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MATHEMATICAL ANALYSIS OF BLOCKAGE OCCURRED IN THE ARTYERY DUE TO BLOOD TRANSPORTATION

Afshan Parveen Dehraj

PhD Scholar, Department of Mathematics & Assistant Professor, Govt Boys Degree College Kandiaro

Dr. Zahid Hussain Shaikh

Assistant Professor, Sukkur IBA University. shaikhzahid@iba-suk.edu.pk

Hisam uddin Shaikh

Professor & Chairman, Department of Mathematics, Shah Abdul Latif University Khairpur

ABSTRACT

In recent years, mathematical modelling, especially using the partial differential equations (PDEs), has proved to be a valuable tool for studying phenomena in science and engineering. In the present study, the flow behavior of blood in an artery with quadrilateral stenosis is examined, which is a typical case occurring in cardiovascular diseases. Some health-related issues, like high blood pressure, elevated cholesterol, diabetes, smoking, overweight, and various other factors have made arterial blockage a growing problem. For analyzing this problem, the governing equations for transport of the flow were applied along with the continuity equation describing the fluid flow behavior in a rectangular channel with an embedded quadrilateral obstruction in the channel. Various mesh configurations were used to improve the numerical accuracy such as coarse, normal, fine and extra-fine meshes. It analysed the flow behaviour, velocity distribution, pressure change, streamline patterns and vortex formation around the blockage in the case of inertia and power-law index. The results indicated that the changes in inertia and the power-law index markedly affect the flow characteristics. Vortices were observed near the corners of the blockage, and their size increased with variations in flow parameters. In addition, it is found that vortices gradually increased as the inertia increased as the power-law index increases; however, as the power-law index decreases with increasing inertia, vortices around the blockage were more pronounced and larger. These results may aid in the understanding of blood flow characteristics in blocked arteries and help make mathematical models of heart disease and other circulatory conditions.

Keywords: Arterial Blockage, Blood Flow, Mathematical Modeling, Partial Differential Equations, Computational Fluid Dynamics, Power-Law Fluid, Vortex Formation, Hemodynamics.

Introduction

In recent years, the use of Computational Fluid Dynamics (CFD) (computational simulation of the flow of fluid masses) has become ubiquitous in many aspects of science, biomedical and engineering research. In biomedical engineering, CFD plays an important role in understanding the behavior of blood flow in the human circulatory system, especially when it comes to arterial blockage due to blood clots. The CFD results, which are obtained by

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numerical simulations, allow the visualization and analysis of flow features in the arteries and veins as well as in cardiovascular structures. A partial differential equation (PDE) based mathematical model is generally used for such problems, particularly the Navier–Stokes equations describing the motion and transport of fluid flows. With these equations and the continuity equation, all the dynamics of the fluids can be studied under various physiological conditions (Kamangar et al., 2017; Memon & Shaikh, 2019). Modelling in real-world problems through PDEs is an important part of solving those problems, especially in the biosciences. They provide a crucial insight into the role that blood clots play in the flow of blood in arteries and veins, which can sometimes cause blood flow to block, and consequently contribute to associated health problems. The essence of fluid transport is the conservation of momentum expressed in momentum equations relating physical quantities like velocity and pressure. These parameters, when studied, can illuminate up flow patterns and explore how obstructions affect flow in a biological conduit. Different obstacle geometries are available to model blockages and its effect on blood circulation.

The equations for fluid motions are nonlinear, and an analytical solution, which is often hard to get due to the complexity of this motion is used as a interpreting technique. Therefore, numerical solutions must be used for modeling the fluid behavior and for controlling the many iterations needed to get to a more accurate solution. It is done with the help of CFD software packages that help define the geometry, specify the physical properties, select the CFD numerical method and compute an approximate solution to the problem efficiently (Yiannis et al., 2007; Bozdar, 2021). COMSOL Multiphysics is used in the present study to study the characteristics of blood flow under steady state steady flow conditions. The velocity and pressure distributions are calculated using the 2D momentum equations. The flow behavior is illustrated by streamlines and pressure contours with respect to the fluid continuity by neglecting the variation of the fluid inertia. The computational domain is the rectangular channel with a fixed quadrilateral obstacle on the lower wall. A non-Newtonian blood flow model is used to represent the blood clot accumulation in arterial stenosis. It is assumed that the walls of the channel satisfy the 'no-slip' boundary condition, which means that the vessel walls are stationary. In the model developed, is simulated using COMSOL Multiphysics, varying the Reynolds numbers are applied to check the roles of flow inertia on velocity and pressure distributions throughout the domain.

MOTIVATION

Mathematical concept of differential equations is largely applicable in the vast area of medical sciences now a days. Especially, in this technological world, the demand of the

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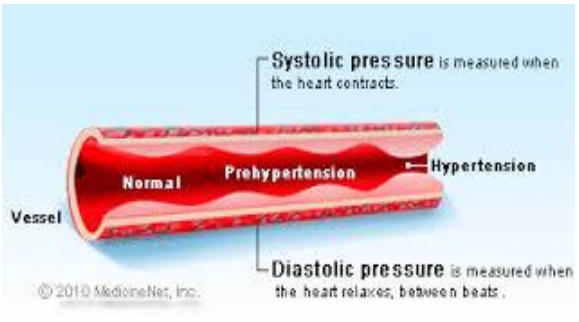
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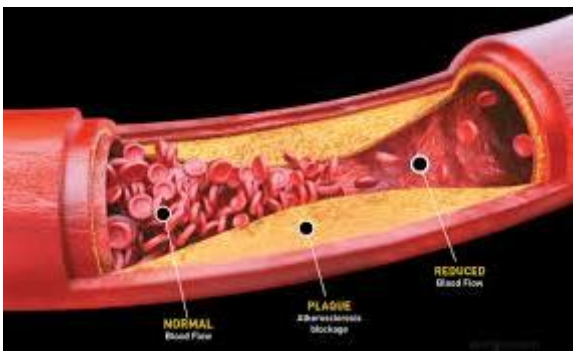
prediction concept through the computational visualizations are more increasing due to grow the large diseases in the blood flows via the human organs of the bodies, like stenosis arteries found because of the blockage problem, fat and attach diseases due to develop the blood clots in the veins and arteries. Mathematical equations especially partial differential equations play a most pivotal role in the vast areas of the engineering also due to develop the concept of computational fluid dynamics fields.

AIMS AND OBJECTIVES

1. To demonstrate the physical parameters as pressure and velocity numerically by the changing the quantitative values of viscosity of fluids through the power law model.
2. To need converge and most accurate results of the physical parameters by the validate the flow patterns of the physical parameters to the other flow pattern behave of research scholars as given in literature.
3. To grow the steady state solutions of the pressure and velocity and examined that how blood flow transported through stenosis arteries with availability of the blockage disease due to heavy tension and many more fat occurred.

PROJECTED FIELD AND CONSISTENT LITERATURE





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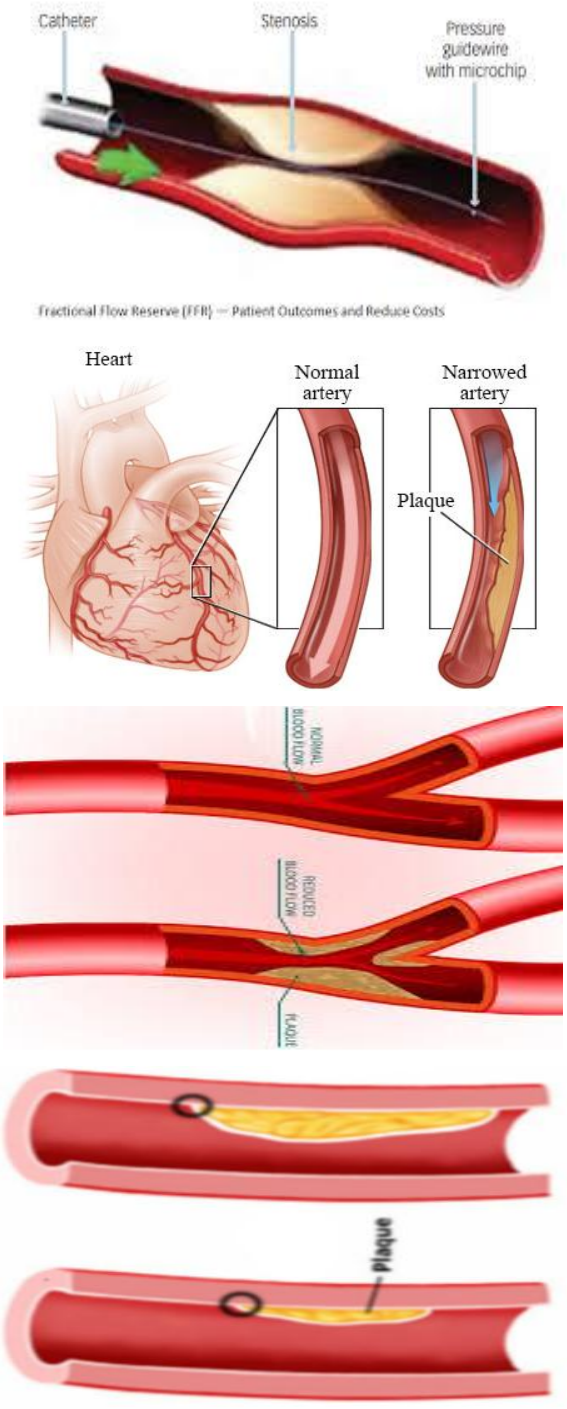


Figure-1: ***Proposed applications of research domain, especially, blood flow through arteries patterns with different blockages***

PROJECTED FIELD

The projected field about a problem is fluid dynamics and preferred here to examine behave of blood flow through arteries with blockage in different shapes. Highly enhanced the

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demand of numerical prediction study of transportation of fluids through closed domain due to severe need of visualization the diseases in human organs especially, arteries, veins and mussels problems. Computational technology benefitted in large to easily understand the fluid flow visualization and how benefitted trough designing the research domains relates to vast number of engineering and industrial applications.

CONSISTENT LITERATURE

Gilwoo Choi, et al. (2015) has studied in article the hemodynamic force acting on plaque and to investigate its relationship with lesion geometry. It was explored that Coronary plaque break happens when plaque stress surpasses plaque strength. Plaque force examination for human coronary sores was performed to explore hemodynamic powers in genuine patient information and afterward glorified stenosis models were dissected to affirm the discoveries from patient data. Coronary plaque crack is a basic occasion that sets off the inception of intense coronary disorder. A computational liquid element was applied to eight one patients or 114 lesions from coronary processed tomography angiography. The axial plaque stress was registered by separating the pivotal part of hemodynamic pressure following up on stenotic lesions, and the axial lesion unevenness was evaluated by the luminal sweep change over length of radius gradient. Sores were divided into upstream-prevailing and downstream predominant injuries as per the Radius Gradient. Clinical utilization of these hemodynamic and mathematical lists might be useful to evaluate the future gamble of plaque crack and to decide the treatment system for patients with coronary vein sickness.

Absaar Ul Jabbar et al. (2012) has explained in his article that Stroke is a medical emergency that occurs when the blood supply to any part of brain is disrupted, resulting in deprived oxygen supply to brain tissues. Researcher examined the impact of plaque shape on blood course through the carotid vein prompting plaque development and break. For this reason three plaque shapes were thought of; trapezoidal, curved and three-sided with same base and tallness estimations, along these lines forcing same region decrease of thirty percentages in vein. A carotid course model in light of measurable investigation called tuning fork model was built. Different Computational Fluid Dynamics reproductions were performed to break down the impact of various plaque shapes on blood stream. Examination of recreation results for the three plaque shapes showed that trapezoidal shape has more impact on blood stream delivering most elevated stream speeds and divider shear stresses. This reality shows that plaques like trapezoidal shape might be more inclined to crack. It was likewise observed that trapezoidal plaques made most minimal divider shear pressure district downstream of the plaque which might expand the greasy stores around there. The

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review proposes that patients with such plaques ought to be considered for a medical procedure at a beginning phase of atherosclerosis to keep away from cardiovascular intricacies.

Kamangar, et al. (2017) has explained in their article "The Influence of Geometrical Shapes of Stenosis on the Blood Flow in Stenosed Artery" that the growth of atherosclerotic plaque on the inner side of the wall of arteries causes the myocardial infarction which is one of the most extensive diseases in human being causing millions of deaths around the globe each year. The current work was completed to examine the blood stream conduct and the seriousness of blockage made in the blood vessel section due the various calculations, for example, curved, trapezium and three-sided states of stenosis. The review was led regarding different sizes of stenosis range from 70% to 90% region blockage of the blood vessel blood stream. The review was done mathematically with the assistance of advance computational liquid powerful programming. It was observed that the state of the stenosis assumes a significant part in general tension drop across the blockage district of conduit. The most significant level of tension drop was noticed for trapezoidal state of stenosis followed by curved and afterward by three-sided formed stenosis. The divider shear pressure across the stenosis is extraordinary for trapezoidal shape followed by three-sided and circular stenosis for same blockage region in the conduit.

Akbar, N S. (2014) has studied in her article that the Arteries which are basically considered as a living tissues need a supply of metabolites including oxygen and removal of waste products. In this study researcher have explained about the blood stream investigation of Prandtl liquid model in tightened stenosed supply routes. The administering conditions for considered model are introduced in tube shaped facilitates. Bother arrangements are developed for the speed, impedance obstruction, divider shear pressure and shearing pressure at the stenosis throat. Consideration has been mostly engaged to the examination of implanted boundaries in joining, separating and non-tightened circumstances. Smooths out have been plotted toward the finish of the article for thought about courses. It is seen that because of increment in Prandtl liquid boundaries, the stenosis shape and greatest tallness of the stenosis the speed profile diminishes.

Yiannis, et al. (2007) has studied in his article that the entire coronary tree is presented to the atherogonic impact of the fundamental gamble factors, atherosclerotic injuries from a particular blood vessel area where low and oscillatory endothellal shear pressure occur. Low endothellal shear pressure ESS is a strong neighborhood boost for atherogenesis, arrangement, and movement of an early atherosclerotic plaque and separation

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to high-take a chance with plaque. Varieties in the neighborhood intravascular hemodynamic climate over the long run lead to dynamic collaborations with the blood vessel divider that could either intensify or improve the movement of an early plaque. An in vivo comprehension of plaque qualities, nearby ESS, and vascular redesigning reaction could prompt an improved comprehension of the pathobiology of coronary corridor illness and give open doors to exceptionally specific preplanned neighborhood intercessions.

Qiu, et al. (2017) has contemplated in article that Atherosclerotic inclined burst plaque is mostly limited in the district of the entry to the stenosis with high shear pressure and the reasons are generally obscure. Our speculation is that such a dissemination of cells in atherosclerotic plaque might rely upon the angiogenesis. Silastic collars actuated areas of high shear pressure in the upstream stream and low shear pressure in the downstream stream in carotid corridors. Contrasted and the low shear pressure area, plaques in the high shear pressure locale showed more intraplaque discharging, less collagen and higher apoptotic paces of vascular smooth muscle cells; endothelial cells in the high shear pressure district were described with honesty and high endothelial nitric oxide synthase articulation. The quantity of intraplaque micro vessels is exceptionally high in the high shear pressure district and the micro vessels in the plaque show ECs were unusual, with layer blebs, intracytoplasmic vacuoles and leukocyte invasion. Our present review uncovers that the uprightness of the endothelium and the weakness of atherosclerotic plaques are all the while restricted in high shear pressure districts, and we give proof to the initial occasion when micro vessels in the intraplaque perhaps answerable for break inclined plaque development in the high shear pressure area.

Jaryl Ng, et al. (2017) has examined in his article that Local hemodynamic powers are notable to balance atherosclerotic advancement, which stays one of the biggest reasons for death around the world. A percutaneous coronary mediation with stent implantation reestablishes blood stream to the downstream myocardium and is just restricted by stent disappointment brought about by restenosis, stent apoplexy, or neo atherosclerosis. Aggregate proof has shown that nearby hemodynamic powers influence restenosis and the platelet initiation process, tweaking the pathophysiological systems that lead to stent disappointment. This article initial covers the pathophysiological systems through which divider shear pressure directs blood vessel illness development/neointima multiplication and the job of shear rate on stent apoplexy. Therefore, the article surveys the current proof on the ramifications of stent plan on the neighborhood hemodynamic powers, and how stent/framework development can impact nearby stream, subsequently influencing the

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gamble of unfavorable occasions.

Erica, D. C. (2016) has examined in their study that cardiovascular diseases are the leading cause of death in developed countries. Among them, atherosclerosis is described by plaque deposition at the blood vessel divider. Atherosclerosis injuries ordinarily happen at explicit locales with complex vascular calculations that are bifurcations and arches. The hemodynamic examinations were directed utilizing ideal models with reasonable physical qualities and a patient-explicit left coronary artery, separated from a modernized hub tomography. The mathematical and exploratory speed fields permit the perception of optional streams, like helical streams and vortexes, described by low speeds and low divider shear pressure zones. The Wall Shear Stress dispersion and stream designs were assessed in solid and stenotic models. For that, it was fostered a mathematical technique for making three-layered unpredictable stenosis. This technique depends on the development of stenosis through a dispersion model, in view of recently recognized regions as being inclined to their appearance, which is a low WSS region. The outcomes showed that remarkable mathematical attributes of the corridor begin stenosis with explicit shapes that standard the hemodynamics. The impact of supply route mathematical impacts uncovered that the non-planarity has a beneficial outcome in helicity lessening the low WSS locales and thusly the atherosclerosis improvement. Mathematical aftereffects of pulsatile blood stream expecting a non-Newtonian conduct, support the non-planarity impact in neighborhood hemodynamics.

Thondapu et al., (2017) has reviewed in their article that Coronary plaque break is the most widely recognized reason for vessel apoplexy and intense coronary disorder. The exact early identification of plaques inclined to crack might permit forthcoming, safeguard treatment; be that as it may, current symptomatic techniques stay lacking to identify these sores. Laid out imaging highlights demonstrating weakness don't give sufficient particularity for indicative break. Likewise, despite the fact that trial and computational investigations have highlighted the significance of endothelial shear pressure in moderate atherosclerosis, the capacity of shear pressure to anticipate plaque movement stays gradual. Alongside test and clinical investigations, propels in computational techniques and coronary imaging have added to a more profound comprehension of plaque inception, advancement, and burst. High-goal picture based computational pressure examinations will probably assume a huge part in distinguishing both as of now known and novel markers, along these lines further developing identification of future offender lesions.This audit analyzes late advances in picture based computational displaying that have explained potential systems of plaque movement and crack, and possibly original highlights of plaques generally inclined to

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indicative burst. With additional review and clinical approval, these markers and methods might work on the particularity of future offender plaque recognition.

Salmi, K. and Thun, V. (2018) have reviewed in their study that in 2015, cardiovascular diseases caused the demise of 17.7 million individuals - 31 % of all passing's worldwide - making it deadlier than some other reason. As this happens in the carotid conduits and the plaque material is liable to powers brought about by pulse and stream, the pressure that happens inside could prompt break of the material. The cracked particles could then make a trip to the mind and cause a stroke. To distinguish and forestall these strokes, figured tomography and ultrasound examines are utilized today. One more approach to dissecting the plaques weakness of crack is with the assistance of biomechanics. In view of the math and material organization of the plaque, and utilizing a limited component investigation, the burdens and hazard of break can be assessed. This proposition investigates how unique plaque calculations, with center around plaque length and cross-section region inclusion, influence the subsequent pressure in the material. The models were imported to the limited component program. This investigation discovered that the pressure in the plaque tissue shows a top at 50-60% plaque inclusion of the cross-sectional region, with the end goal that the gamble of break is by all accounts the most noteworthy at this area coverage.

Nash Allan-Rahill et al. (2018) has inspected in their article that Shear pressure delicate nanoparticles are a promising new field for drug conveyance. This original technique might permit the designated arrival of medications like statins or vasodilators to areas of high shear in the circulatory system, as happens close to a stenosis. Nonetheless, these investigations have just inspected stream qualities close to plaques and have not considered the development of nanoparticles inside these streams or the complicated course of medication dissemination from the molecule's shear area into the plaque. The review laid out here considers the whole cycle from nanoparticle passage upstream of the plaque through drug dispersion into the tissue. The aftereffects of these recreations showed that the plaque development at 35% stenosis causes adequate shear pressure to break the nanoparticles, delivering the medication into the blood. Most medication, whenever it was let out of the nanoparticles, was found to diffuse into the downstream 50% of the plaque. This computational review has made up for a significant shortcoming in the group of examination on this clever medication conveyance strategy. It has checked the burst of nanoparticles under 35% stenotic circumstances while showing ensuing medication dispersion designs, which recommends that this strategy may not be appropriate for

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focusing on drug conveyance to blood vessel plaques. However, shear pressure touchy nanoparticle drug conveyance may not in a perfect world objective medication to blood vessel stenoses, this clever strategy might demonstrate helpful for displaying tumorigenic frameworks, where liquid shear pressure has been displayed to influence malignant growth cell motility.

Sumi, et al. (2010) has investigated in their article that Plaque disintegration is a reason for atherothrombosis that specially happens on smooth muscle cell and proteoglycan-rich rather than lipid-rich plaques. In any case, its basic instruments stay obscure. The Objective of study was to decide if upset blood stream incites erosive injury and clots development on SMC-rich neointima. Anyway Methods was Three weeks after expand injury, SMC-rich neointima with expanded tissue factor action created in bunny femoral veins that were restricted with a vascular occlude to upset blood stream after stenosis. Neointimal injury and blood clot arrangement were surveyed at 15, 30, and 180 min after the vascular limiting. Toward the finish of Results was Endothelial separation, platelet bond and neointimal cell apoptosis became clear at the post-stenotic districts of every femoral course within fifteen minute of narrowing. Mural thrombi made out of platelet and fibrin created after half hour, and afterward occlusive thrombi were produced in three out of five vessels after three hour. The indistinguishable vascular limiting of typical femoral courses likewise actuated endothelial separation with little platelet thrombi at post stenotic areas, however fibrin and occlusive thrombi didn't create. Computational reenactment examination demonstrated that oscillatory shear pressure adds to the advancement of erosive harm to the neointima. At the ends of these outcomes recommend that upset post-stenotic blood stream can prompt erosive injury in SMC-rich plaques and advance clots arrangement that outcomes in vascular occasions.

Understanding of Mathematical Equations in the Field of Fluid Dynamics and Corresponding Discretization Through Package

Introduction

In this chapter, discuss the theory and background of basic structural equations to solve a stable state for speed and pressure and then calculate fluid flow through an extended channel with and without unsafe content. Imagine a trend that leads to initial and non-slip limit terms. In fact, the governing equations that appear here are nonlinear nature of equations based on conservation laws such as mass protection, speed law, energy protection law. In these laws of conservations, can explained the fluid motions like liquid and gases with their role of viscosity through power law model (Sheikh, etc., 2012, 2013 & 2016)

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Mathematically, these protective laws are illuminated by linear differential equations called continuity equations and nonlinear equations called momentum equations. These equations are useful for clarifying the link between mass and mass transportation, as well as the large scale of transportation mass so that the mass entering through these inlets and the large amount of mass spread through domain outlets differ. Our study of interest aims to highlight the trend of fluid flow in channels using the Mass and Momentum conservation laws. Here, the focus is only on the flow of invincible, laminar, Newtonian and non-Newtonian fluids, testing a rectangular channel with two-dimensional deep anus. A parabolic velocity profile is applied to inlet, zero pressure data and non-slip state at the outlet are applied to the walls of the investigated channel to detect the direction altogether in the flow directional and pressure area of interest.

Understanding of Mathematical equations by the fluid motions

The equations generally, well known in the area of fluid phenomena through the two basic conservative laws to transport the fluids with continuous justification through the channel with quadrilateral baffles/blockages at the walls of the channel.

Mass conservative laws

This law is only applicable in the fluid dynamics equations are examined the fluid moved through domain is continuous or in other words. Can explain that the divergent free vector. Through equation, the law explained as continuity equation in general form as;

$$\nabla \cdot \mathbf{u} = 0 \tag{3.1}$$

The domain is particularly, shortened as two – dimensional and based upon the vector field as u = (u, v) with respect to x and y. This equation can be provided as under;

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{3.2}$$

Momentum conservative laws

This momentum conservative law is basically a differentiable form of the most well-known Newton's law of motion and also, known as extension in the heat equation with transient and accelerate term. Theory of this conservative law is based upon the force is directly proportion to the acceleration. Now the dependent unknown is a liquid fluids with two dimensions x and y and it can be expended in general form as for each fluids;

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} - \rho (\boldsymbol{u} \cdot \nabla) \boldsymbol{u} = \mu \nabla^2 \boldsymbol{u} - \nabla p + F \tag{3.3}$$

Material Time derivative	Convection term	Diffusion term	Pressure term	Extra Material term

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Where ∇^2 shows the Laplacian operator.

$$\nabla^2 = \left(\frac{\partial^2}{\partial x^2} i + \frac{\partial^2}{\partial y^2} j + \frac{\partial^2}{\partial z^2} \right) \tag{3.4}$$

Equation (3.3) is expressed for every type of fluids in general form and consisted large number of fluid properties and various unknowns. Therefore, for easy computations of different unknowns, equation can be shifted towards non – dimension form with introduce the fluid inertia or known as Reynolds number that can be expressed as,

$$\frac{\partial \boldsymbol{u}}{\partial t} = \frac{1}{Re} \nabla^2 \boldsymbol{u} - (\boldsymbol{u} . \nabla) \boldsymbol{u} - \nabla p \tag{3.5}$$

$$Re = \frac{\text{Inertial forces}}{\text{Viscous forces}} = \frac{\rho u_c L_c}{\nu} \tag{3.6}$$

The research study consisted on the rectangular channel with fitted quadrilateral baffle that limited towards two – dimensions. Therefore, equation (3.5) can be shifted into two – dimension as

$$\frac{\partial u}{\partial t} = \frac{1}{Re} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - u \left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \right) - \frac{\partial p}{\partial x} \tag{3.7a}$$

$$\frac{\partial v}{\partial t} = \frac{1}{Re} \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - v \left(\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} \right) - \frac{\partial p}{\partial y} \tag{3.7b}$$

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Initial and Boundary Conditions

These conditions consisted into initial for time and boundary conditions for space terms and it is necessary for the computational steady state solution of (3.7). The conditions for

$$\nabla . u = 0 \qquad u(x, 0) = u_0 \text{ and } p(x, 0) = p_{max} \tag{3.8}$$

Due to domain as rectangular channel with quadrilateral baffle that consisted into various zones in the domain. Upper and lower boundaries with quadrilateral baffles are known as stationary walls so adopted no – slip boundary conditions as (u = v = 0). In the domain, right side wall is called as outlet of the fluids passed where fixed zero pressure because of free fluid moved and left side of the domain is called as inlet of the channel where imposed parabolic velocity profile with maxim pressure as given below;

$$u = V_{mean} \times 6 \times y \times (1 - y) \tag{3.9}$$

Introduction to COMSOL Multiphysics

This is a multi-disciplinary computational tool that provided a complete lab work of problem designing relates either science, engineering or many type of industries without any severe labor work and saved huge cost of amount. Though, relates with the fluid flow phenomena. Heat transfer, chemical reactions, food processing, electrical circuits and complete structure of electric wiring system, building structures and many more (www.comsol.com).

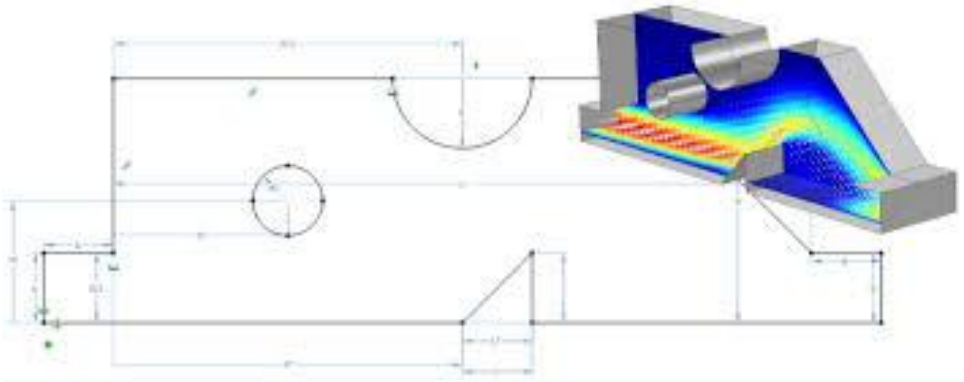


Figure: Pipe Structure designing through CFD module

The package provided by two graduate students of Sweden University names as Littmark and Saeidi for their research work in 1986 and successfully completed to develop complete and unique platform for resolve the all real life complex problems through Mathematical equations, physical concepts and approximate solution through control iterative work by computational process. Now a days, this package benefitted completely to resolve any simple as well as complex non – linear Mathematical equation based problem through iterative process with good convergence and stabilize number of methods. This package

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COMSOL MultiPhysics provided complete finite element discretization process through compete matrix system like stiffness matrices, sparse matrix, dense matrix and many more. After that, many type of direct and iterative solve be imposed in a system to approximate final converge solution of unknowns. Similarly, easily plotted the all unkowns through fluid flow patterns, heat transfer, reactions, mixing and electric suppliers. CFD package is not limited but the concern data file can be imported from any other package and also it can export their data file for further clarification through Mathematical code like Matlab (Khan, et al. (2020), Memon and Shaikh (2019)).

Galerkin Least Square Finite Element Scheme

Galerkin Least Square Finite Element is an emerging and robust technique used by COMSOL Multiphysics 5.0. In the field of computational fluid dynamics, technique plays a vital role in achieving conflicting and reliable solutions to the Nevier-Stoke equation. This technique involves minimizing the residual normality near the finite element of the shape function. In the field of fluid dynamics, this is the only Galerkin method that has been applied, which initiates a number of constraints, such as the terms of convection and diffusion and the assessment of oscillation weakness as if the equations in the transport phenomena themselves. Is the use of the connected operator? To discover a stable state solution for the flow of adhesive and non-viscous fluids through simple and complex geometries, these are finite element schemes that play a dynamic role in the field of fluid dynamics. While solving Navier-Stokes equations in terms of fluid pressure and velocity, there are various finite element schemes such as Taylor-Galerkin approach, upwind scheme, stabilization technique, separately.

Galerkin method for obtaining a numerical solution of the Navier-Stokes equation is difficult in two ways: first, the unconnected phenomena of invincibility due to the inclusion of convection terms, and second, the matrix derived from weak formulation is positive. And there is no harmony. . For some reason, gas elimination (direct method) will be applied instead of repetitive methods for system convergence solution. A similar system can be used to solve the penalty method for estimating the pressure due to fluctuations in the continuity equation. There are two major ups and downs of the penalty method, first, it takes a long time to assemble a solution taking into account the small cost of pressure, and second, the term pressure, which is a significant quantity in engineering sciences, must be brought to the fore. Remove oscillations due to pressure matrix which may be in poor condition. Another useful method is to solve the Navier-Stokes equation to achieve limited differences, speed and pressure, which takes considerable time and memory when applied through

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programming code.

The Least Square Formulation for Solution of Pressure and Velocity

The main interest here to formulate the fluid flow transport through rectangular channel with fitted quadrilateral baffle/blockage and focused on the 2nd order momentum equation combined with continuity equation that are provided as under;

$$\nabla . \mathbf{u} = 0 \tag{3.10}$$

$$\frac{1}{\mathrm{Re}} grad^2 . \mathbf{u} - \mathrm{grad}\, P - \mathbf{u} . grad \mathbf{u} - f = 0 \tag{3.11}$$

Here, Re is imposed in the momentum equation for non – dimension the system for quick computation of main fluid flow parameters as pressure (p) and velocity field (u, v).

$$\mathrm{Re} = \frac{\rho U_{avg} L}{\mu} \tag{3.12}$$

As preferred here the COMSOL MultiPhysics simulations with selection of least square Galerkin approach so needs the first order system due to limitation of least square residuals. Therefore, chosen extra parameter a vorticity (w) from the vector calculus that called as curl of the velocity. Through this vorticity, the equation (3.11) can be easily shifted towards the first order system that defined as;

$$w = \nabla \times u \tag{3.13}$$

Though, adopted the vorticity (3.13) into the (3.11 and 3.12), the following system became as below;

$$\nabla . \boldsymbol{u} = 0 \tag{3.14a}$$

$$\frac{1}{\mathrm{Re}} \nabla^2 . \times \boldsymbol{w} - \nabla P - \boldsymbol{u} . \nabla \boldsymbol{u} - f = 0 \tag{3.14b}$$

$$\boldsymbol{w} - \nabla \times \boldsymbol{u} = 0 \tag{3.14c}$$

The system (3.14) is known as complete system of equations for all type of fluids movement and no particular dimensions. As problem preferred here two – dimensions that is rectangular channel with quadrilateral baffles. Therefore, the system (3.14) can be provided towards two – dimension as;

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial x} = 0 \tag{3.15a}$$

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial x} + \frac{\partial P}{\partial x} + \frac{1}{\mathrm{Re}} \frac{\partial w}{\partial y} = f_x \tag{3.15b}$$

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$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + \frac{\partial P}{\partial y} - \frac{1}{Re}\frac{\partial w}{\partial x} = f_y \qquad (3.15c)$$

$$w + \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = 0 \qquad (3.15d)$$

For finite element discretisation process with least square residuals, needed the system (3.15) into the required matrix system as below;

$$A_1 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ u & 0 & 1 & 0 \\ 0 & u & 0 & \frac{1}{Re} \\ 0 & -1 & 0 & 0 \end{pmatrix} \quad A_2 = \begin{pmatrix} 0 & 1 & 0 & 0 \\ v & 0 & 0 & \frac{1}{Re} \\ 0 & v & 1 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

$$A = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad f = \begin{pmatrix} 0 \\ f_x \\ f_y \\ 0 \end{pmatrix} \quad \mathbf{u} = \begin{pmatrix} u \\ v \\ p \\ w \end{pmatrix}$$

Now, resolve the all matrices through the least square residual process to form a unique stiffness matrix (k)

$$L\psi_j = \psi_{j,x} A_1 + \psi_{j,y} A_2 + \psi_{j,z} A_3 + \psi_j A \qquad (3.16)$$

$$K_{e_1} = \int_{\Omega_e} < L\psi_1, L\psi_2, L\psi_3 >^T . < L\psi_1, L\psi_2, L\psi_3 > d\Omega_e \qquad (3.17)$$

$$K_{ij} = \int_{\Omega e_1} L\psi_i * L\psi_j \, d\Omega_{e_1} \qquad (3.18)$$

$$i=1,2,3 \; j=1,2,3$$

The complete stiffness matrix is developed as below;

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$$K = \begin{matrix} u_1 & v_1 & p_1 & w_1 \end{matrix} \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} \ldots \lambda_{1m} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} & \lambda_{24} \ldots \lambda_{2m} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} & \lambda_{34} \ldots \lambda_{3m} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ \lambda_{m1} & \lambda_{m2} & \lambda_{m3} & \lambda_{m4} \ldots \lambda_{nm} \end{bmatrix} \quad (3.19)$$

Now the matrix K can be converted toward the system of linear equations through matrix form as K**u** = f.

$$\lambda_{11}u_1 + \lambda_{12}v_1 + \lambda_{13}p_1 + \lambda_{14}w_1 + \ldots . \lambda_{1m}u_m + \lambda_{1m}v_m + \lambda_{1m}p_m + \lambda_{1m}w_m = 0$$
$$\lambda_{21}u_1 + \lambda_{22}v_1 + \lambda_{23}p_1 + \lambda_{24}w_1 + \ldots . \lambda_{2m}u_m + \lambda_{2m}v_m + \lambda_{2m}p_m + \lambda_{2m}w_m = 0$$
$$\lambda_{31}u_1 + \lambda_{22}v_1 + \lambda_{33}p_1 + \lambda_{34}w_1 + \ldots . \lambda_{3m}u_m + \lambda_{3m}v_m + \lambda_{3m}p_m + \lambda_{3m}w_m = 0$$
.
.
.
$$\lambda_{m1}u_1 + \lambda_{m2}v_1 + \lambda_{m3}p_1 + \lambda_{m4}w_1 + \ldots . \lambda_{mm}u_m + \lambda_{mm}v_m + \lambda_{mm}p_m + \lambda_{mm}w_m = 0 \quad (3.20)$$

Here needed the most appropriate and converge tool iterative method to compute final fluid flow parameters individually that known as Newton's algorithm.

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Newton's Scheme

This is very oldest iterative method that is familiar with the name of Newton's Raphson method for the computation of single unknowns from the linear and non – linear equations and highly proved that the method is most accurate and 2nd order convergence rate in computations. The formation is provided as under;

$$X^{n+1} = X^n + \frac{f(X^n)}{f'(X^n)} \qquad Where\ n = 0, 1, 2..... \qquad (3.21)$$

But here the system of linear equations are involved with couple of different unknown consisted in the above given system. So needed the further extension in the formulation (3.21).

Here introduced the Jacobean matrix system for system of linear equations that can be computed jointly as defined below the form of Newton's scheme as;

$$U^{n+1} = U^n + J^{-1} * U^n \qquad (3.22)$$

Though, J^{-1} provided the Jacobean matrix system that can be consisted as al deferential coefficients of each unknowns like velocity field (u, v), pressure (p) and further vorticity (w);

$$J(h_1, h_2, h_3, ,, h_m) = \begin{bmatrix} \frac{\partial h_1}{\partial u_1} & \frac{\partial h_1}{\partial v_1} & \frac{\partial h_1}{\partial p_1} & \frac{\partial h_1}{\partial w_1} \cdots & \frac{\partial h_1}{\partial u_m} & \frac{\partial h_1}{\partial v_m} & \frac{\partial h_1}{\partial p_m} & \frac{\partial h_1}{\partial w_m} \\ \frac{\partial h_2}{\partial u_1} & \frac{\partial h_2}{\partial v_1} & \frac{\partial h_2}{\partial p_1} & \frac{\partial h_2}{\partial w_1} \cdots & \frac{\partial h_2}{\partial u_m} & \frac{\partial h_2}{\partial v_m} & \frac{\partial h_2}{\partial p_m} & \frac{\partial h_2}{\partial w_m} \\ \frac{\partial h_3}{\partial u_1} & \frac{\partial h_3}{\partial v_1} & \frac{\partial h_3}{\partial p_1} & \frac{\partial h_3}{\partial w_1} \cdots & \frac{\partial h_3}{\partial u_m} & \frac{\partial h_3}{\partial v_m} & \frac{\partial h_3}{\partial p_m} & \frac{\partial h_3}{\partial u_m} \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ \frac{\partial h_m}{\partial u_1} & \frac{\partial h_m}{\partial v_1} & \frac{\partial h_m}{\partial p_1} & \frac{\partial h_m}{\partial w_1} \cdots & \frac{\partial h_m}{\partial u_m} & \frac{\partial h_m}{\partial v_m} & \frac{\partial h_m}{\partial p_m} & \frac{\partial h_m}{\partial w_m} \end{bmatrix} \qquad (3.23)$$

Here required the particular number of initial guessing for each parameter for the computational process for each unknowns of (3.22) as u_0, v_0, p_o and w_o and also, required value of the Reynolds number due to non – dimensions as selected Re = 01 for initiate the computational and iterative process of 3.22. Further check the accuracy after completing 1st iteration. If accurate then stop otherwise, solution counted as initial guessing and changed the Reynolds number as Re = 10 for further process of 3.22. This computational process will be repeated till the required termination level will obtained for good accurate and converge result.

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Influence of Blockage Occurred in the Artery Due to Blood Transportation with Power Law Index Rate

INTRODUCTION

The blockage occurred in the arteries and veins are common bio sciences problems due to large number of diseases increased now a days just as heavy blood pressure due to wrong diets, short sleeps and rough tensions. Also, blockage occurred due to severe incidents occurred and stored the blood in particular regions in the human body and due to cholesterol problems, the blockage occurred in the arteries of the human body. The blockage appearance can be visualized through medical science reports and heavy camera based reports like MRI or CT scan. Due to increase the demands of the computer technology with implementation of mathematical equation, easily understand the blood flow phenomena with appearance of the different shapes of the blockage stored in the corners of the arteries and veins of the human body. New computational packages provided the visualization images of the blood flow patterns in very low cost and saved the heavy labor work in experiments (Jabbar, et al. (2012), Chao, et al. (2015) and Kamangar, et al. (2017)).

The CFD predictions with statistical measurements was carried out by the Chao, et al. (2015) and examined with the limited tests of angiography treatment of common patients through the stress focused in the arteries. The artery was shaped with like the rectangular channel included the some curved solid shape known as hindrances during the blood flow and occurred the blockage and caused heavy pain in the arteries/geometry. Due to hindrances, to fix the symmetric boundary conditions at the lower wall of the domain and tested eighty one patients who had large stress in the arteries because of the occurrence of the blood clots in the artery. These CFD predicted results was compared with the clinical reports through the topography treatment applied on the patients that is generally called as angiography. Due to large process of treatment and very low time simulations, easily understand the nature of the problem and visualized the blood clots available in the lower boundary of the artery and successfully applied the proper treatment of large number of patients after visualized the locations of the blood clot occurred due to heavy stress in the arteries.

Consequently, another scholar Kamangar, et al. (2017) was demonstrated the CFD approaches with selection of the finite element method and adopted the simulation process via the computational package ANSYS CFX. Different shapes hindrance visualized in the stenosis arteries so adopted the triangular and trapezium shapes with change in the ratios

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(70 to 90). After applying the clinical treatment and CFD simulations, it was clarified that the pressure drop diffused immediately because of the size of the blood clot known as hindrances or blockages and proved that the CFD simulations was better than the clinical heavy reports due to save large time and heavy cost of the treatment. Mostly, pressure drop diffused in the availability of trapezium blockages in the artery (Stenosis) and same level of pressure drop occurred in the shape of triangular and elliptic type blockage in the stenosis arteries. Also, observed the large velocity profile due to grow the ratio of the blockage in the stenosis arteries. Many Mathematicians with the collection of the CFD tools was contributed in the biosciences and predicted large number of results of the different diseases available in the real life and heavy cost required to understand the disease due to clinical test and reports (Qiu et al. (2017), Jabbar et al. (2012) and Chatzizisis et al. (2007).

In this chapter, predicted the different behave of fluids through the blockage occurred in the channel like artery by applying the momentum transport equation joined with divergence free vector velocity. Finite element discretization adopted to model the fluid flow phenomena with varying viscosity of the fluids through power law models at different index rate and observed the inertia rate from lower to upper. Newton's iterative solver is preferred for the each parameter as velocity and pressure after adopted the discretization process and further plotted the flow patterns and pressure isobars on different index rates. The independent study of mesh analysis and flow patterns process are adopted here for good comparison the predicted results computed through CFD package COMSOL MultiPhysics.

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PROBLEM DEFINTION

The problem preferred here to rectangular channel with stationary walls includes the quadrilateral stationary baffles with fixed no –slip boundary conditions at all walls except inlet and outlet of the domain. Whereas, fitted parabolic velocity profile at the inlet of the domain with maximum fixed pressure. On the other hand, fitted zero pressure at the outlet of the domain due to free fluid flows. The length and height of the domain is given in the domain as figure – 4.1. After that, tested the different discretization process through mesh analysis to improve the accuracy in the numerical predictions as given complete statistics of the mesh independent study of the domain.

Statistics	Extra coarse	Normal Mesh	Finer Mesh
Triangular elements	1309	6710	29466
Quadrilateral elements	336	816	2176
Edge elements	195	456	1176
Vertex elements	14	14	14
Number of elements	1645	7526	31642
Minimum element quality	0.1175	0.1191	0.1185
Average element quality	0.7601	0.862	0.899
Element area ratio	0.003331	0.004131	0.001955
Maximum element growth	4.33	4.283	4.235
Average growth rate	1.63	1.3200	1.277
Number of degrees of freedom solved for:	3267	13200	52494
Solution time:	2 s	2s	6S
Physical memory:	902 MB	918MB	1.12GB
Virtual memory:	1020 MB	1032MB	1.22GB

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Error Estimate	10-06

Table – 4.1: Statistics of the mesh Structure

DISCUSSIONS ABOUT THE PREDICTED RESULTS

The discussion focused here about the numerical predictions of different fluids behaved through rectangular channel with fitted quadrilateral baffles/blockage and predictions computed through the numerical procedure via finite element discretization with newton's iterative solver and all predictions measured through the CFD package COMSOL MultiPhysics. Here discussed different behave of fluid flows though changed the power law index rate to examine non – Newtonian fluids and also influences of fluid inertia are discussed in detail.

Figure – 4.1 provided the complete profile of the problem selection to visualize the fluid flows with baffles/blockage and detailed boundary conditions are fixed at every zone of the domain. Similarly, figure – 4.2 provided the detail study of the mesh structure of the domain and adopted completely the independent study via presented the extra coarser mesh, normal mesh and finer mesh for final accurate results. Furthermore, for comparison of the numerical results, figure – 4.3 provided the flow pattern trends for the comparison purpose and proved that the COMSOL results via newton's algorithm are best choice for the fluid flow visualizations. After that, complete other fluid flow results are provided as below;

Influence of the Reynolds number on the change of viscosity fluids at lower than unity (Newtonian fluids)

Streamline flow pattern trend is discussed here for the non – Newtonian fluids by fitting the power law model in the momentum transport equation limited for liquid flows whereas density remained constant. Here fixed power law index rate ($n < 1$) with different measurements of the fluid inertia (Reynolds number) from lower to higher rates. Figure – 4.4 (a – d) provided the streamline flow paths through rectangular channel with fitted quadrilateral baffles/blockage at Reynolds number 01 to 750. At lowest Reynolds number (Re = 01), no any eddies found in the right corner of the quadrilateral baffles in the channel but the small eddies found in the right corners of the upper and lower quadrilateral baffles/blockages at Reynolds number (Re = 250). Due to increase the Reynolds number up to 750, eddies found in corners of the baffles with increasing in size. Figure – 4.4(e –h) provided the same flow patterns with enhancement in eddies appearance in the corners of the baffles/blockage. Due to fixed quadrilateral blockage, appeared small eddy in the channel and very slowly enhanced the size of eddy because of the growing value of Reynolds

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number and these eddies appeared symmetric patterns due to laminar flows. Consequently, figure – 4.4 (i – j) provide the flow pattern observed the different size eddies in the lower and upper corner of the blockage. Due to high value of the Reynolds number (fluid inertia), large size eddies appeared and very quickly filled the region of the corner of the blockage in the artery or channel. Also, completely filled the region with large eddies in the channel up to the 2000 inertia.

Influence of the Reynolds number on the change of viscosity fluids at higher than unity (Newtonian fluids)

Here discussed another fluid behave though flow patterns at fixed power law index rate that higher than the Newtonian fluids like thick fluids transportations. Figure –4.5(a – d) provided the flow patterns of the shear thickening fluids (n =1.1), eddies are highly effected due to thick fluids moved in the artery/channel, Eddies are completed vanished at lower and medium positions of the Reynolds number. But very tinny eddies are observed at Reynolds number (750) with very small enhancement in eddies observed at the corners of the quadrilateral baffles. In the other hand, figure – 4.5 (e – h) provide the other flow patterns with found some change in eddies found in the corners of the baffles. Here due to increase the Reynolds number (fluid inertia), the very small change in eddies observed as increasing size eddies appeared in the corners of the blockage in the artery. Consequently, figure – 4.5 (i – j) provided the large size eddies observed in the corners of the baffles with increase slowly towards outflow of the channel and does not fill the region of the corners on the 2000 fluid inertia that found change other than the shear thinning fluids.

Flow patterns are not enough to present the fluids visualizations on each fixed power law index rate with all values of the Reynolds number on shear thinning as well as shear thickening type of non – Newtonian fluids. Figure – 4.6 provided in these graphs, it is clearly, visualized the enhancement due to increase the Reynolds Number. In the graphs, it is clear shown the higher enhancement other than the graph that is clear comparison of eddies development in the streamline patterns of the blockage in the artery/channel. Consequently, figure – 4.7 provided same enhancement proved here in two graphs of shear thinning and shear thickening fluids. Both graphs shows continuous enhancement due to increase Reynolds number. Also, visualized the higher enhancing appeared in the graph other than graph (because of the thin fluids movements that shows the reality of the fluids behave transportations. Also, complete statistics of eddies length with eddies intensity at minimum and maximum positions are presented in the tables – 4.1 and 4.2 with includes all Reynolds number and power law indices rate.

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SUMMARY

Most appropriate and high converge rate technique Newton's method is applied for the approximate result of physical components. Most probable velocity and pressure is discussed here through the selection of partial differential equations. Physically known as momentum transport equation with couple of continuity equation. The predicted solution will be adopted to visualize the blood flow features in the shape of disease effected artery and through this mathematical solution, easily visualize the blood flow patterns in the presence of stenosis or available blood clots in the artery. This approximate solution is matched with previous research scholars contributed in the field of biosciences with the help of CFD.

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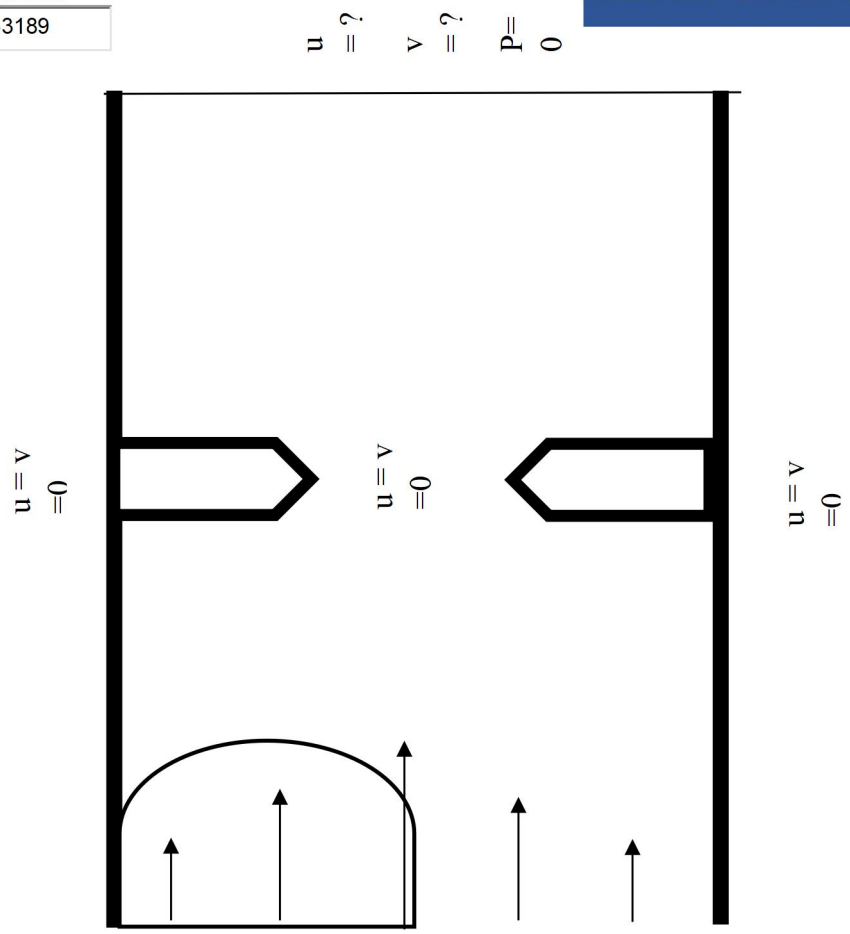
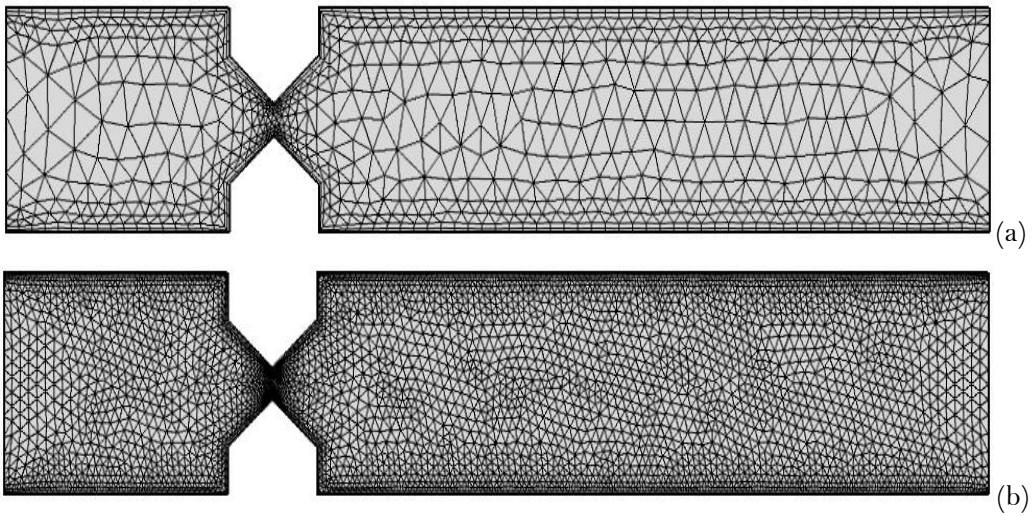


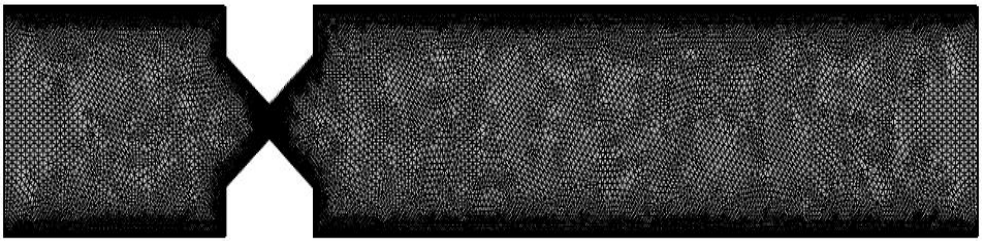
Figure –5.1: Schematic diagram of the flow domain with two opposite quadrilateral obstacles includes initial and boundary conditions.



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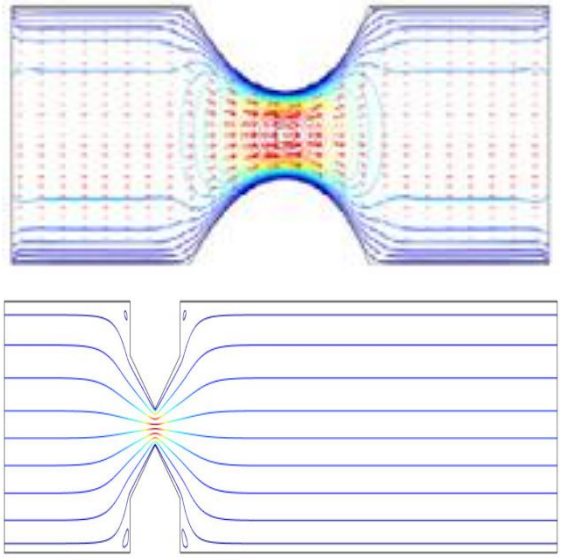
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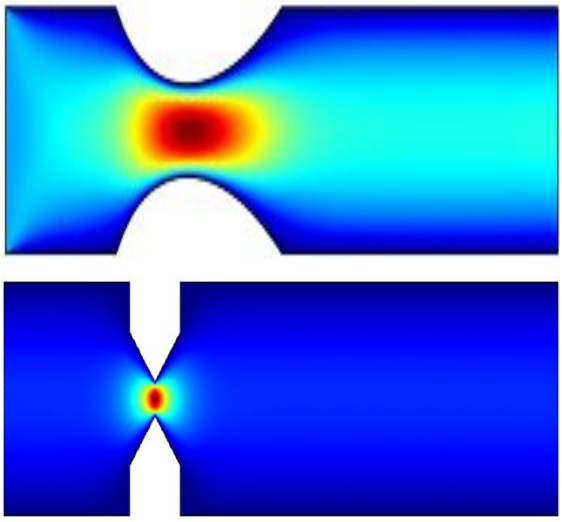


(c)

Figure –5.2: Independent study of mesh analysis through rectangular channel with two opposite quadrilateral obstacles.



(a_1) Nasrin, 2020 (a_1) Present work

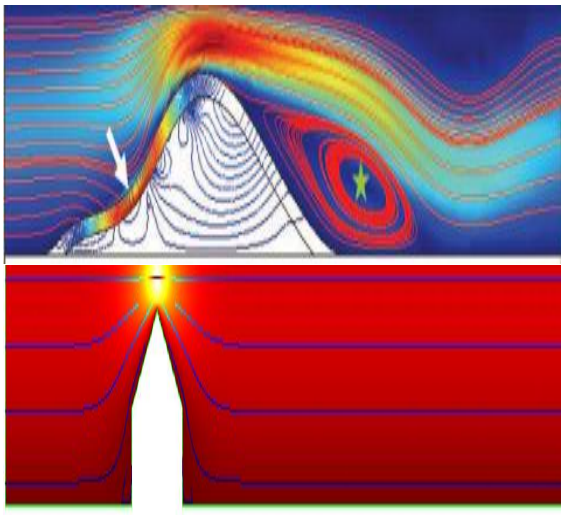


(a_2) Nasrin, 2020 (a_2) Present work

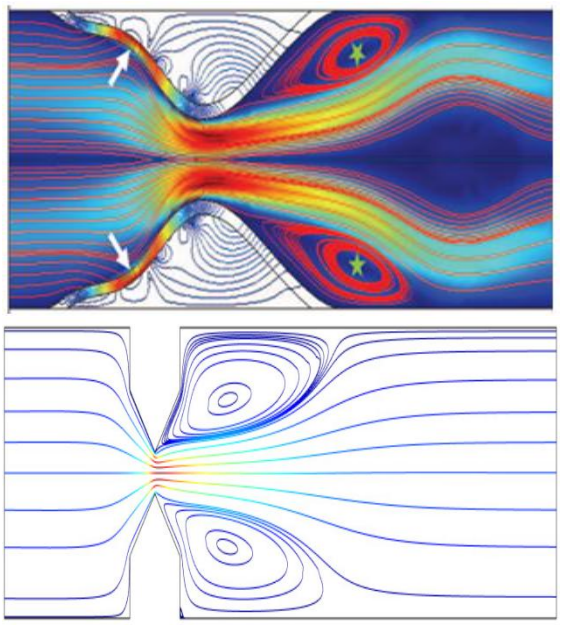
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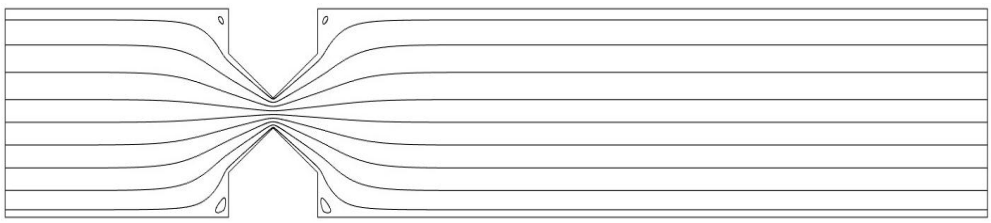


(b_1) Yong, 2006 (b_1) Present work



(b_2) Nasrin, 2020 (b_2) Present work

Figure –4.3: Flow Pattern comparison through rectangular channel with two opposite obstacles.

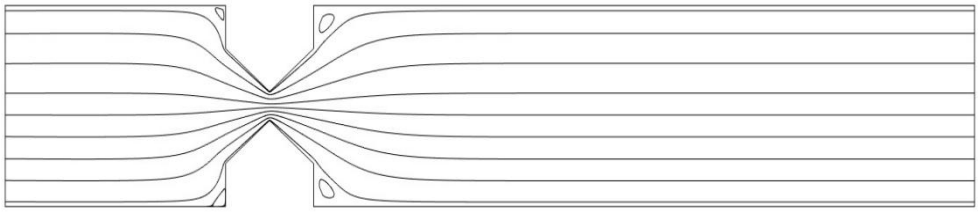


(a) Re=01 R_f = 0.00000344

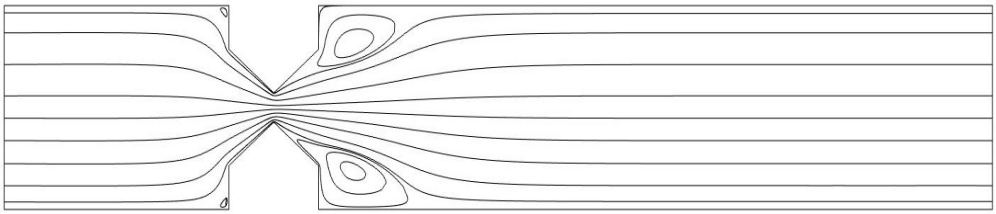
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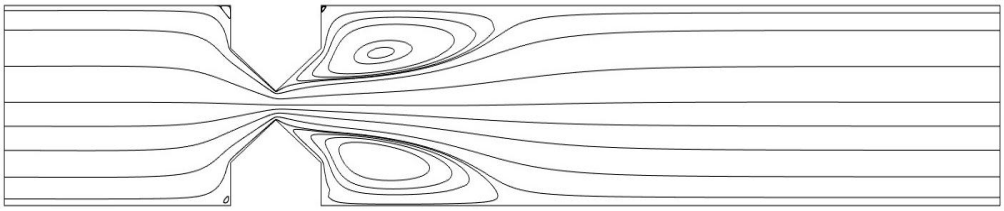
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(b) Re=250 R_f = 0.000841

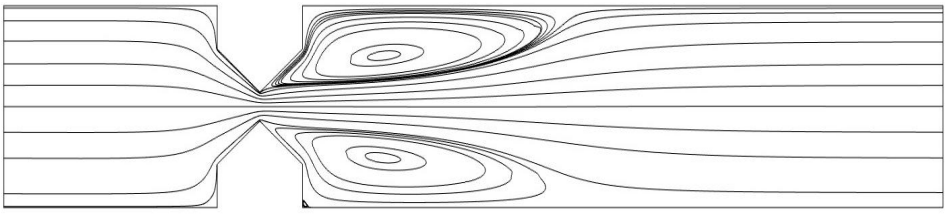


(c) Re=500 R_f = 0.00165

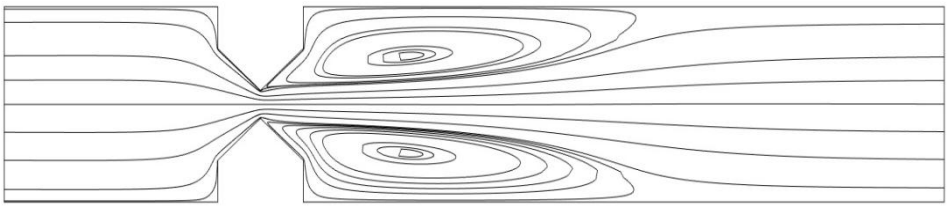


(d) Re=750 R_f = 0.00244

Figure –4.4(a – d): Velocity magnitudes through streamlines at different Reynolds number with fixed power law index rate (n = 0.90).



(e) Re=1000 R_f =0.00320

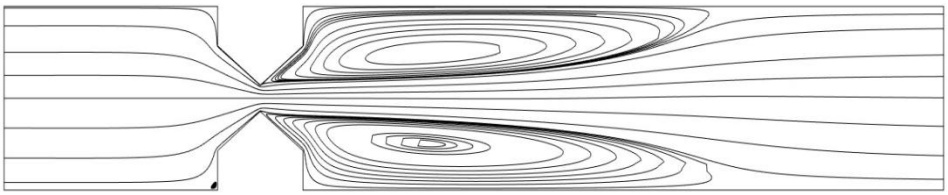


(f) Re=1200 R_f =0.00381

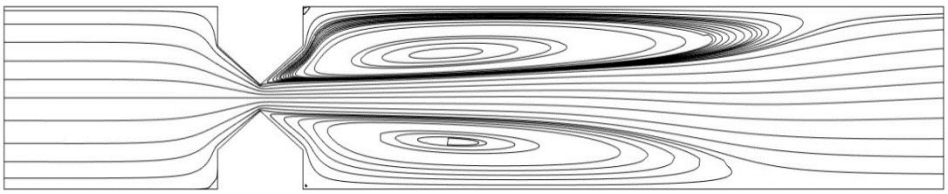
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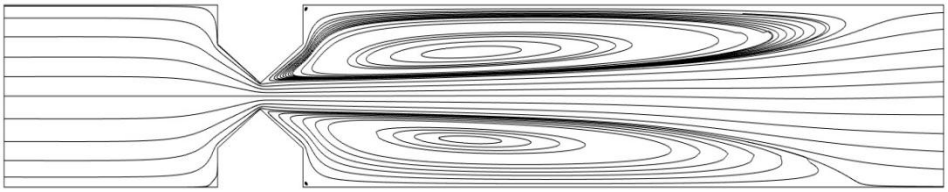


(g) Re=1400 R_f = 0.00441

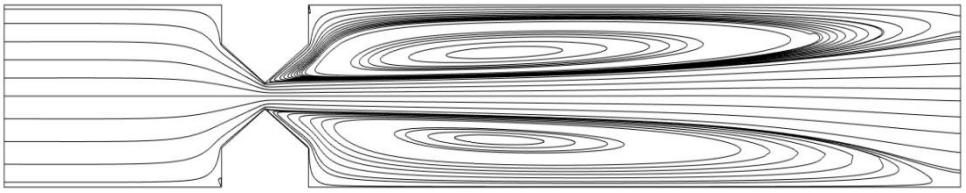


(h) Re=1600 R_f = 0.00502

Figure –4.4(e – h): Velocity magnitudes through streamlines at different Reynolds number with fixed power law index rate (n = 0.90)

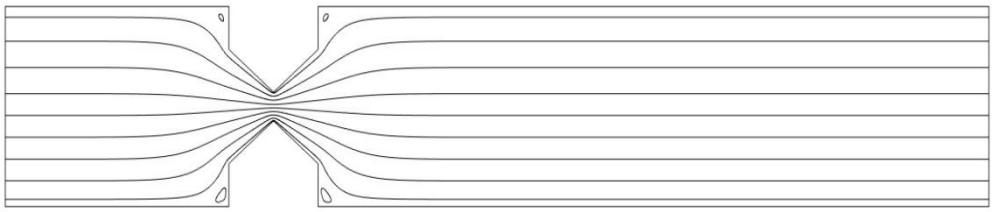


(i) Re=1800 R_f = 0.00563



(j) Re=2000 R_f = 0.00624

Figure –4.4(i – j): Velocity magnitudes through streamlines at different Reynolds number with fixed power law index rate (n = 0.90)

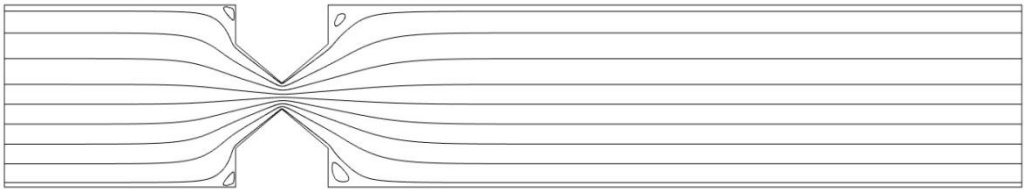


(a) Re=01 R_f = 0.000000865

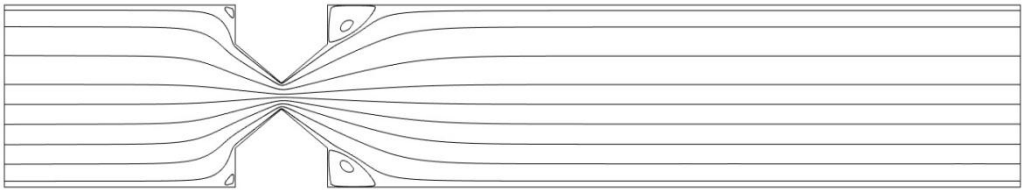
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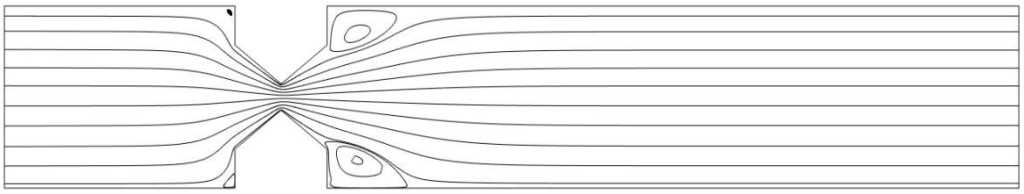
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(b) Re=250 $R_f = 0.000219$

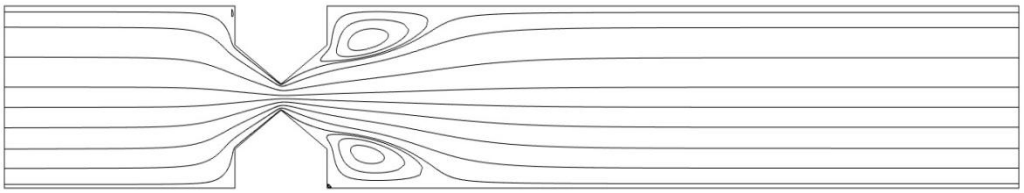


(c) Re=500 $R_f = 0.000435$

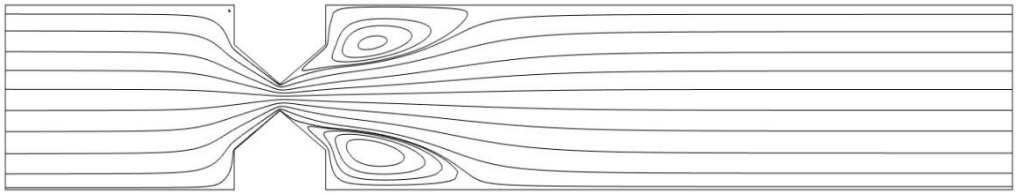


(d) Re=750 $R_f = 0.000648$

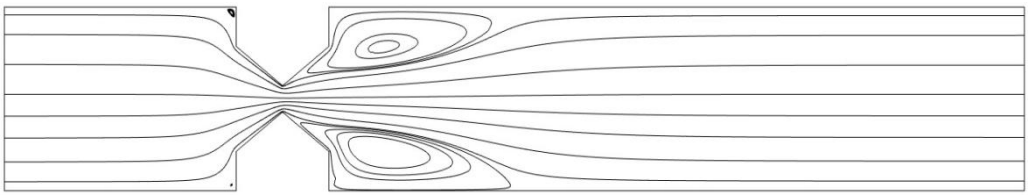
Figure –4.5(a – d): Velocity magnitudes through streamlines at different Reynolds number with fixed power law index rate (n = 1.1).



(e) Re=1000 $R_f = 0.000857$



(f) Re=1200 $R_f = 0.00103$

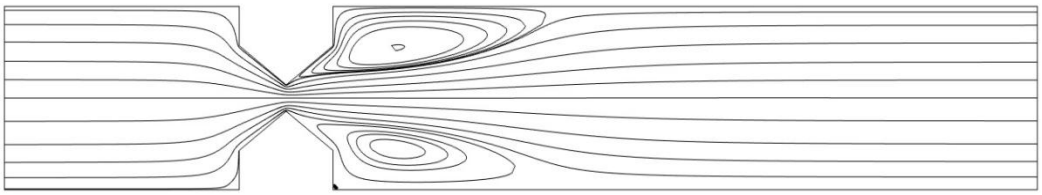


(g) Re=1400 $R_f = 0.00119$

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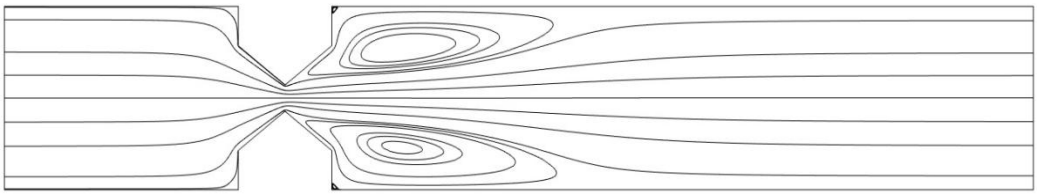
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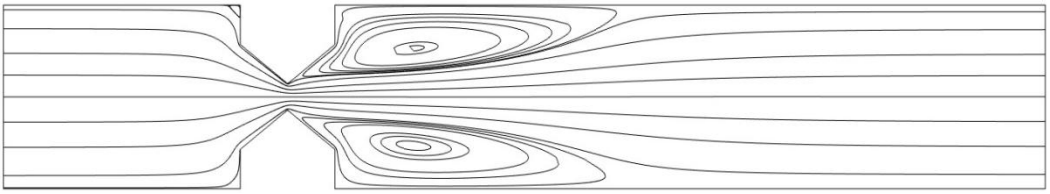


(h) Re=1600 $R_f = 0.00136$

Figure –4.5(e – h): ***Velocity magnitudes through streamlines at different Reynolds number with fixed power law index rate (n = 1.1)***

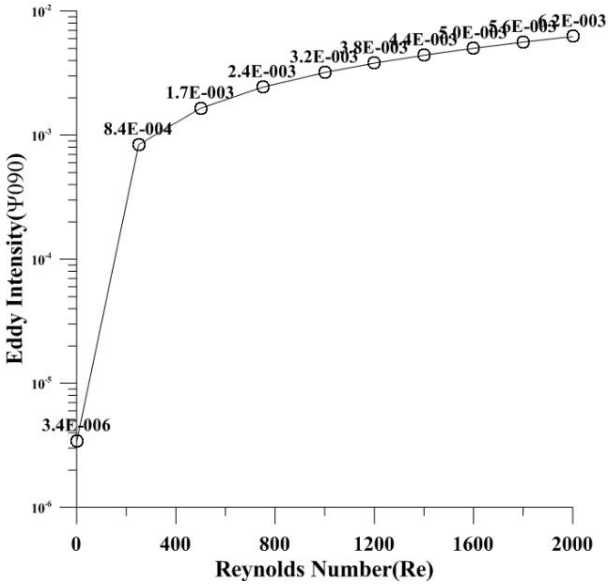


(i) Re=1800 $R_f = 0.00152$



(j) Re=2000 $R_f = 0.00168$

Figure –4.5(i – j): ***Velocity magnitudes through streamlines at different Reynolds number with fixed power law index rate (n = 1.1).***

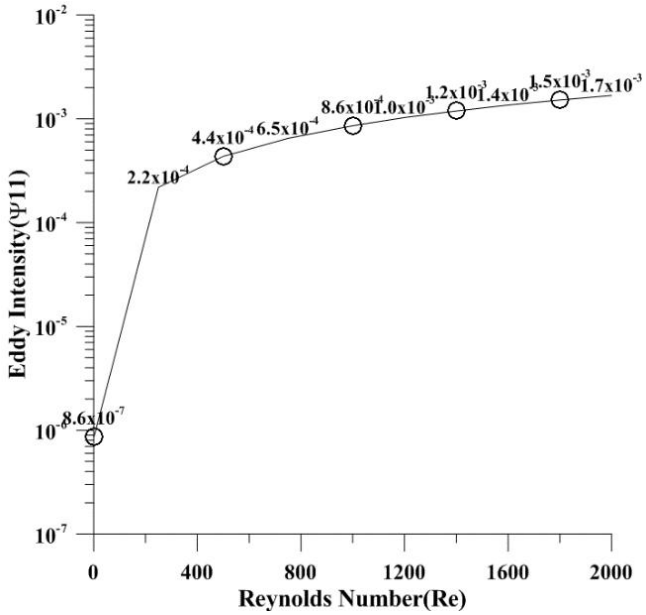


(a)

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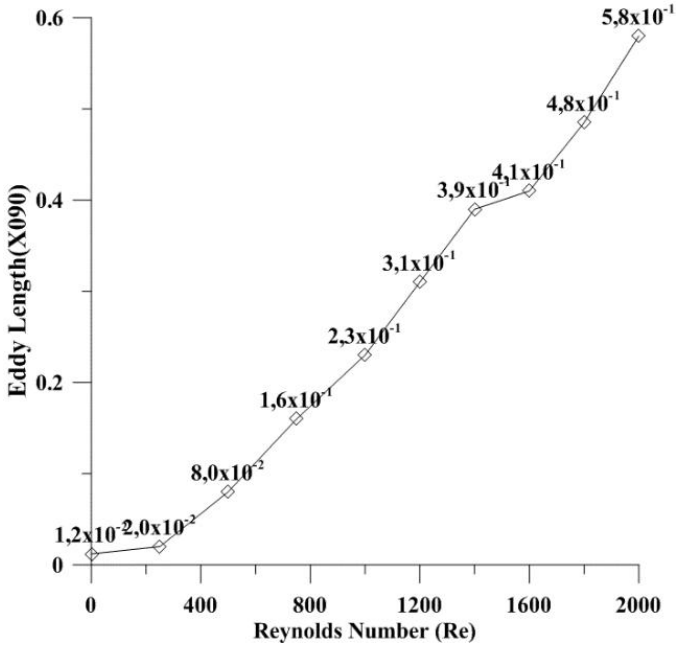
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(b)

Figure –4.6: Eddy Intensity ($\Psi_{0.90}$ and $\Psi_{1.1}$) is a function of Reynolds number (Re) with two opposite obstacles in a rectangular channel.

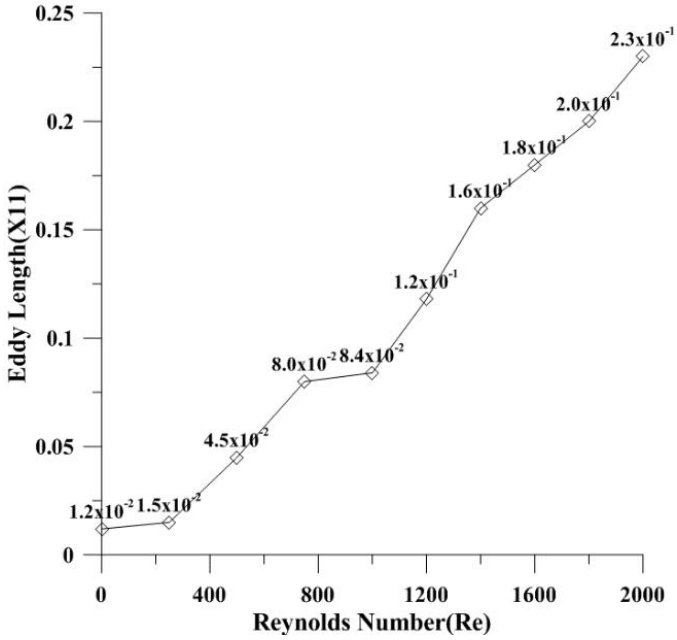


(a)

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(b)

Figure –4.7 Vortex lengths ($X_{0.90}$ and $X_{1.1}$) is a function of Reynolds number (Re) with two opposite obstacles in rectangular channel.

Recirculation Flow rate (Ψ)					
Reynolds Number (Re)	**(n=0.90)**		**Reynolds Number (Re)**	**(n=1.1)**	
	($\Psi_{1\ min}$)	**($\Psi_{1\ max}$)**		**($\Psi_{2\ min}$)**	**($\Psi_{2\ max}$)**
01	7.37e-10	3.44e-06	01	1.85e-10	8.65e-07
250	1.09e-09	8.41e-04	250	3.17e-08	2.19e-04
500	1.19e-08	1.65e-03	500	6.19e-08	4.35e-04
750	3.44e-11	2.44e-03	750	9.31e-09	6.48e-04
1000	2.01e-09	3.20e-03	1000	3.03e-11	8.57e-04
1200	1.74e-08	3.81e-03	1200	4.26e-08	1.03e-03
1400	1.29e-07	4.41e-03	1400	4.59e-08	1.19e-03
1600	2.41e-08	5.02e-03	1600	52.50e-08	1.36e-03
1800	4.45e-08	5.63-03	1800	1.82e-11	1.52e-03
2000	5.86e-08	6.24e-03	2000	5.21e-09	1.68e-03

Table – 1: Statistics of the vortex intensity (Ψ_1) is a function of Reynolds numbers (Re) with two opposite obstacles in a rectangular channel.

Vortex length

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Reynolds Number (Re)	(α =0.90) (X_1)	Reynolds Number (Re)	(α =1.1) (X_1)
01	0.012	01	0.012
250	0.020	250	0.015
500	0.080	500	0.045
750	0.160	750	0.080
1000	0.230	1000	0.084
1400	0.390	1400	0.160
1800	0.485	1800	0.200
2000	0.580	2000	0.230

Table – 02: Statistics of the vortex length (X) is a function of Reynolds numbers (Re) with two opposite obstacles in a rectangular channel.

CONCLUSION AND FUTURE WORK

CONCLUSION

Newton's method, implemented in COMSOL Multiphysics, was able to calculate the velocity field. A computational platform such as COMSOL Multiphysics has been found to be a useful tool for solving complicated fluid flow problems and is commonly used in a variety of scientific and engineering applications. In the present study, two groups of non-Newtonian fluids—shear-thinning fluid and shear-thickening fluid—in were studied to examine the blood flow behaviors in the quadrilateral blockage channel which was studied to represent the stenosed artery. Incompressible flow assumption was used to utilize the power-law model to check fluid viscosity. In case of shear-thinning fluids, a small vortex was noticed close to the corner of the blockage at Reynolds number of 1. The hydrodynamical effect of flow separation and recirculation was found to be very much associated with the flow inertia as measured by the Reynolds number, the size of the vortex increasing very quickly as the Reynolds number increased. The vortex, at higher Reynolds numbers, extended to a significant part of the near-wake stagnant flow region near the blockage, resulting in greater flow disturbance in the channel. The shear thickening fluids showed different flow behavior as compared to the shear thinning fluids because of their higher apparent viscosity. When the Reynolds number was raised a very small vortex was observed, but its development was slow and relatively small. A recirculation region formed in the corner regions, although a little bigger as the inertia increases with Reynolds number even at a Reynolds number of 200 the whole corner region was not fully filled. In conclusion, the results show that the flow behavior in an obstructed channel depends strongly on the fluid

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rheology and is greatly affected by the formation of vortices. Shear-thinning fluids tend to favor the development of stronger vortices and flow recirculation while shear-thickening fluids tend to inhibit the growth of vortices because they are harder to deform.

FUTURE WORK

This present study can be carried out further by the use of additional non-Newtonian fluid models in order to have a better knowledge about the behaviour of blood flow in different non-Newtonian blood flows. Specially, more complicated constitutive models (Bird-Carreau) can be used in replacing the Power-Law model to obtain the more realistic blood viscosity. Also, further studies could be conducted on the effect of various blockage geometry and sizes and determination of positions within the channel to examine influence on velocity distribution, relation of pressures and vortex formation. In addition, the analysis could be extended to include several obstacles for simulating the more complex arterial stenosis condition. Moreover, the current laminar flow study could be extended to other flow conditions such as transitional and turbulent flow situations, so that the fluid dynamics under higher flow rate conditions and more realistic physiological conditions can be understood. These extensions would give a much broader understanding of blood-flow behavior in blocked arteries and aid in the development of more useful biomedical and engineering uses.

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