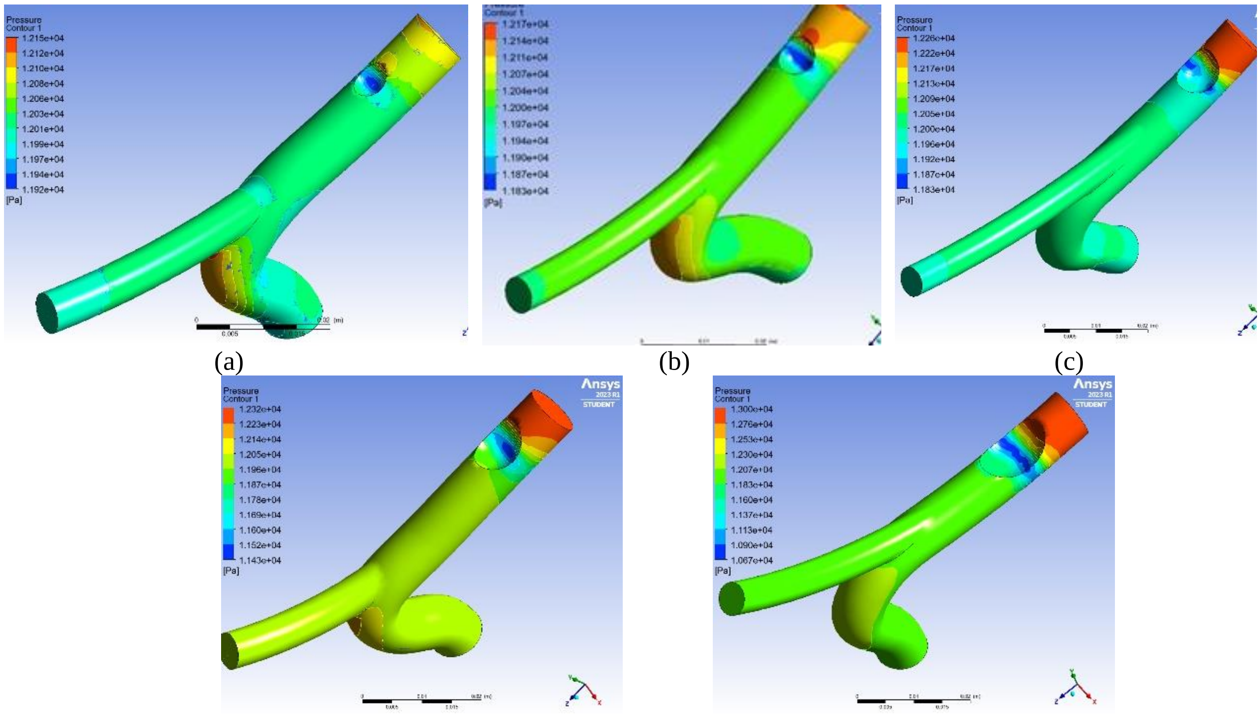



**Figure 11 Simulation of Blood Flow Pressure with Diameter 6,381 mm and Initial Velocity 0,2 m/s to (a) $d = 9,343\ mm$ (b) $d = 7,862\ mm$ (c) $d = 6,381\ mm$**

**Figure 11** is the result of a simulation of the effect of pressure on time, the results show that there is a change in flow pressure on the way to narrowing, for a diameter of 9.343 mm, 7.862 mm and 6.381 the flow pressure goes down or towards narrowing at 0.1 s.

## d. Fluent Simulation

### a) Simulation of Blood Flow Pressure to Determine the Effect of Stenosis



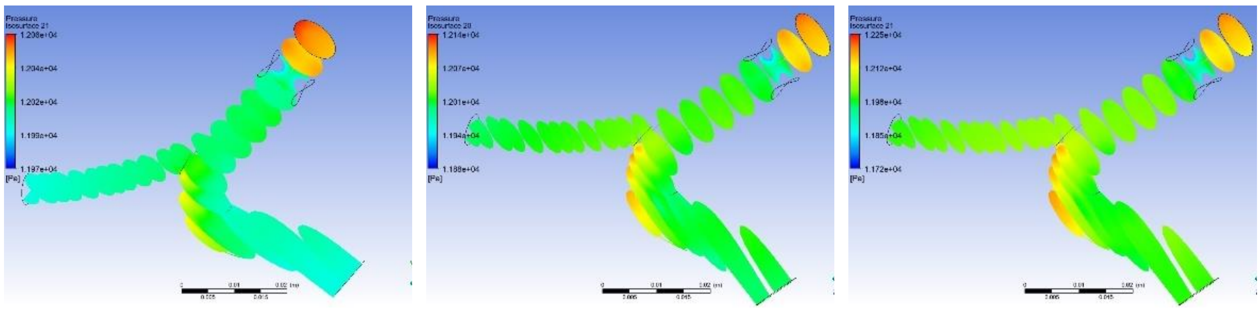
(a) (b) (c)

(d) (e)

**Figure 12 Blood Pressure Simulation with $d = 9,343\ mm\ and\ v_0 = 0.4\ m/s$ to (a) Stenosis 20% (b) Stenosis 35% (c) Stenosis 50% (d) Stenosis 65% (e) Stenosis 80%**

Figure 12 is the result of a blood flow pressure simulation at a diameter of 9.343 mm, an initial velocity of 0.2 m/s with three stenosis namely 20%, 35%, 50%, 65%, and 80%. The five simulations show the change in the contour of the stenosis color area. The color contour resulting from stenosis of 20%, 35%, 50%, 65%, and 80% is lower or more dominated by blue, the blue contour represents the lowest pressure value. Based on the interval pressure values, the lowest pressure results were obtained from stenosis of 20%, 35%, 50%, 65%, and 80%, namely 11920 Pa, 11830 Pa, 11831 Pa, 11430 Pa, and 10670 Pa. Figure 12(c) produces the smallest blood flow pressure in a narrowed area of 80%, it can be interpreted that the greater the stenosis or narrowing, the smaller the pressure on blood flow.

### b) Simulation of Blood Flow Velocity to Determine the Effect of Initial Velocity

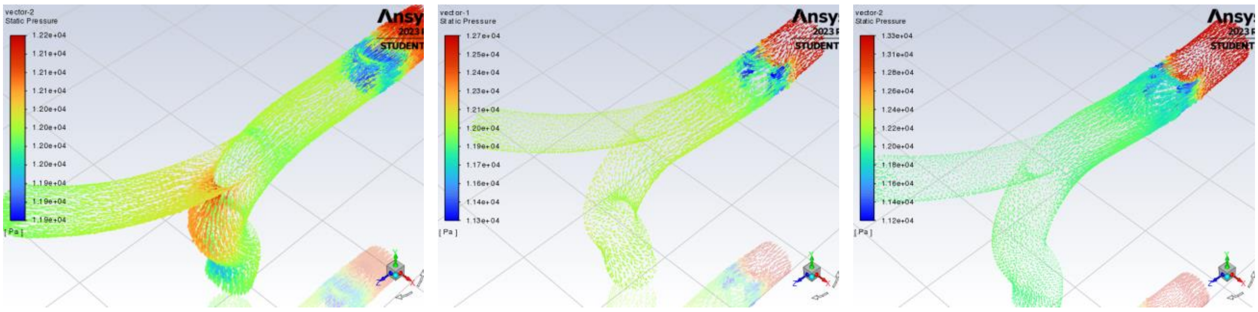


(a) (b) (c)

**Figure 13 Blood Flow Pressure Simulation with $d = 9,343\ mm$ and Stenosis 35% to (a) $v_0 = 0,2\ m/s$ (b) $v_0 = 0,3 m/s$ (c) $v_0 = 0,4\ m/s$**

Figure 13 is the result of a blood flow pressure simulation at a diameter of 9.343 mm, 35% stenosis with three initial velocities namely 0.2 m/s, 0.3 m/s, and 0.4 m/s. the third simulation shows the change in the contour of the stenosis color area. Based on the value of the lowest pressure interval generated by the simulation with initial velocities of 0.2 m/s, 0.3 m/s, and 0.4 m/s, namely velocity of 11970 Pa, 11880 Pa, and 11720 Pa, the smaller the pressure generated. The conclusion obtained is that the greater the initial velocity, the smaller the pressure generated.

### c) Simulation of Blood Flow Velocity to Determine the Effect of Diameter



(a) (b) (c)

**Figure 14 Blood Flow Pressure Simulation with Stenosis 50% and $v_0 = 0,3m/s$ to (a) $d = 9,343\ mm$ (b) $d = 7,862\ mm$ (c) $d = 6,381\ mm$**

**Figure 14** is the result of a blood flow pressure simulation with 50% stenosis, an initial velocity of 0.3 m/s, and three diameters, namely 9.343 mm, 7.862 mm, and 6.381 mm. The lowest pressure values based on diameters of 9,343 mm, 7,862 mm and 6,381 mm are 11,900 Pa, 11,300 Pa, 11,200 Pa. The simulation with a diameter of 6.381 mm has a smaller flow pressure compared to the simulation with a diameter of 9.343 mm and 7.862 mm, so it can be concluded that the smaller the diameter, the smaller the pressure generated.

**Table 2. Potential for Ischemic Heart Disease**

| Diameter | Initial Velocity | Stenosis | Maximum Velocity ($m/s$) |
|---|---|---|---|
| 9,343 $mm$ | 0.2 $m/s$ | 20% | 0.3817 |
| | | 35% | 0.4666 |
| | | 50% | 0.6427 |
| | | 65% | 0.7559 |
| | | 80% | 0.9236 |
| | 0.3 $m/s$ | 20% | 0.3840 |
| | | 35% | 0.5278 |
| | | 50% | 0.6891 |
| | | 65% | 0.8552 |
| | | 80% | 1.0316 |
| | 0.4 $m/s$ | 20% | 0.4282 |
| | | 35% | 0.5381 |
| | | 50% | 0.7256 |
| | | 65% | 0.9096 |
| | | 80% | 1.1157 |
| 7,862 mm | 0.2 m/s | 20% | 0.3942 |
| | | 35% | 0.5168 |
| | | 50% | 0.6970 |
| | | 65% | 0.7775 |
| | | 80% | 0.9499 |
| | 0.3 m/s | 20% | 0.4308 |
| | | 35% | 0.5506 |
| | | 50% | 0.7330 |
| | | 65% | 0.9166 |
| | | 80% | 1.0348 |
| | 0.4 m/s | 20% | 0.4589 |
| | | 35% | 0.6033 |
| | | 50% | 0.8020 |
| | | 65% | 0.9813 |
| | | 80% | 1.1185 |
| 6,381 $mm$ | 0.2 m/s | 20% | 0.4369 |
| | | 35% | 0.5577 |
| | | 50% | 0.7070 |
| | | 65% | 0.7672 |
| | | 80% | 1.0221 |

| Diameter | Initial Velocity | Stenosis | Maximum Velocity $(m/s)$ |
|---|---|---|---|
| | 0.3 m/s | 20% | 0.4782 |
| | | 35% | 0.5758 |
| | | 50% | 0.7844 |
| | | 65% | 0.7858 |
| | | 80% | 1.0385 |
| | 0.4 m/s | 20% | 0.4862 |
| | | 35% | 0.6441 |
| | | 50% | 0.8103 |
| | | 65% | 1.0584 |
| | | 80% | 1.2114 |

**Table 2** states that the simulation results that do not have the potential for ischemic heart disease are blood vessel simulations with (diameter; initial velocity; stenosis): (9.343 mm; 0.2 m/s; 20%), (9.343 mm; 0.3 m/s). ; 20%),(9,343 mm;0.4 m/s; 20%), (7,862 mm;0.2 m/s; 20%),(7,862 mm;0.3 m/s; 20%), and (6.381 mm; 0.2 m/s; 20%). The simulation is said to be prone to ischemic heart disease, if the highest speed value is more than the normal highest speed, namely 0.45 m/s.

## 4. CONCLUSIONS

Based on the results and discussion obtained by speed simulation results with the influence of diameter, stenosis, and initial velocity, it is concluded that the smaller the diameter, the greater the stenosis, and the greater the initial velocity, the faster the resulting flow, the greater the flow. The pressure simulation results show that the smaller the diameter, the greater the stenosis, and the greater the initial velocity, the smaller the resulting pressure value.

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