GENERALIZED POWER-LAW MODEL OF MAGNETOHYDRODYNAMIC BLOOD FLOW IN AN INCLINED STENOSED ARTERY WITH BODY ACCELERATION

AHMED BAKHEET SAEED

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mathematics)

Faculty of Science
Universiti Teknologi Malaysia

JUNE 2017

To my beloved wife.

ACKNOWLEDGEMENT

In the name of Allah, the Beneficent, the Merciful. Foremost, thanks to Almighty Allah (S.W.T.) for giving me the knowledge, strength, courage and determination to undertake this study.

A special thank and the deepest appreciation to my supervisor Prof. Norsarahaida S. Amin for her advice, guidance and encouragement during this period which were a beneficial contribution to this study. I appreciate her total patience and confidence and the responsibility granted to me, which support me until the completion this thesis.

I also appreciate the effort of my co-supervisor Dr. Zuhaila Ismail for her guidance and suggestions. I would like to extend my thanks to the staff, Faculty members, and technicians of the Faculty of Sciences, Universiti Teknologi Malaysia, who contributed to my research.

My thanks to Al-Mustansiriyah University and the Ministry of Higher Education and Scientific Research, Iraq for providing a scholarship to carry out this study.

Last but not least, I would like to express my deepest appreciation to my friends Dr. Sarifuddin, Dr. Esam Abdul Ameer , Dr. Mbaya Jibrin, Dr. Yale Ibrahim, Dr. Norazlina Subani, and all friends who helped and supported me to complete this study.

ABSTRACT

This thesis focuses on the development of a mathematical model to investigate the effect of magnetic field and body acceleration on blood flow characteristics, heat and mass transfer from a stenosed artery, a condition due to the abnormal narrowing of a blood vessel. The arterial segment is assumed to be a cylindrical tube in an inclined position with oscillating boundary condition and the stenosis taking the shape of a cosine function. The momentum equation is based on the generalized power law model which is expected to handle the variations in blood rheology as blood flows through a different-sized vessel, with the index $n < 1, n > 1$ and $n = 0$ describing the shear-thinning, shear-thickening and Newtonian fluid respectively. The full governing equations comprising the generalized power-law equation, heat and mass equations are non-linear partial differential equations whose numerical procedure involves the discretization of the equations using the Marker and Cell (MAC) method, where pressure along the tube is calculated iteratively using the Successive-Over-Relaxation (SOR) technique. The results have been compared and validated with existing results in certain limiting cases. New results in terms of pressure, streamlines, heat and mass distribution are obtained for various parameter values of each of the external body forces. Specifically, for a stenosis with 48% occlusion, separation is seen to occur for Newtonian fluids at $Re = 1000$ and this region can be seen to increase in the case of shear thickening fluids, while the shear-thinning fluid is shown to be free of separation region. Moreover, blood velocity, wall shear stress and pressure drop decrease with increase n, while heat and mass transfer increase. It is also demonstrated through the simulations that under the influence of magnetic field, the velocity in the centre of the artery and the separation region are reduced with a sufficient strength of magnetic field, depending on the severity of stenosis. For a 75% and 84% occlusion, the separation zones entirely disappear with magnetic strength 8 and 12 Tesla respectively, while the pressure drop, wall shear stress, heat and mass transfer increase. On the other hand, increasing periodic body acceleration leads to increase velocity and the pressure drop while reducing heat and mass transfer. Inclination angle increases the velocity and wall shear stress but decreases the pressure drop and heat and mass transfer. Based on the results, patients with blood vessel disease are advised not to do a high-intensity exercise; it can put extra strain on the heart leading to a risk in chest pain or even cardiac arrest. Regular exercise and suitable intensity of magnetic field could enhance vascular health.

ABSTRAK

Tesis ini memberi tumpuan kepada pembangunan model matematik untuk mengkaji kesan medan magnet dan pecutan jasad terhadap ciri-ciri aliran, pemindahan haba dan pemindahan jisim bagi aliran darah di dalam arteri berstenosis, iaitu suatu keadaan di mana saluran darah menyempit secara abnormal. Segmen arteri diandaikan suatu tiub silinder kedudukan condong dengan syarat sempadan berayun dan stenosis sebagai berbentuk fungsi kosinus. Persamaan momentum adalah berdasarkan kepada model hukum kuasa teritlak yang boleh mengendalikan variasi reologi darah yang mengalir melalui saluran darah pelbagai saiz, dengan indeks $n < 1, n > 1$ dan $n = 0$ masing-masing mencirikan bendalir penipisan ricih, penebalan ricih dan Newtonan. Persamaan menakluk yang terdiri daripada persamaan hukum kuasa teritlak, persamaan haba dan persamaan jisim adalah persamaan pembezaan separa tak linear dengan prosidur pengiraan berangkanya melibatkan pendiskretan persamaan tersebut menggunakan kaedah Marker dan Cell (MAC), di mana tekanan di sepanjang tiub dikira secara lelaran menggunakan teknik Successive-Over-Relaxation (SOR). Keputusan kajian telah dibanding dan disahkan keputusan dengan hasil kajian sedia ada bagi beberapa kes mengehadkan. Keputusan baru bagi tekanan, garis arus, taburan haba dan jisim diperoleh untuk pelbagai nilai parameter bagi setiap daya jasad luaran. Khususnya, bagi stenosis yang tersumbat sebanyak 48%, pemisahan dilihat berlaku untuk bendalir Newtonan pada nilai $Re = 1000$ dan rantau ini diperhatikan meningkat bagi bendalir penebalan ricihan, manakala bagi bendalir pencairan ricihan, didapati bebas dari rantau pemisahan. Selain itu, halaju darah, tekanan ricih dinding dan kejatuhan tekanan menurun dengan peningkatan n, sebaliknya, pemindahan haba dan jisim bertambah. Melalui simulasi juga ditunjukkan bahawa di bawah pengaruh medan magnet, halaju di pusat arteri dan rantau pemisahan menurun dengan kekuatan medan magnet yang sesuai, bergantung kepada tahap stenosis. Untuk arteri yang tersumbat 75% dan 84%, zon pemisahan hilang sepenuhnya masing-masing dengan kekuatan magnet 8 dan 12 Tesla, manakala kejatuhan tekanan, tekanan dinding ricih, pemindahan haba dan jisim meningkat. Sebaliknya, peningkatan berkala pecutan jasad membawa kepada peningkatan halaju dan kejatuhan tekanan di samping pengurangan pemindahan haba dan jisim. Sudut kecondongan meningkatkan halaju serta tegasan ricih dinding tetapi mengurangkan kejatuhan tekanan dan pemindahan haba dan jisim. Berdasarkan keputusan, dijangkakan pesakit dengan masalah saluran darah dinasihatkan untuk tidak melakukan senaman berintensiti tinggi; ia boleh memberikan tekanan tambahan ke atas jantung yang boleh membawa kepada risiko sakit dada atau serangan jantung. Senaman yang kerap dan intensiti medan magnet yang sesuai boleh meningkatkan kesihatan vaskular.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATIONS

CFD	-	Computational fluid dynamics
FHD	-	Ferrohydrodynamics
KE	-	Kinetic Energy
LDL	-	Low-density lipoprotein
MAC	-	Marker and Cell method
MHD	-	Magnetohydrodynamic
MRI	-	Magnetic Resonance Imaging
SOR	-	Successive-Over-Relaxation method
WHO	-	World Health Organization

LIST OF SYMBOLS

β	-	Combination factor
δ	-	The critical height of the stenosis
$\dot{\gamma}$	-	Shear rate
Δz	-	Increment in the axial directions
Δx	-	Increment in the radial directions
Δt	-	Time increment
ΔP	-	Pressure drop
μ	-	Blood viscosity
ω_u	-	Under relaxation parameter
ω_o	-	Over relaxation parameter
ϕ	-	Phase difference of the acceleration
ρ	-	Density of blood
σ	-	Electrical conductivity
$\boldsymbol{\tau}$	-	Stress tensor
τ_w	-	Wall Shear stress
τ_{xx}	-	Shear force at x-axis
I_0	-	Bessel function
$\mathbf{J}$	-	Current density
k	-	Thermal conductivity
k_R	-	Wall oscillation
K_T	-	Thermal diffusion ratio
L	-	The finite difference arterial segment
M	-	Hartmann number
g	-	Gravitational force

a_0	-	Amplitude
B_0	-	Uniform magnetic field
B_1	-	Induced magnetic field
C	-	Mass concentration
C_s	-	The reference concentration at the inlet
C_p	-	The specific heat
D_m	-	coefficient of mass diffusion
E	-	Electric field
F	-	Body force
Fr	-	Froude number
f_b	-	Body acceleration frequency
$G(t)$	-	Periodic body acceleration
p	-	Pressure
P_a	-	Pressure at the beginning of the throat
P_b	-	Pressure at the end of the throat
Pr	-	Prandtl number
R_0	-	Constant radius of the non-stenotic artery
$R(z,t)$	-	Radius of the arterial segment in the stenotic region
Re	-	Reynolds number
Sc	-	Schmidt number
Sh_D	-	Sherwood number
Sr	-	Soret number
T	-	Blood temperature
T_i	-	The respective temperatures at the inlet
T_m	-	The mean blood temperature
θ	-	Angle between the force vector F and the x direction
$u(r,z,t)$	-	The radial velocity component
U	-	Cross-sectional average velocity
$\mathbf{V}$	-	Fluid velocity field
$w(r,z,t)$	-	The axial velocity component

LIST OF APPENDIX

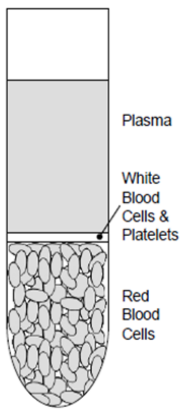
CHAPTER 1

INTRODUCTION

1.1 Research Background

The understanding of the dynamics of blood flow is important in the investigation of the vascular disease development and in the modelling of blood flow. The mathematical depiction of blood flow can be very complicated, yet some simplified models provide a fairly good understanding of the behaviour of blood when flowing through the vessels. The study of the behaviour of blood flow in the blood vessels provides an understanding of the connection between flow and the development of diseases such as atherosclerosis, aneurysms and thrombosis and how the characteristics of the blood flow are changed under these conditions. The understanding of the flow dynamics in the presence of external forces such as gravity, body acceleration and magnetic field will help improve the design of the model. The affecting of several properties of blood and vessels can be improved if the blood flow behaviour through certain conditions is well understood.

Blood is essential for life. It receives oxygen from the lungs and nutrients from the intestine and delivers them to whole body cells. Blood is mainly composed of plasma, which carries proteins, platelets (thrombocytes), red blood cells (erythrocytes) and white blood cells (leukocytes). Red blood cells contain a protein called hemoglobin, which has a high affinity for iron. The average hemoglobin iron concentration is 17% by volume for males and approximately 15% by volume for females (Ramsay, 1957). The main constituent of the blood is red blood cells, which make about 45% by volume of the blood, while the platelets and white blood cells are less than 1%. At rest, the red blood cell shape is biconcave disks with a diameter of roughly $8\mu m$ and across at its thickest point $2.5\mu m$. The membrane of the cell is quite flexible so that in the flow, the cell shape is less defined.



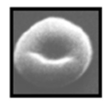
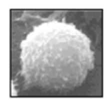
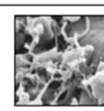
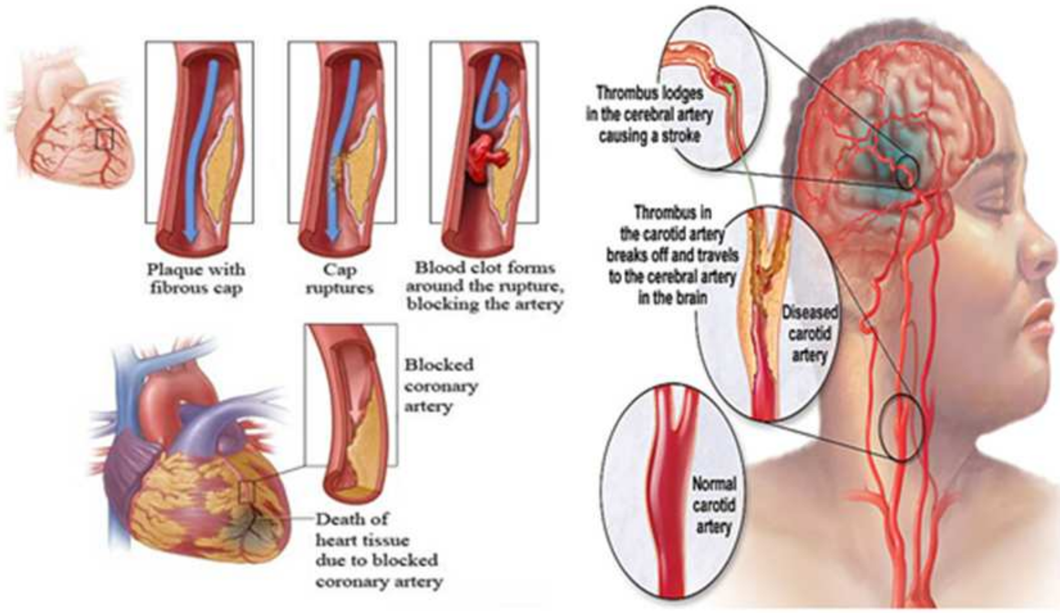
Cell Type	Shape		Number Density (per mm^3)	% Volume of Blood
Red Blood Cells Erythrocytes	Biconcave Disk		4-6 x 10^6	45
White Blood Cells Leucocytes	Spherical		4-11 x 10^3	1
Platelets	Various		250-500 x 10^3	

Figure 1.1: Blood constituents (Caro *et al.*, 1978).

Blood rheology can be described as a non-Newtonian viscosity model and may depend on the size of blood vessel. The assumption of Newtonian behaviour is acceptable for high shear rate flow, as in larger arteries with radius greater than $1mm$. However, this supposition is not valid when the shear rate is low as in smaller arteries and in the downstream of the stenosis, blood exhibits non-Newtonian in small arteries (Mandal, 2005). From a biomechanics perspective, blood would not obey the simple, one parameter and linearized law of viscosity established by Newton. Fluids that exhibit a non-linear relationship between the shear stress and the rate of shear strain are called Non-Newtonian. According to Enderle *et al.* (2000), the non-Newtonian behaviour of blood must be modelled by higher order constitutive equations. Investigations have showed that the shear-thinning blood rheology can be represented as a function of shear rate by various commonly used mathematical models, such as, power law, Casson, Carreau and their derivatives Cross, Walburn-Schneck, Carreau-Yasuda and the generalized power law models (Cho and

Kensey, 1991; Ballyk *et al.*, 1994). However, power-law and the Walburn-Schneck models estimate the blood behaviour well at low shear rates; but at high shear rates they predict decreasing viscosities and hence fail to hold the Newtonian behaviour at such high shear rates (Johnston *et al.*, 2004). According to Pries *et al.* (1992), Carreau-Yasuda and Casson models hold the experimental blood behaviour well at both low and high shear rates. Moreover, a modified Casson model also can be utilized to represent the haematocrit of the blood (Das *et al.*, 2000). According to Ballyk *et al.* (1994), the generalized power law model can be considered to be a general non-Newtonian model for blood viscosity. It encompasses the power law model at low shear rates, the Newtonian model at mid-range and high shear rates, (more than $200s^{-1}$) and has the Casson model as a special case for a given haematocrit value. In addition, there is a close agreement between the generalized power law and Carreau model at low shear rate (between 0.5 and $50s^{-1}$). Hence, for this study, blood rheology is adequately described by the generalized power law model.

Recently there are many types of research have been carried out on stenosed arteries: arteries with a blockage caused by atherosclerosis, which literally implies the solidifying of the arterial walls. The artery walls are normally smooth to allow blood flow easily through the artery and for easy transportation of oxygen, nutrients and other vital substances from blood to the body tissues. Stenosis tends to cause a hardening of the walls as well as a narrowing of the vessels (Young, 1968; Biswas, 2000; Biswas and Chakraborty, 2009; Sankar and Lee, 2009). Therefore, it is no wonder that this topic is of a significant concern to the community and numerous researchers. Stenosed artery is one of the widespread diseases that lead to serious circulatory complaints, by narrowing or occluding the blood vessels. Stenosis in arteries providing blood to the cerebrum can lead to a diseased condition called cerebral strokes, likewise, in the coronary arteries; it can bring myocardial infarction that cause a heart attack (heart failure) (Sinha and Singh, 1984). Furthermore, it was observed by researchers, that the resistance of the stenosis was basically reliant on its minimum cross-sectional area instead of its length (Chakravarty and Datta, 1989).



(a) Heart failure (b) Stroke

Figure 1.2: Vascular disease.

(http://www.mayoclinic.org/diseases-conditions/stroke/symptoms-causes/dxc-20117265)

The study of magnetohydrodynamic (MHD) blood flow problems has found applications in numerous fields like blood stream estimations, MHD power generation, etc. The utilization of MHD principles in medication and biological science is of interest in the literature of biomathematics (Vardanyan, 1973; Sud *et al.*, 1974; Sud *et al.*, 1978). Blood has been recorded to have different magnetic susceptibility values depending on its oxygenation state. Deoxygenated blood, which travels through veins towards the heart, behaves as a paramagnetic solution and has a magnetic susceptibility of 3.5×10^{-6}. Oxygenated blood, which is found in arteries and is pumped from the heart, has diamagnetic properties, with a magnetic susceptibility of -6.67×10^{-7} (Haik *et al.*, 1999a). The magnetic relaxation of blood has been experimentally measured to be in the order of a few seconds, meaning that it will take at least a second for blood to reach its equilibrium magnetization when exposed to a magnetic field (Higashi, 1993). The externally applied magnetic field to the blood flow is governed by MHD principles. By Lenz's law, the Lorentz's force will contradict the stream of conducting liquid and the mathematical model ignores the impact of magnetization. The principles of MHD can be utilized to reduce the blood flow in the arterial system and therefore it may be used in the treatment of certain cardiovascular diseases that accelerated blood flow such as hypertension and haemorrhages (Korchevskii and Marochunik, 1965). MHD can also be used in the improvement of magnetic tools for cell separation, as targeted drugs transport i.e. utilizing magnetic particles as drug bearers, magnetic injury treatment, reduce bleeding during surgery, and cancer tumor treatment using magnetic hyperthermia (Haik *et al.*, 1996; Plavins and Lauva, 1993; Ruuge and Rusetski, 1993). As opposed to the MHD, Ferrohydrodynamics (FHD) which deals with electrically poor conductors fluid (no induced electric current), and takes into account the magnetization effects on the flow in the magnetic field. Thus, the FHD equations consider the magnetization of the fluid. The rising force subject to magnetization depends on the presence of a spatially varying magnetic field and with a uniform magnetic this force disappears (Haik *et al.*, 1999a; Haik *et al.*, 1999b; Haik *et al.*, 1996; Haik *et al.*, 2001; Haik *et al.*, 2002). However, blood exhibits substantially high static electrical conductivity (Frewer, 1974; Gabriel *et al.*, 1996; Jaspard and Nadi, 2002). Magnetic tools sold to patients usually use uniform magnetic fields produced by permanent magnets and not varying magnetic fields.

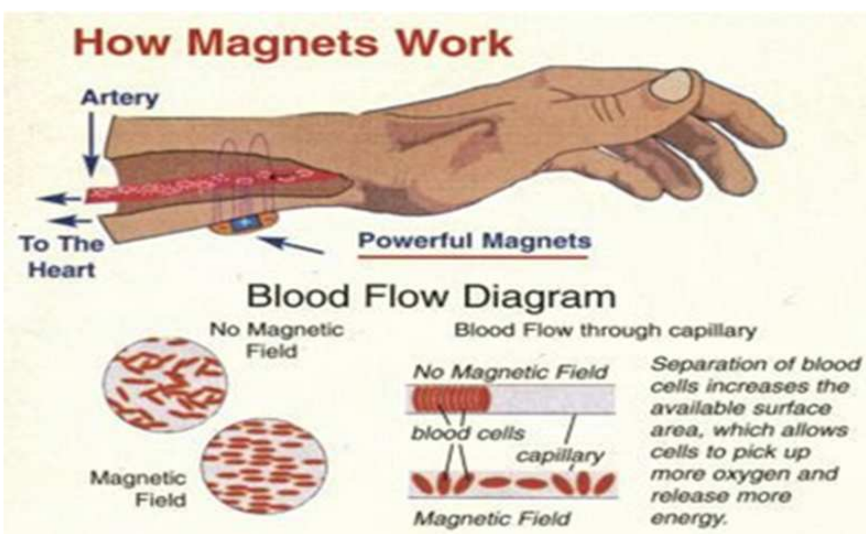


Figure 1.3: Effect of magnetic field on blood flow.

(http://www.frequencyrising.com/magnettherapy.htm)

Figure 1.4: Magnetic therapy.

(http://alaml-algaded.com/google150cc6a3ffa5c10e.html/magnetic-therapy/)

In some conditions the human body is subject to external body accelerations or variations, for example, when vibration treatment is applied to a patient with coronary disease, during flying in a spacecraft, or sudden movement of the body during sports actions, etc. In all such cases, a specific portion of the whole body may be exposed to an external acceleration that may cause disturbance to the blood flow. Though human body has the natural capacity to adapt to the changes, but long exposure to such variations may lead to some serious health problems like headaches, nausea, abdominal pain, abnormal pulse rate, and hemorrhage in the face, lungs and brain (Majhi and Nair, 1994). So the investigation of the impact of the magnitude, duration and frequency of the periodic acceleration may play a critical part in the finding, diagnosis and treatment of heart disease.

The normal temperature of the human blood is about $37°$C. When it increases above $41°$C, irreversible ill effects occurs in the proteins of blood and this is the cause of death after such high fever (Cokelet, 1987). When magnetic field was imposed the temperature increase of more than $3°$C and injuries of 12 and $20cm^2$ closed after $21 - 26$ days. Similar injuries that were not imposed to magnetic field showed sores and scabs even after 50 days. Moreover, hypothermia or hyperthermia is widely used for many purposes such as open heart surgeries and cancer treatment. Especially for the tumor treatment, the role of the temperature is substantially important (Ahuja and Hendee, 1978). For rising of $1°$C the time of cure is reduced to the half for a particular biological result like the decrease of cancer cells of a tumor (Lin *et al.*, 1999).

Although it was reported that oscillatory and low wall shear stress are often positively associated with localized atherosclerosis (Ku *et al.*, 1985; Friedman *et al.*, 1981), the correlation between wall shear stress and formation of atherosclerotic is yet to be persuasively established. It has been proposed that wall shear stress is not the only mechanism responsible for enhancing the formation and develop atherosclerosis (Joshi *et al.*, 2004; Steinman *et al.*, 2002; Kaazempur-Mofrad *et al.*, 2004). Mass transport is a movement of atherogenic molecules and dissolved gases such as Low-density lipoprotein (LDL), oxygen (O_2) and carbon dioxide (CO_2) within the blood flow and arterial wall or vice versa. This action has been proved to contribute to the formation of atherosclerosis (Fry and Vaishnav, 1980; Kaazempur-Mofrad *et al.*, 2005). Caro *et al.* (1971) proposed that atherosclerosis may occur as a result of shear dependent mass transport mechanism of cholesterol between blood and the arterial wall. In order to make an appropriate assessment regarding the possible relationship between the spots of atherosclerotic lesions and the mass transfer patterns, an accurate characterization of mass transfer behaviour is very important. Moreover, a clear knowledge of mass transfer in stenosed artery is of considerable medical interest in the investigation of the formation and development of atherosclerosis. The presence of stenosis in the artery causes blood flow separation and complex hemodynamic features and these in turn affect mass transfer phenomenon.

1.2 Problem Statement

Blood flowing in stenosis artery possess serious Pathophysiological problems because it has numerous arterial diseases such as endothelial damage, hemolysis, thrombosis and other injuries. These can lead to the malfunction of the cardiovascular system which is in close correlation with blood flow characteristics and deformability of the vessel wall.

It is well-known that numerous vessels in physiological systems are not horizontal, but have a certain inclination to the axis. The force of gravity comes into blood flow due to the consideration of inclined artery. On the other hand, blood flow patterns, pressure, mass concentration as well as temperature are often affected by external forces such as magnetic field and body acceleration and various pathological conditions which include stenosis causing serious problems in the cardiovascular system but these conditions have not been fully investigated by previous investigators. Studying the effect of these forces on the blood flow characteristics with heat and mass transfer will help in better understanding of the roles of blood dynamical factors in the development and progression of arterial diseases.

An important factor which needs to be considered in blood flow analyses is the heat transfer. Lack of proper investigation of this parameter will result in irreversible damage in the blood proteins and hence causes high fever and probably loss of life. Therefore, it is important to consider the energy equation where the blood temperature can be calculated to determine the behaviour of heat transfer through an inclined stenosis artery in the presence of a magnetic field and body acceleration.

Blood exhibits various types of rheology behaviour depending on the size of the vessel, and the presence of stenosis will change the size of the vessel in a specific location. Therefore to handle these variations, the blood flow is characterized by the generalized power law model taking into account the shear-thinning, shear-thickening and Newtonian contrarily to other blood models which cannot handle all these blood rheology behaviour.

Pressure has not been calculated previously but this research applied Marker and Cell (MAC) method to discretize the governing equations where the pressure equation is derived and solved iteratively using successive over relaxation (SOR) technique. The main advantage of MAC method is that the pressure boundary conditions at the inlet and outlet are not needed.

1.3 Research Objectives

The main objective of this research is to develop a mathematical model of the unsteady two-dimensional blood flow with heat and mass transfer in inclined stenosed artery subject to a magnetic field and body acceleration and the specific objectives are:

1. Determine the effect of a magnetic field on the characteristics of blood flow modelled as a generalized power law in a stenosed artery.
2. Determine the response of blood flow to body acceleration in an inclined stenosed artery.
3. Investigate the effects of body acceleration and magnetic field on the heat and mass transfer in an inclined stenosed artery.
4. To develop a matlab code based on the mathematical model that can simulate the behavior of the blood flow characteristics with heat and mass transfer.

1.4 Scope of the Study

In this study, the artery having stenosis is taken as an inclined cylindrical tube with elastic wall containing an incompressible non-Newtonian electrically conducting fluid. This involves the consideration of realistic situations which often give rise to complex mathematical equations. The blood flow is considered to be unsteady, laminar, two-dimensional, axisymmetric and fully developed, characterized by the generalized power-law model with energy and mass conservation equations. The blood flow is considered to take place in presence of external forces (magnetic field, body acceleration and inclination angles). As a numerical technique, the MAC method is developed in the cylindrical coordinate system in order to tackle the highly nonlinear governing equations of motion.

1.5 Significance of the Study

Cardiovascular disease is the main killer disease in almost all countries around the world. World Health Organization (WHO) reported that about 75% of all deaths in the industrialized world are caused due to circulatory disease. Almost 9.4 million people die annually from cardiovascular disease. Thus, cardiovascular diseases are the number one cause of death in the world. Cardiovascular disease causes 17.3 million deaths in 2008 about 30% of all global deaths. It is estimated that nearly 23.6 million people will die from cardiovascular diseases, mostly from stroke and heart disease by 2030 (WHO, 2003). Moreover, Heart disease, stroke and other cardiovascular diseases accounted for more than $786,641$ deaths of all 2515458 deaths, approximately one in three American deaths (Mozaffarian *et al.*, 2015). Thus, intensified efforts need to prevent and control this disease.

The present research can estimate the behavior of blood flow, wall shear stress, pressure, temperature and mass concentration and this in turn can help to predict and diagnosis certain problems such as heart attacks non-invasively, and suitable alternative treatment can then be given. In addition, some diseases such as arthritis, gout etc. patients are often advised to take protective pads or tractions and by applying proper magnetic field attached with those instruments we may enhance their activities. Again, in the case of magnetotherapy, by maintaining a proper magnetic field, blood flow velocity and pressure drop may be regulated. Furthermore, The present temperature profiles distributed over the various locations of the stenosed artery may have some implications in hyperthermia in a way to initiate and help develop more accurate models of ablative therapies and improve ablation procedures.

1.6 Thesis Organization

This thesis is divided into seven chapters including this introductory chapter that presented a general introduction of the research background containing the basic information about blood, cardiovascular system diseases, the external forces (inclination, magnetic field and body acceleration) as well as heat and mass transfer. Then in this introduction chapter the problem statements, the objectives, scope and the significance of the study were presented.

In Chapter 2 a brief review of literature that related to the considered problems is provided. It consists of discussions of generalized power law model in blood flow, the external forces, heat and mass transfer, and MAC method. All the problems throughout of this thesis considered the generalized power law and were solved using MAC method.

Chapter 3 describes the mathematical model and the differential form of equations that governed the flow streaming namely the generalized power law model with energy and mass concentration equations. This chapter also presents the solution procedure to solve the problems using the numerical method MAC which is carried out in staggered grid.

Chapter 4 accounts for the unsteady blood flow, behaving as generalized power law model in a stenosed artery, under the effect of an externally applied magnetic field. The effects of the generalized power law index, Hartmann number and the severity of stenosis on the axial velocity, wall shear stress, pressure and streamlines are studied. The MAC method is validated with the previous works for the axial velocity and pressure drop. New results in terms of pressure, streamlines and wall shear stress are presented for different values of Hartmann number, Reynolds number and area occlusion of stenosis.

Chapter 5 addresses the generalized power law model for a two-dimensional unsteady blood flow, in an inclined stenosed artery subject to body acceleration. The solution procedures are the same as in Chapter 4.

Chapter 6 is an improvement from problems encountered in the previous chapters by considering mass concentration and the energy of the fluid in order to investigate the effect of severity of stenosis and the external forces on the heat and mass transfer to blood flowing through inclined stenosed artery. Chapter 7 is the last chapter which consists of a summary of the study, conclusion and several suggestions for future work.

REFERENCES

Ahmed, S. A. and Giddens, D. P. (1983). Velocity Measurements in Steady Flow through Axisymmetric Stenoses at Moderate Reynolds Numbers. *Journal of Biomechanics*, 16(7): 505–516.

Ahuja, A. S. and Hendee, W. R. (1978). Effects of Particle Shape and Orientation on Propagation of Sound in Suspensions. *The Journal of the Acoustical Society of America*, 63(4): 1074–1080.

Akbar, N. S. (2014). Heat and Mass Transfer Effects on Carreau Fluid Model for Blood Flow through a Tapered Artery with a Stenosis. *International Journal of Biomathematics*, 7(1): 1450004.

Akbarzadeh, P. (2016). Pulsatile Magneto-Hydrodynamic Blood Flows through Porous Blood Vessels Using a Third Grade Non-Newtonian Fluids Model. *Computer Methods and Programs in Biomedicine*. 126: 3-19.

Ali, F., Sheikh, N. A., Khan, I. and Saqib, M. (2017). Magnetic Field Effect on Blood Flow of Casson Fluid in Axisymmetric Cylindrical Tube: A Fractional Model. *Journal of Magnetism and Magnetic Materials*, 423: 327–336.

Alshare, A. and Tashtoush, B. (2016). Simulations of Magnetohemodynamics in Stenosed Arteries in Diabetic or Anemic Models. *Computational and Mathematical Methods in Medicin*, 2016.

Anderson, J. D. (2003). *Modern Compressible Fluid Flow with Historical Perspective*. 3rd Ed., New York: MeGraw-Hill Publishing Company.

Andersson, H. I., Halden, R. and Glomsaker, T. (2000). Effects of Surface Irregularities on Flow Resistance In Differently Shaped Arterial Stenoses. *Journal of Biomechanics*, 33(10): 1257–1262.

Arntzenius, A. C., Laird, J. D., Noordergraaf, A., Verdoun, P. D. and Hussian, P. H. (1972). Body Acceleration Synchronous with Heart Beat. *Bibliotheca Cardiologica*, 29(1): 1–5.

Asano, K. (2007). *Mass Transfer: from Fundamentals to Modern Industrial Applications*. New York: John Wiley and Sons.

Back, L. H., Radbill, J. R., Cho, Y. I. and Crawford, D. W. (1986). Measurement and Prediction of Flow through a Replica Segment of a Mildly Atherosclerotic Coronary Artery of Man. *Journal of Biomechanics*, 19(1): 1–17.

Back, L. H., Radbill, J. R. and Crawford, D. W. (1977). Analysis of Oxygen Transport from Pulsatile Viscous Blood Flow to Diseased Coronary Arteries of Man. *Journal of Biomechanics*, 10(11): 763–774.

Bali, R. and Awasthi, U. (2007). Effect of Magnetic Field on the Resistance to Blood Flow through Stenotic Artery. *Applied Mathematics and Computation*, 188(2): 1635–1641.

Bali, R. and Awasthi, U. (2012). A Casson Fluid Model for Multiple Stenosed Artery in the Presence of Magnetic Field. *Applied Mathematics*, 3: 436–441.

Ballyk, P. D., Steinman, D. A. and Ethier, C. R. (1994). Simulation of Non-Newtonian Blood-Flow in an End-to-side Anastomosis. *Journal of Biorheology*, 31(5): 565–586.

Beigzadeh, B., and Halabian, M. (2016). The Effect of Static Magnetic Field on Hemodynamic Properties of Blood Flow Containing Magnetic Substances. *Journal of Computational Applied Mechanics*, 47(2): 181–194.

Beg, O. A., Bhargava, R., Rawat, S., Halim, K. and Takhar H. S. (2008). Computational Modeling of Biomagnetic Micropolar Blood Flow and Heat Transfer in a Two-Dimensional Non-Darcian Porous Medium. *Meccanica*, 43(4): 391–410.

Berger, S. A. and Jou, L. D. (2000). Flows in Stenotic Vessels. *Annual Review of Fluid Mechanics*, 32(1): 374–382.

Bhargava, S., Rawat, S. Takhar, H. S. and Beg, O. A. (2007). Pulsatile Magneto-Biofluid Flow and Mass Transfer in a Non-Darcian Porous Medium Channel. *Meccanica*, 43(3): 247–262.

Biswas, D. (2000). *Blood Flow Models: A Comparative Study*. New Delhi: Mittal Publications.

Biswas, D. and Chakraborty, U. S. (2009). Pulsatile Flow of Blood in a Constricted Artery with Body Acceleration. *Applied Mathematics*, 4(2): 329–342.

Biswas, D. and Paul, M. (2013). Study of Blood Flow inside an Inclined Non-Uniform Stenosed Artery. *International Journal of Mathematical Archive*, 4(5): 33–42.

Biswas, D. and Paul, M. (2015). Suspension Model for Blood Flow through a Tapering Catheterized Inclined Artery with Asymmetric Stenosis. *Applications and Applied Mathematics*, 10(1): 474–495.

Burton, A. C. (1966). *Physiology and Biophysics of the Circulation, Introductory Text*. Chicago: Year Book Medical Publisher.

Burton, R. R., Levercott Jr, S. D. and Michaelsow, E. D. (1974). Man at High Sustained +G Acceleration: A Review. *Aerospace*, 46: 1251–1253.

Caro, C. G., Fitz-Gerald, J. M. and Schroter, R. C. (1971). *Atheroma and Arterial Wall Shear. Observation, Correlation and Proposal of a Shear Dependent Mass Transfer Mechanism for Atherogenesis*. Proceedings of the Royal Society London, 177(1046): 109–159.

Caro, C. G., Pedley, T. J., Schroter, R. C. and Seed, W. A. (1978). *The Mechanics of the Circulation*. Oxford University Press.

Casson, N. A. (1959). *Flow equation of pigment oil suspension of printing ink type: In Rheology of Disperse Systems*. Ed. C. C. Mill, 84–120. London: Pergamon Press.

Chakeres, D. W., Kanarlu, A., Boudoulas, H. and Young, D. (2003). Effect of Static Magnetic Field Exposure of Up to 8 Tesla on Sequential Human Vital Sign Measurements. *Journal of Magnetic Resonance Imaging*, 18(3): 345-352.

Chakraborty, S., Biswas, D. and Paul, M. (2011). Suspension Model Blood Flow through an Inclined Tube with an Axially Non-Symmetrical Stenosis. *Korea-Australia Rheology Journal*, 23(1): 25–32.

Chakravarty, S. and Datta, A. (1989). Effects of Stenosis on Arterial Rheology through a Mathematical Model. *Mathematical and Computer Modelling*, 12(12): 1601–1612.

Chakravarty, S. and Sannigrahi, A. (1994). Effect of Body Acceleration on Blood Flow in an Irregular Stenosed Artery. *Mathematical and Computer Modelling*, 19(5): 93–103.

Chakravarty, S. and Sannigrahi, A. (1999). A Nonlinear Mathematical Model of Blood Flow in a Constricted Artery Experiencing Body Acceleration. *Mathematical and Computer Modelling*, 129(8): 9–25.

Chakravarty, S. and Sen, S. (2005). Dynamic Response of Heat and Mass Transfer in Blood Flow through Stenosed Bifurcated Arteries. *Korea-Australia Rheology Journal*, 17(2): 47–62.

Charm, S. E. and Kurland, G. S. (1965). Viscometry of Human Blood for Shear Rate of $0100, 000 sec^{-1}$. *Nature*, 206: 617–618.

Charm, S. E. and Kurland, G. S. (1974). *Blood Flow and Microcirculation*. New York, USA: Wiley.

Chaturani, P. and Isaac, W. A. (1995). Blood Flow with Body Acceleration Force. *International Journal of Engineering Science*, 33(12): 1807–1820.

Chaturani, P. and Palanisamy, V. (1991). Pulsatile Flow of Blood with Periodic Body Acceleration. *International Journal of Engineering Science*, 29(1): 113–121.

Chaturani, P. and Upadhya, V. S. (1977). Gravity Flow of Fluid with Couple Stress Along an Inclined Plane with Application to Blood Flow. *Journal of Biorheology*, 14(5): 237–246.

Chester, W. (1957). The Effect of a Magnetic Field on Stokes Flow in a Conducting Fluid. *Journal of Fluid Mechanics*, 3(3): 304–308.

Chinyoka, T. and Makinde, O. D. (2014). Computational Dynamics of Arterial Blood Flow in The Presence of Magnetic Field and Thermal Radiation Therapy. *Advances in Mathematical Physics*, 2014.

Cho, Y. I. and Kensey, K. R. (1991). Effects of the Non-Newtonian Viscosity of Blood on Flows in a Diseased Arterial Vessel. Part 1. Steady Flows. *Journal of Biorheology*, 28(3): 241–262.

Cokelet, G. R. (1987). *The Rheology and Tube Flow of Blood*. New York: McGraw-Hill.

Cowling, T. G. (1957). *Magnetohydrodynamics*. New York: Interscience Publication.

Das, B., Johnson, P. C. and Popel, A. S. (2000). Computational Fluid Dynamic Studies of Leukocyte Adhesion Effects on Non-Newtonian Blood Flow through Microvessels. *Journal of Biorheology*, 37(3): 239–258.

Elgazery, N. S. (2009). The Effects of Chemical Reaction, Hall and Ion-Slip Currents on MHD Flow with Temperature Dependent Viscosity and Thermal Diffusivity. *Communications in Nonlinear Science and Numerical Simulation*, 14(4): 1267–1283.

El-Shahed, M. (2003). Pulsatile Flow of Blood through a Stenosesd Porous Medium under Periodic Body Acceleration. *Journal of Applied Mathematics and Computation*, 138(2): 479–488.

El-Shahed, M. and Haroun, M. H. (2005). Peristaltic Transport of Johnson-Segalman Fluid under Effect of a Magnetic Field. *Mathematical Problems in Engineering*, 6(6): 663–677.

Elshehawey, E. F., Elbarabry, E. M., Elsoud, A .S. N. and Elshahed, M. (2000). MHD Flow of an Elastico Viscous Fluid under Periodic Body Acceleration. *International Journal of Mathematics and Mathematical Sciences*, 23(11): 795–799.

Enderle, J., Susan, B. and Bronzino, B. (2000). *Introduction to Biomedical Engineering*. London: Academic Press.

Ethier, C. R. (2002). Computational Modeling of Mass Transfer and Links to Atherosclerosis. *Annals of Biomedical Engineering*, 30(4): 461–471.

Frewer, R. A. (1974). The Electrical Conductivity of Flowing Blood. *Biomedical Engineering*, 9(12): 552–555.

Friedman, M. H. and Ehrlich, L. W. (1975). Effect of Spatial Variations in Shear on Diffusion at the Wall of an Arterial Branch. *Circulation Research*, 37(4): 446–454.

Friedman, M. H., Hutchins, G. M., Bargeron, C. B., Deters, O. J. and Mark, F. F. (1981). Correlation Between Intimal Thickness and Fluid Shear in Human Arteries. *Atherosclerosis*, 39(3): 425–436.

Fry, D. L. and Vaishnav, R. N. (1980). *Mass Transport in the Arterial Wall*. Basic Hemodynamics and Its Role in Disease Processes. University Park Press.

Gabriel, S., Lau, R. W. and Gabriel, C. (1996). The Dielectric Properties of Biological Tissues: III. Parametric Models for the Dielectric Spectrum of Tissues. *Physics in Medicine and Biology*, 41(11): 2271.

Gerrard, J. H. and Taylor, L. A. (1977). Mathematical Model Representing Blood Flow in Arteries. *Medical and Biological Engineering and Computing*, 15(6): 611–617.

Gmitrov, J. (2007). Static Magnetic Field Effect on the Arterial Baroreflex-Mediated Control of Microcirculation: Implications for Cardiovascular Effects Due to Environmental Magnetic Fields. *Radiation and Environmental Biophysics*, 46(3): 281–290.

Griffin, M. J. (2012). *Handbook of Human Vibration*. New York: Academic Press.

Haemmerich, D., Wright, A. S., Mahvi, D. M., Lee, Jr. F. T. and Webster, J. G. (2003). Hepatic Bipolar Radiofrequency Ablation Creates Lesions Close to Blood Vessels a Finite Element Study. *Medical and Biological Engineering and Computing*, 41(3): 317–323.

Haik, Y., Chen, C. and Chatterjee, J. (2002). Numerical Simulation of Biomagnetic Fluid in a Channel with Thrombus. *Journal of Visualization*, 5(2): 187–195.

Haik, Y., Pai, V. and Chen, C. (1996). *Development of Biomagnetic Fluid Dynamics*. Proceedings of the IX International Symposium on Transport Properties in Thermal Fluids Engineering, Singapore, Pacific Center of Thermal Fluids Engineering. Hawaii: U.S.A., June 25-28: 121–126.

Haik, Y., Pai, V. and Chen, C. J. (1999a). *Biomagnetic Fluid Dynamics*. Cambridge: Cambridge University Press: 439–452.

Haik, Y., Pai, V. and Chen, C. J. (1999b). Development of Magnetic Device for Cell Separation. *Journal of Magnetism and Magnetic Material*, 194(1): 254–261.

Haik, Y., Pai, V. and Chen, C. J. (2001). Apparent Viscosity of Human Blood in a High Static Magnetic Field. *Journal of Magnetism and Magnetic Materials*, 225(1): 180–186.

Haldar, K. and Ghosh, S. N. (1994). Effect of a Magnetic Field on Blood Flow through an Indented Tube in the Presence of Erythrocytes. *Indian Journal of Pure and Applied Mathematics*, 25(3): 345–352.

Harlow, F. H. and Amsden, A. (1970). *The SMAC method: A Numerical Technique for Calculating Incompressible Fluid Flows*. Technical Report LA-4370, Los Alamos National Laboratory.

Harlow, F. H. and Welch, J. D. (1965). Numerical Calculation of Time-Dependent Viscous Incompressible Flow of Fluid with Free Surface. *Physics of Fluids*, 8(12): 2182–2189.

Harris, W. and Tekleab, Y. (2012). *Tow Dimensional Model of Blood Plasma Flow with Oxygen Transport and Blood Cell Membrane Deformation*. Seventh International Conference on Computation Fluid Dynamics. Hawaii: Big Island, 9-13 July..

Haynes, R. H. and Burton, A. C. (1959). Role of Non-Newtonian Behavior of Blood in Homodynamic. *American Journal of Physiology*, 197: 943–952.

Hershey, D. and Chow, S. J. (1966). Blood Flow in Rigid Tubes: Thickness and Slip Velocity of Plasma Film at the Wall. *Journal of Applied Physiology*, 21(1): 27–36.

Hershey, D., Byrnes, R. E., Deadens, R. L. and Roam, A. M. (1964). *Blood Theology: Temperature Dependent of the Power Law Model*. Boston: Presented at the A.I.CH.E. Meeting.

Higashi, T. (1993). Orientation of Erythrocytes in a Strong Static Magnetic Field. *Blood Journal*, 82(4): 1328–1334.

Hirt, C. W. (1968). Heuristic Stability Theory for Finite Difference Equations. *Journal of Computational Physics*, 2(4): 339–355.

Huckaback, C. E. and Hahn, A. W. (1968). A Generalized Approach to the Modeling of Arterial Blood Flow. *Journal of Applied Physiology*, 27(4): 27–34.

Hussain, M. A., Subir, K. and Puniyani, R. R. (1999). Relationship between Power Law Coefficients and Major Blood Constituents Affecting the Whole Blood Viscosity. *Journal of Bioscience*, 24(3): 329–337.

Ichioka, S., Minegishi, M., Iwasaka, M., Shibata, Nakatsuka, M. T., Harii, K., Kamiya, A. and Ueno, S. (2000). High-Intensity Static Magnetic Fields Modulate Skin Microcirculation and Temperature in Vivo. *Bioelectromagnetics*, 21(3): 183–188.

Ikbal, M. A., Chakravarty, S., Wong, K. L., Mazumdar, J. and Mandal, P. K. (2009). Unsteady Response of Non-Newtonian Blood Flow through a Stenosed Artery in Magnetic Field. *Journal of Computational and Applied Mathematics*, 230(1): 243–259.

Ikbal, M. A., Chakravarty, S., Sarifuddin and Mandal, P. K. (2010). Numerical Simulation of Mass Transfer to Micropolar Fluid Flow past a Stenosed Artery. *International Journal for Numerical Methods in Fluids*, 67(11): 1655–1676.

Ismail, Z., Abdullah, I., Mustapha, N. and Amin, N. (2008). A Power-Law Model of Blood Flow through A Tapered Overlapping Stenosed Artery. *Applied Mathematics and Computation*, 195(2): 669–680.

Jagadeesha, S. and Rao, I. R. (2012). Solute Transfer in a Power-Law Fluid Flow through Permeable Tube. *Advanced in Theoretical and Applied Mechanics*, 5(7): 309–322.

Jaspard, F. and Nadi, M. (2002). Dielectric Properties of Blood: An Investigation of Temperature Dependence. *Physiological Measurement*, 23(3): 547.

Jauchem, J. R. (1997). Exposure to Extremely-Low-Frequency Electromagnetic Fields and Radiofrequency Radiation: Cardiovascular Effects in Humans, Review. *International Archives of Occupational and Environmental Health*, 70(1): 9–21.

Johnston, B. M., Johnston, P., Corney, S. and Kilpatrick, D. (2004). Non-Newtonian Blood Flow in Human Right Coronary Arteries: Steady State Simulations. *Journal of Biomechanics*, 37(5): 709–720.

Johnston, B. M., Johnston, P., Corney, S. and Kilpatrick, D. (2006). Non-Newtonian Blood Flow in Human Right Coronary Arteries: Transient Simulations. *Journal of Biomechanics*, 39(6): 1116–1128.

Joshi, A. K., Leask R. L., Myers, J. G., Ojha, M., Butany, J. and Ethier, C. R. (2004). Intimal Thickness is Not Associated with Wall Shear Stress Patterns in the Human Right Coronary Artery. *Arteriosclerosis, Thrombosis, and Vascular Biology*, 24(12): 2408–2413.

Kaazempur-Mofrad, M. R. and Ethier, C. R. (2001). Mass Transport in an Anatomically Realistic Human right Coronary Artery. *Annals of Biomedical Engineering*, 29(2): 121–127.

Kaazempur-Mofrad, M. R., Isasi, A. G., Younis, H. F., Chan, R. C., Hinton, D. P., Sukhova, G., LaMuraglia, G. M., Lee, R. T. and Kamm, R. D. (2004). Characterization of the Atherosclerotic Carotid Bifurcation Using MRI, Finite Element Modeling, and Histology. *Annals of Biomedical Engineering*, 32(7): 932–946.

Kaazempur-Mofrad, M. R., Wada, S., Myers, J. G. and Ethier, C. R. (2005). Mass Transport and Fluid Flow in Stenotic Arteries: Axisymmetric and Asymmetric Models. *International Journal of Heat and Mass Transfer*, 48(21): 4510–4517.

Katiyar, V. K. and Basavarajappa, K. S. (2002). Blood Flow in the Cardiovascular System in the Presence of Magnetic Field. *International Journal of Applied Science and Computations*, 9: 118–127.

Kavitha, A., Hemadri R. R., Sreenadh, S., Saravana, R. and Srinivas, A. N. S. (2011). Peristaltic Flow of a Micropolar Fluid in a Vertical Channel with Longwave Length Approximation. *Advances in Applied Science Research*, 2(1): 269–279.

Khanafer, K., Bull, J. L., Pop, I. and Berguer, R. (2007). Influence of Pulsatile Blood Flow and Heating Scheme on the Temperature Distribution during Hyperthermia Treatment. *International Journal of Heat and Mass Transfer*, 50(23): 4883–4890.

Kinouchi, Y., Yamaguchi, H. and Tenforde, T. S. (1996). Theoretical Analysis of Magnetic Field Interactions with Aortic Blood Flow. *Bioelectromagnetics*, 17(1): 21–32.

Korchevskii, E. M. and Marochunik, L. S. (1965). Magneto Hydrodynamic Version of Movement of Blood. *Biophysics*, 10: 411–414.

Kothandapani, M., Prakash, J. and Pushparaj, V. (2015). Analysis of Heat and Mass Transfer on MHD Peristaltic Flow through a Tapered Asymmetric Channel. *Journal of Fluids*, 2015(3).

Krishna, K. S., Ramana, M. M., Chenna, K. R. and Ravi, K. Y. (2011). Peristaltic Pumping of a Magnetohydrodynamic Casson Fluid in an Inclined Channel. *Advances in Applied Science Research*, 2(2): 428–436.

Krishna, K. S., Saroj, V. D. and Ravi, R. Y. (2013). Peristaltic Motion of a Micropolar Fluid under the Effect of a Magnetic Field in an Inclined Channel. *The International Journal of Engineering and Science*, 2: 31–40.

Ku, D. N., Giddens, D. P., Zarins, C. K. and Glagov, S. (1985). Pulsatile Flow and Atherosclerosis in the Human Carotid Bifurcation: Positive Correlation Between Plaque Location and Low and Oscillating Shear Stress. *Atherosclerosis*, 5(3): 293–302.

Kuipers, N. T., Sauder, C. L. and Ray, C. A. (2007). Influence of Static Magnetic Fields on Pain Perception and Sympathetic Nerve Activity in Humans. *Journal of Applied Physiology*, 102(4): 1410–1415.

Kumar, S. and Chandra, S. (2009). Heat Transfer and Fluid Flow Characteristic of Blood Flow in Multi-Stenosis Artery with Effect of Magnetic Field. *Indian Journal of Biomechanics*, Special Issue: 186–190.

Kundu, P. K. and Cohen, I. M. (2008). *Fluid Mechanics*. 4th Ed., Amsterdam Boston: Academic Press.

Layek, G. C. and Midya, C. (2007). Effects of Constriction Height on Flow Separation in a Two Dimensional Channel. *Communications in Nonlinear Science and Numerical Simulation*, 12(5): 745–759.

Li, J. and Huang, H. (2010). *Effect of Magnetic Field on Blood Flow and Heat Transfer through a Stenosed Artery*. 3rd International Conference on Biomedical Engineering and Informatics (BMEI).

Lienhard, J. H. V and Lienhard, J .H. V. (2013). *A Heat Transfer Textbook*. 3th Edition, Cambridge, USA: Courier Corporation.

Lih, M. M. (1975). *Transport Phenomena in Medicine and Biology*. New York: Wiley.

Lin, W. L., Yen, J. Y., Chen, Y. Y., Jin, K. W. and Shieh, M. J. (1999). Relationship Between Acoustic Aperture Size and Tumor Conditions for External Ultrasound Hyperthermia. *Medical Physics*, 26(5): 818–824.

Ma, P., Li, X. and Ku, D. N. (1994). Heat and Mass Transfer in a Separated Flow Region for High Prandtl and Schmidt Numbers under Pulsatile Conditions. *International Journal of Heat and Mass Transfer*, 37: 2723–2736.

Mahapatra, T. R., Layek, G. C. and Maiti, M. K. (2002). Unsteady Laminar Separated Flow through Constricted Channel. *International Journal of Non-Linear Mechanics*, 37(2): 171–186.

Maikap, T. K., Mahapatra, T. R., Niyogi, P. and Ghosh, A. K. (2005). Numerical Investigation of Laminar Separated Flow through a Channel with Symmetric Double Expansion. *Acta Mechanica*, 179(3): 197–210.

Majhi, S. N. and Nair, V. R. (1994). Pulsatile Flow of Third Grade Fluids under Body Acceleration-Modeling Blood Flow. *International Journal of Engineering Science*, 32(5): 839–846.

Mallik, B. B., Nanda, S., Das, B., Saha, D., Das, D. S. and Paul, K. (2013). Pulsatile Flow of Casson Fluid in Mild Stenosed Artery with Periodic Body Acceleration and Slip Condition. *Scholars Journal of Engineering and Technology*, 1(1): 27–38.

Mandal, A. P., Sarifuddin and Mandal, P. K. (2015). An Unsteady Analysis of Arterial Drug Transport From Half-Embedded Drug-Eluting Stent. *Applied Mathematics and Computation*, 266(1): 968–981.

Mandal, P. K. (2005). An Unsteady Analysis of Non-Newtonian Blood Flow through Tapered Arteries with a Stenosis. *International Journal of Non-Linear Mechanics*, 40(1): 151–164.

Mandal, P. K., Chakravarty, S. and Mandal, A. (2007a). Numerical Study of The Unsteady Flow of Non-Newtonian Fluid through Differently Shaped Arterial Stenoses. *International Journal of Computer Mathematics*, 84(7): 1059–1077.

Mandal, P. K., Chakravarty, S., Mandal, A. and Amin, N. (2007b). Effect of Body Acceleration on Unsteady Pulsatile Flow. *Applied Mathematics and Computation*, 189(1): 766–779.

Markham, G. and Proctor, M. V. (1983). *Modifications to the Two-Dimensional Incompressible Fluid Flow Code ZUNI to Provide Enhanced Performance*. Central Electricity Generating Board Report TPRD/L/0063/M82.

McKay, J. C., Prato, F. S. and Thomas, A. W. (2007). A literature Review: the Effects of Magnetic Field Exposure on Blood Flow and Blood Vessels in the Microvasculature. *Bioelectromagnetics*, 28(2): 81–98.

McKee, S., Tomé, M. F., Ferreira, V. G., Cuminato, J. A., Castelo, A., Sousa, F. S. and Mangiavacchi, N. (2008). The MAC Method. *Computers and Fluids*, 37(8): 907–930.

Mekheimer, K. S. (2004). Peristaltic Flow of Blood under Effect of a Magnetic Field in a Non-Uniform Channels. *Applied Mathematics and Computations*, 153(3): 763–777.

Merrill, E. W., Cokelet, G. R., Britten, A. and Wells, R. E. (1963). Non- Newtonian Rheology of Human Blood - Effect of Fibrinogen Deduced by Subtraction. *Circulation Research*, 13(1): 48–56.

Merrill, E. W., Cokelet, G. R., Britten, A. and Wells, R. E. (1964). Rheology of Human Blood and Red Cells Plasma Membrane. *Biophysiology Anatomy*, 4: 51–63.

Middleman, S. (1995). Modeling Axisymmetric Flows: Dynamics of Films, Jets, and Drops. *Academic Press*, 1995.

Midya, C., Layek, G. C., Gupta, A. S. and Mahapatra, T. R. (2003). Magnetohydrodynamic Viscous Flow Separated in a Channel with Constrictions. *Journal of Fluid Engineering*, 125: 952–962.

Mirsa, J. and Pal, B. (1999). A Mathematical Model for the Study of the Pulsatile Flow of Blood under an Externally Imposed Body Acceleration. *Mathematical and Computer Modelling*, 29(1): 89–106.

Mosayebidorcheh, S., Hatami, M., Mosayebidorcheh, T. and Ganji, D. D. (2016). Effect of Periodic Body Acceleration and Pulsatile Pressure Gradient Pressure on Non-Newtonian Blood Flow in Arteries. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 38(3): 703-708.

Mozaffarian, D., Benjamin, E. J., Go, A. S., Arnett, D. K., Blaha, M. J., Cushman, M., ... and Howard, V. J. (2015). *Heart Disease and Stroke Statistics - 2016*. Update A Report from the American Heart Association. Circulation, 131(4): e29.

Mustapha, N., Amin, N., Chakravarty, S. and Mandal, P. K. (2009). Unsteady Magnetohydrodynamic Blood Flow through Irregular Multi-Srtenosed Arteries. *Computers in Biology and Medicine*, 39(10): 896–906.

Mustapha, Chakravarty, S., Mandal, P. K. and Amin, N. (2008). Unsteady Response of Blood Flow through a Couple of Irregular Arterial Constrictions to Body Acceleration. *Journal of Mechanics in Medicine and Biology*, 8(3): 395–420.

Mustapha, N., Mandal, P. K., Johnston, P. R. and Amin, N. (2010). A Numerical Simulation of Unsteady Blood Flow through Multi-Irregular Arterial Stenoses. *Applied Mathematical Modelling*, 34(6): 1559–1573.

Nadeem, S. and Akbar, N. S. (2009). Influence of Heat Transfer on a Peristaltic Transport of HerschelBulkley Fluid in a Non-Uniform Inclined Tube. *Communications in Nonlinear Science and Numerical Simulation*, 14(12): 4100–4113.

Nadeem, S. and Akbar, N. S. (2011). Influence of Heat and Chemical Reactions on Walters B Fluid Model for Blood Flow through a Tapered Artery. *Journal of the Taiwan Institute of Chemical Engineers*, 42(1): 67–75.

Nadeem, S., Akbar, N. S., Hayat, T. and Hendi, A. A. (2012). Influence of Heat and Mass Transfer on Newtonian Biomagnetic Fluid of Blood Flow through a Tapered Porous Arteries with a Stenosis. *Transport in Porous Media*, 91(1): 81–100.

Ogulu, A. and Abbey, T. M. (2005). Simulation of Heat Transfer on an Oscillatory Blood Flow in an Indented Porous Artery. *International Communications in Heat and Mass Transfer*, 32(7): 983-989.

Paterson, A. R. (1983). *A First Course in Fluid Dynamics*. Clarendon: The press Syndicate of the University of Cambridge.

Pedley, T. J. (1980). *The Fluid Mechanics of Large Blood Vessels*. Cambridge University Press.

Perktold, K., Peter, R. and Resh, M. (1989). Pulsatile Non-Newtonian Blood Flow Simulation through a Bifurcation with an Aneurism. *Biorheology*, 26(6): 1011–1030.

Plavins, J. and Lauva, M. (1993). Study of Colloidal Magnetite Binding Erythrocytes: Prospects for Cell Separation. *Journal of Magnetism and Magnetic Material*, 122: 349–353.

Prasad, M. K. and Radhakrishnamacharya, G. (2008). Flow of Herschel-Bulkley Fluid through an Inclined Tube of Non-Uniform Cross-Section with Multiple Stenosis. *Archives of Mechanics*, 60: 161–172.

Pries, A. R., Neuhaus, D. and Gaehtgens, P. (1992). Blood-Viscosity in Tube Flow Dependence on Diameter and Hematocrit. *American Journal of Physiology*, 263(6): H1770–H1778.

Rabby, M. G., Shupti, S. P. and Molla, M. M. (2014). Pulsatile Non-Newtonian Laminar Blood Flows through Arterial Double Stenoses. *Journal of Fluids*, 2014.

Rana, K. and Neeves, K. B. (2016). Blood Flow and Mass Transfer Regulation of Coagulation. *Blood Reviews*, 30(5): 357–368.

Ramsay, W. N. M. (1957). The Determination of the Total Iron-Binding Capacity of Serum. *Clinica Chimica Acta*, 2(3): 221–226.

Rappitsch, G. and Perktold, K. (1996). Computer Simulation of Convective Diffusion processes in Large Arteries. *Biomechanics*, 39(2): 207–215.

Rappitsch, G., Perktold, K. and Pernkopf, E. (1997). Numerical Modelling of Shear-Dependent Mass Transfer in Large Arteries. *International Journal for Numerical Methods in Fluids*, 25(7): 847–857.

Rathod, V. P. and Habeeb, A. (2008). Pulsatile Inclined Two Layered Flow under Periodic Body Acceleration. *Journal of Indian Academy of Mathematics*, 30(1): 137–151.

Rathod, V. P., Begum N. and Sheeba, R. I. (2006). Inclined Pulsatile Flow of Blood with Periodic Body Acceleration. *Acta Ciencia Indica*, 32(4): 1509–1516.

Rathod, V. P., Rani, I. S., Tanveer, S. and Rajput, G. G. (2004a). *Pulsatile Flow of Blood under Periodic Body Acceleration and through Vessels of Exponentially Divergence*. Proceeding of National Conference Advances Fluid Dynamics, 127–138.

Rathod, V. P. and Tanveer, S. (2009). Pulsatile Flow of Couple Stress Fluid through a Porous Medium with a Periodic Body Acceleration and Magnetic Field. *Malaysian Mathematical Sciences Society*, 32(2): 245–259.

Rathod, V. P., Tanveer, S., Rani, I. S. and Rajput, G. G. (2004b). *Pulsatile Flow of Blood with Periodic Body Acceleration and Magnetic Field through an Exponentially Diverging Vessel*. Proceeding of National Conference Advances Fluid Dynamics, 106–117.

Reiner, M. and Blair, G. S. (1959). The Flow of Blood through Narrow Tubes. *Nature*, 23: 354.

Romig, M. F., Thomas F., Irvine, Jr. and James, P. H. (1964). The Influence of Electric and Magnetic Fields on Heat Transfer to Electrically Conducting Fluids, in Advances in Heat Transfer. *Elsevier*, 267–354.

Ruuge, E. K. and Rusetski, A. N. (1993). Magnetic Fluid as Drug Carriers: Targeted Transport of Drugs by a Magnetic Field. *Journal of Magnetism and Magnetic Material*, 122(1): 335–339.

Sankar, A. R., Gunakala, S. R. and Coissiong, D. M. G. (2013). Two-layer Blood Flow through a Composite Stenosis in the Presence of a Magnetic Field. *Journal of Application or Innovation in Engineering and Management*, 2(12): 2319–4847.

Sankar, D. S. and Lee, U. (2009). Mathematical Modeling of Pulsatile Flow of Non-Newtonian Fluid in Stenosed Arteries. *Communications in Nonlinear Science and Numerical Simulation*, 14(7): 2971–2981.

Sanyal, D. C., Das, K. and Debnath, S. (2007). Effect of Magnetic Field on Pulsatile Blood Flow through an Inclined Circular Tube with Periodic Body Acceleration. *Journal of Physical Sciences*, 11: 43–56.

Sarifuddin and Mandal, P. K. (2016). Effect of Diffusivity on the Transport of Drug Eluted from Drug-Eluting Stent. *International Journal of Applied and Computational Mathematics*, 2(2): 291–301.

Sarifuddin, Chakravarty, S., Mandal, P. K. and Andersson, H. I. (2009a). Mass Transfer to Blood Flowing through Arterial Stenosis. *Zeitschrift fr angewandte Mathematik und Physik*, 60(2): 299–323.

Sarifuddin, Chakravarty, S., Mandal, P. K. and Andersson, H. I. (2009b). Effect of Heat and Mass Transfer on Non-Newtonian Flow Links to Atherosclerosis. *International Journal of Heat and Mass Transfer*, 52(25): 5719–5730.

Sarifuddin, Chakravarty, S. and Mandal, P. K. (2009c). Effect of Asymmetry and Roughness of Stenosis on Non-Newtonian Flow Past an Arterial Segment. *International Journal of Computational Methods*, 6(3): 361–388.

Sarifuddin, Chakravarty, S. and Mandal, P. K. (2013). Physiological Flow of Shear-Thinning Viscoelastic Fluid Past an Irregular Arterial Constriction. *Korea-Australia Rheology Journal*, 25(3): 163–174.

Sarifuddin, Chakravarty, S., Mandal, P. K. and Layek, G. C. (2008). Numerical Simulation of Unsteady Generalized Newtonian Blood Flow Through Differently Shaped Distensible Arterial Stenoses. *Journal of Medical Engineering and Technology*, 32(5): 385–399.

Sharma, P. R., Ali, S. and Katiyar, K. (2011). Mathematical Modeling of Heat Transfer in Blood Flow through Stenosed Artery. *Journal of Applied Sciences Research*, 7(1): 68–78.

Sharma, M. K., Singh, K. and Bansal, S. (2014). Pulsatile MHD Flow in an Inclined Catheterized Stenosed Artery with Slip on the Wall. *Journal of Biomedical Science and Engineering*, 7(4): 194.

Shaw, S., Murthy, P. V. S. N. and Pradhan, S. C. (2010). The Effect of Body Acceleration on Two Dimensional Flow of Casson Fluid through an Artery with Asymmetric Stenosis. *The Open Transport Phenomena Journal*, 2(1): 55–68.

Shereliff, J. A. (1965). *A Textbook of Magnetohydrodynamics*. New York: Pergamon Press.

Sicilian, J. M. and Hirt, C. W. (1984). An Efficient Computation Scheme for Tracking Contaminant Concentrations in Fluid Flows. *Journal of Computational Physics*, 56(3): 428-447.

Sinha, A. and Misra, J. C. (2014). MHD Flow of Blood through a Dually Stenosed Artery: Effects of Viscosity Variation, Variable Hematocrit and Velocity-Slip. *Canadian Journal of Chemical Engineering*, 92(1): 23–31.

Sinha, A., Misra, J. C. and Shit, G. C. (2016). Effect of Heat Transfer on Unsteady MHD Flow of Blood in A Permeable Vessel in the Presence of Non-Uniform Heat Source. *Alexandria Engineering Journal*, 55(3): 2023–2033.

Sinha, A. and Mondal, A. (2015). Mathematical Analysis of Pulsatile Blood Flow and Heat Transfer in Oscillatory Porous Arteries. *International Journal of Advances in Applied Mathematics and Mechanics*, 2(3): 211–224.

Sinha, P. and Singh, C. (1984). Effects of Couple Stresses on the Blood Flow through an Artery with Mild Stenosis. *Biorheology*, 21(3): 303–315.

Srinivasacharya, D. and Rao, G. M. (2015). MHD Effect on the Couple Stress Fluid Flow Through a Bifurcated Artery. *Procedia Engineering*, 127: 877–884.

Sreenadh, S., Pallavi A. R. and Satyanarayana, B. H. (2011). Flow of a Casson Fluid through an Inclined Tube of Non-Uniform Cross Section with Multiple Stenoses. *Advances in Applied Science Research*, 2(5): 340–349.

Steinman, D. A., Thomas J. B., Ladak H. M., Milner J. S. and Rutt, J. D. (2002). Spence, Reconstruction of Carotid Bifurcation Hemodynamics and Wall Thickness Using Computational Fluid Dynamics and MRI. *Magnetic Resonance in Medicine*, 47(1): 149–159.

Sud, K. and Sekhon, G. (1985). Arterial Flow under Periodic Body Acceleration. *The Bulletin of Mathematical Biology*, 47(1): 35–52.

Sud, K. and Sekhon, G. (1986). Analysis of Blood through a Model of the Human Arterial System under Periodic Body Acceleration. *Journal of Biomechanics*, 19(11): 929–941.

Sud, K. and Sekhon, G. (1987). Flow through a Stenosed Artery Subject to Periodic Body Acceleration. *Medical and Biological Engineering and Computing*, 25(6): 638–644.

Sud, K. and Sekhon, G. (1989). Blood Flow through the Human Arterial System in the Presence of a Steady Magnetic Field. *Physics in Medicine and Biology*, 34(7): 795–805.

Sud, K., Suri, P. K. and Mishra, R. K. (1974). Effect of Magnetic Field on Oscillating Blood Flow in Arteries. *Study Biophysica*, 46(3): 163–171.

Sud, V. K., Suri, P. K. and Mishra, R. K. (1978). Laminar Flow of Blood in an Elastic Tube in the Presence of Magnetic Field. *Study Biophysica*, 69: 175–186.

Sun, N., Wood, N. B., Hughes, A. D., Thom, S. A. and Xu, X. Y. (2007). Influence of Pulsatile Flow on LDL Transport in the Arterial Wall. *Annals of Biomedical Engineering*, 35(10): 1782–1790.

Sutton, G. W. and Sherman, A. (1965). *Engineering Magnetohydrodynamics*. New York: McGraw-Hill.

Tanwar, V. K., Varshney, N. K., and Agarwal, R. (2016). Effect of Body Acceleration on Pulsatile Blood Flow through a Catheterized Artery. *Advances in Applied Science Research*, 7(2): 155–166.

Tarbell, J. M. and Qiu, Y. (2000a). *Arterial Wall Mass Transport: the Possible Role of Blood Phase Resistance in the Localization of Arterial Disease*. The Biomedical Engineering Handbook, 2nd Ed. New York: CRC, 100-1.

Tarbell, J. M. and Qiu, Y. (2000b). Numerical Simulation of Oxygen Mass Transfer in a Compliant Curved Tube Model of a Coronary Artery. *Annals of Biomedical Engineering*, 28(1): 26–38.

Tashtoush, B. and Magableh, A. (2007). Magnetic Field Effect on Heat Transfer and Fluid Flow Characteristics of Blood Flow in Multi-Stenotic Arteries. *Journal of Heat and Mass Transfer*, 44(3): 297–304.

Tiari, S., Ahmadpour, B. M., Tafazzoli-Shadpour, M. and Sadeghi, M. R. (2011). *An Experimental Study of Blood Flow in a Model of Coronary Artery with Single and Double Stenosis*. Proceedings of the 18th Iranian Conference on Biomedical Engineering (ICBME), 14–16.

Tomé, M. F. and McKee, S. (1994). GENSMAC: A Computational Marker and Cell Method for Free Surface Flows in General Domains. *Journal of Computational Physics*, 110(1): 171–186.

Tu, C. and Deville, M. (1996). Pulsatile Flow of Non-Newtonian Fluids through Arterial Stenoses. *Journal of Biomechanics*, 29(7): 899–908.

Tu, C., Deville, M., Dheur, L. and Vanderschuren, L. (1992). Finite Element Simulation of Pulsatile Flow through Arterial Stenosis. *Journal of Biomechanics*, 25(10): 1141–1152.

Tungjitkusolmun, S., Staelin, S. T., Haemmerich, D., Tsai, J. Z., Cao, H., Webster, J. G., Lee, Jr. F. T., Mahvi, D. M. and Vorperian, V. R. (2002). Three Dimensional Finite Element Analyses for Radio-Frequency Hepatic Tumor Ablation. *Biomedical Engineering IEEE Transactions*, 49(1): 3–9.

Tzirtzilakis, E. E. (2005). A Mathematical Model for Blood Flow in Magnetic Field. *Physics of Fluids*, 17(7): 103–115.

Tzirtzilakis, E. E. (2008). Biomagnetic Fluid Flow in a Channel with Stenosis. *Physica D: Nonlinear Phenomena*, 237(1): 66–81.

Vajravelu, K., Sreenadh, S. and Babu, V. R. (2005). Peristaltic Transport of a HerschelBulkley Fluid in an Inclined Tube. *International Journal of Non-Linear Mechanics*, 40(1): 83–90.

Vardanyan, V. A. (1973). Effect of Magnetic Field on Blood Flow. *Biophysics*, 18: 515–521.

Varshney, G., Katiyar, V. K. and Kumar, S. (2010a). Effect of Magnetic Field on the Blood Flow in Artery Having Multiple Stenosis: a Numerical Study. *International Journal of Engineering, Science and Technology*, 2(2): 67–82.

Varshney, G., Katiyar, V. K. and Kumar, S. (2010b). Numerical Modeling of Pulsatile Flow of Blood through a Stenosed Tapered Artery under Periodic Body Acceleration. *Journal of Mechanics in Medicine and Biology*, 10(2): 251–272.

Verma, S. R. and Srivastava, A. (2013). Effect of Magnetic Field on Steady Blood Flow through an Inclined Circular Tube. *International Journal of Engineering Research and Applications (IJERA)*, 3(4): 428–432.

Villoresi, G., Kopytenko, Y. A., Ptitsyna, N. G., Tyasto, M. I., Kopytenko, E. A, Iucci, N. and Voronov, P. M. (1994). The Influence of Geomagnetic Storms and Man Made Magnetic Field Disturbances on the Incidence of Myocardial Infarction in St. Petersburg (Russia). *Medical Physics*, 10: 107–117.

Voltairas, P. A., Fotiadis, D. I. and Michalis, L. K. (2002). Hydrodynamics of Magnetic Drug Targeting. *Journal of Biomechanics*, 35(6): 813–821.

Wada, S., Koujiya, M. and Karino, T. (2002). Theoretical Study of the Effect of Local Flow Disturbances on the Concentration of Low-Density Lipoproteins at the Luminal Surface of End-to End Anastomosed Vessels. *Medical and Biological Engineering and Computing*, 40(5): 576–587.

Wang, Y. N., Ali, N. and Hayat, T. (2009). Peristaltic Motion of a Magnetohydrodynamic Generalized Second-Order Fluid in an Asymmetric Channel. *Journal of Applied Mathematical Sciences*, 27(2): 415–435.

Welch, J. E., Harlow, F. H., Shannon, J. P. and Daly, B. J. (1996). *The MAC method*. Los Alamos Scientific Lab. Report LA-3425. Los Alamos.

WHO (2003). *Cardiovascular Diseases (CVDs)*. Retrieved on March, 2013, from http://www.who.int/mediacentre/factsheets/fs317/en/index.html..

Xenos, M. A. and Tzirtzilakis, E. E. (2013). MHD Effects on Blood Flow in a Stenosis. *Advances in Dynamical Systems and Applications*, 8(2): 427–437.

Yao, H., Ang, K. C., Yeo, J. H. and Sim, E. K. W. (2000). Computational Modelling of Blood Flow through Curved Stenosed Arteries. *Journal of Medical Engineering and Technology*, 24(4): 163–168.

Young, D. F. (1968). Effects of a Time-Dependent Stenosis of Flow through a Tube. *Journal of Engineering and Industrial*, 90(2): 248–254.