CHAPTER 1

INTRODUCTION

In recent times, there could be noticed an increasing, considerable attention and great enthusiasm in the viscometric studies and mathematical modeling of blood flow in different flow situations (Fung 1981, 1984, Pedley 1980, Puniyani and Nimi 1998, Biswas 2000). Human systems are complex and there functionings are more complex and complicated. The quest for unveiling the functions of human physiological systems in general and cardiovascular system in particular, is quite old. The mechanics of physiological systems along with their locations, structure, complex situation and diverse functions, is dealt in biomechanics. It aims at understanding the mechanics of living systems and also the fundamental understanding, diagnosis, prognosis, treatment and cure of cardiovascular, renal, arterial diseases etc. (Fung 1981). Cardiovascular (cvs) system is considered as one of the most important physiological system (Guyton 1970, Boyd 1963, Fung 1981). It has three basic components viz, cardio, the heart, body fluid blood and vascular system i.e., arteries, veins and capillaries which together form a closed system. Human blood is a marvellous viscous fluid which flows through blood vessels, supplies nutrients to organs and tissues present in the body and, brings back the metabolic waste products for their proper elimination. Blood is a complex fluid and, its composition and functioning are equally complex. Blood vessels are also complicated due to their location, non-uniformity, branching, tapering, inclining etc., and the output of the flow source, the heart is also complicated due to its complex constitution and pumping mechanism. It is therefore important to get an insight into the complicated blood flow situations. In order to understand the flow behaviour of blood, different flow geometries are proposed by many investigators (Pedley 1980, Fung 1981, Puniyani and Nimi 1998, Biswas 2000).

Human blood is a suspension of different tiny cells in a continuous aqueous substance, called plasma. The heart pumps blood which is transported to different parts of the body by arteries, veins and capillaries (Guyton 1970, Fung 1981). Further, the arteries present in the human body are not always uniform in shape. Due to this non-uniformity in blood vessels, there arises a variation in pressure gradient in blood flow. The complex geometry of arteries is also an important factor that affects the
hydrodynamic factors (Guyton 1970, Puniyani and Nimi 1998). There is no doubt that
tapering in arteries is a significant aspect in mammalian arterial system and the flow
along a tapering wall, may alter the flow situation to a great extent.

It may be worth mentioning that an arterial constriction, occurring due to an
abnormal growth at the lumen of an artery and its gradual advances is closely
associated with the changes in blood flow, flow patterns, pressure drop and resistance
to flow (Liu et al. 2004, Poltem et al. 2006). This unwanted formation is usually
called stenosis or atherosclerosis which is a kind of vascular disease (Boyd 1963,
Guyton 1970). Which is reported as the leading cause of death in developed countries
(Caro 1981). As a result, the bore of blood vessels becomes narrowed and there arises
occlusion in regular flow, due to the presence of blockage in the artery. This
unfamiliar growth develops in three stages, viz, mild, moderate and severe and in
turn, blood flow is disturbed partially to wholly. When the artery is block severely,
there may be complete cut off in blood supply or, an artery may be completely sealed
off. This results in cardiovascular diseases, like angina pectoris, stroke, coronary
thrombosis, myocardial infarction etc. (Guyton 1963, Biswas 2000).

Sometimes, for many useful medical and clinical purposes, artificial catheters are
inserted in an artery. Pressure-flow relationship changes considerably in a stenosed
artery and the same alters significantly when a catheter is inserted in a stenosed artery,
as it could further enhance the impedance to flow (Biswas and Charaborty 2010).
Therefore it may be physiologically important to investigate pressure-flow
relationship through a catheterized stenosed artery.

In blood flow modeling, boundary conditions used for a velocity field, is the usual
no-slip condition for classical viscous theory (Schlichting 1968). However, a number
of studies of suspensions in general and blood flow in particular both theoretical
(Vand 1948, Bloch 1968, Brunn 1975, Nubar 1967, Bennet 1967) and experimental
(Bugliarello and Hayden 1962) have suggested the likely presence of slip at the flow
boundaries. It seems that the employment of velocity slip at the vessel wall or, at the
interface for two-layered model, may be quite rational in blood flow modeling.

As it is reported that blood leaves a peripheral plasma (Newtonian fluid) near
the vessel wall and a core region of red cell suspension (non-Newtonian fluid) (Fung
1981, Biswas 2000), it would be rational to consider two-layered models in blood flow. In two-layered models, blood is assumed to behave like a Newtonian fluid (Schlichting 1968) and a non-Newtonian fluid (Kapur et al. 1982, Fung 1984) in this constricted artery.

1.1 Circulatory system
In human body, there prevails different bodily systems for performing various physiological functions and maintaining body balance and metabolic processes. Among these systems, circulatory system is regarded as one of the most important system, due to its functioning in the river of blood. Also, cardiovascular system is included in the circulatory system (Boyd 1963, Guyton 1970). Human cardiovascular system (cvs) comprises of three primary components viz, cardio— the heart, blood vessels—a network of different flexible, porous and visco-elastic tubes and blood—a suspension of different tiny cells, suspended in an aqueous continuous substance, called plasma. Further, together these components form a closed system (Fung 1981, Guyton 1970).

1.1.1 Cardio—A Muscular double pump
The output of the flow source is the cardio or, heart which is a hard working muscular double pump. It is conical in shape, weighing 340 grams, red brown in colour and moving through 90,000 kilometer of blood vessels. Due to the intermittent pumping of heart muscles, there produces a pressure difference between its diastolic and systolic states. This pressure drop arising due to expansion and contraction when divided by an artery segment, results in the pressure gradient which drives the blood to flow in the circulatory channel (Guyton 1970).

1.1.2 Blood Vessels—A Network of Tubes
Heart is connected with a network of blood vessels which are the inseparable part of the circulatory system. The primary functions of blood vessels are to transport nutrients to organs and tissues and, metabolic wastes to the places of disposal. The important components of cvs are arteries, veins and capillaries. The vessels are elastic, porous and flexible, arteries carry oxygenated blood to every part of
the body and veins return the deoxygenated blood to the reservoir heart for recycling. Aorta is the largest artery and the smallest artery is an arteriole.

1.1.3 Blood—A Body Fluid

Human blood is a suspension of red cells (erythrocytes) white cells (leukocytes) and platelets (thrombocytes) in an aqueous substance, called plasma (Guyton 1970, Fung 1981). Blood flows through blood vessels and supply oxygen and other nutrients to organs and tissues and, brings back carbon dioxide and other wastes due to metabolic processes. Among the cells, red cells are biconcave and huge in numbers, white cells are rounded and smaller in number and, platelets are very less and the smallest in number. By volume, the red cells compose about 45% of whole blood and the plasma constitutes about 55%. The most important striking feature of blood is that it remains fluid even at hematocrit (the volume fraction occupied by erythrocytes) of 95 to cent percent (Guyton 1970, Fung 1984) due to the presence of huge number of red cells in plasma, blood is red in colour and a highly viscous fluid.

1.2 Tapered Vessels

Blood vessels are an inseparable part of cardiovascular system. The primary function of these vessels is to allow circulation of the marvelous body fluid without any hindrance to flow. The main vessels include arteries, veins and capillaries which are connected to each other and with the heart. Through this network of tubes, blood flows, transports nutrients and collects metabolic wastes from each and every body organ or tissue. In this way, blood vessels play an important role in supplying nutrition and regulating metabolic process (Guyton 1970, Fung 1981, Boyd 1963). Our heart pumps blood which is transported to different parts of the body through arteries, veins and capillaries. Blood vessels are generally circular, uniform and smooth in shape as such blood flows without any impedance to flow. However, the arteries present in human body are not always uniform in shape rather, they are branching, bifurcating, tapering, bending, inclining etc. and due to this non-uniformity in blood vessels, there arises a variation in pressure gradient in the blood flow. The complex geometry of arteries is also an important factor which affects the hemodynamic factors (Guyton 1970, Puniyani and Nimi 1998). In view of above, blood flow through tapered vessels in horizontal and inclining positions, may be significant from the physiological point of view. Further, flow through tapering
vessels becomes more complicated due to the emergence of an arterial constriction at the vessel wall. The flow situation is aggravated due to the insertion of an artificial catheter in the constricted arterial segment. It may be rational to consider these flow situations, in the present investigation.

1.3 Arterial Stenosis

The word stenosis is a generic medical term which means a narrowing of bodily passage, tube or orifice (Guyton 1979). It is thickening and hardening of the arterial walls. Due to this gradual thickening of vessel wall, the artery may be partially blocked or sealed off completely due to the formation of blood clot, obstructing the flow of blood through the circulatory system which is called thrombosis. Sometimes stenosis or atherosclerosis strikes the arteries of the heart. As a result, blood supply inside coronary arteries becomes obstructed which is called coronary thrombosis. This result in myocardial infarction which is followed by a cassation of cardiac contraction that in turn results in another kind of heart attack (Guyton 1970). It seems important to include some information about the initiation, growth, problems and treatment procedure on atherosclerosis.

1.3.1 Initiation of Stenosis

It may be initiated due to the deposits of cholesterol, fat, plaque and other lipids at the inner arterial wall, at one or more locations. This plaque impedes regular blood flow. Although, there is no clear cut information for such abnormal formation at an artery wall, it is believed that deposits of fatty substances, cellular waste products, cholesterol, calcium and fibrin, could be responsible for the development of stenosis (Mishra et al. 2011). The gradual accumulation of fat and lipid particles in the lumen of an artery, causes several kinds of stenosis viz, mild moderate and severe. In the mild formation, blood is partially disturbed but the complications aggravate due to the subsequent growths moderate and severe which may lead to a complete cut off in the blood supply to different parts.

1.3.2 Development

The abnormal and unusual growth in the form of a tumor at an artery wall, creates problems in blood circulation. The factors which influence the development in stenosis growth are the mechanical hydrodynamic factors like, lateral wall pressure, turbulence and wall shear stress etc. once stenosis is formed, it may advance through stages, due to gradual deposits of pearly
materials like lipid, cholesterol and other fatty substances on the innermost arterial wall (Guyton 1970). This development may be referred as mild, moderate and severe which reduce the effective diameter of the bore in blood vessel, create hindrance to regular flow and, lead to different cvs and arterial diseases.

1.3.3 Problems Thereof

Stenosis or atherosclerosis is a pathological process that takes place in the arteries and may be one of the causes of heart attacks, stroke and peripheral arterial diseases (Guyton 1970). An artery when blocked by plaque or a blood clot, reduces blood flow to the brain and may cause a stroke. The formation and gradual advancement of stenosis at several locations of cvs, can create serious circulatory disorders (Mac Donald 1979). The plaque, made up of excess cholesterol or other fats in the artery wall, may lead to narrowing of arteries and decreases the blood flow which causes chest pain or pain in legs. Apart from this, plaque can sometimes become unstable and rupture the vessel wall, leading to heart attacks and strokes.

1.3.4 Treatment Procedure

Undoubtedly, there cannot be more frightening than a heart attack which may lead to chest pain and other serious physiological complications in the body. As long as our heart receives proper supply of nutrients, it stays in a normal state and healthy conditions. However, certain risk factors like blood pressure, diabetes, smoking and high blood cholesterol, set the stage of heart disease. This lead to deposition of cholesterol and such deposition of fat in blood vessels, is called atherosclerosis or stenosis which is a vascular disease and cause blockage (i.e. mild form) still allowing enough oxygen and blood to flow through, but its gradual growth leading to moderate and severe stenosis, create serious complications in the flow like, scaling off a wholly cut off blood supply to different locations. The two ways to treat block arteries may be included as angioplasty and bi-pass surgery, the standard treatment till 1970. However, these have side effects which in many cases may turn fatal. A new treatment that could be less risky has this procedure i.e. a balloon is inflated for 30 to 60 seconds and drug coated on the balloon is released to prevent the cell from accumulating and blocking the arteries overtime. In our model, we have employed a velocity slip at the constricted wall of interface in two-layered models, and so, such drugs or device in producing slip at the constricted wall, may act as alternative to
angioplasty or bi-pass surgery and stents, benefit in the long run and improve the condition considerably.

1.4 Two-layered Model
Blood flow through tapered arteries prevailing in cvs, has been investigated by many authors. They have employed the velocity slip or no-slip condition at the tapering wall. In such modeling, blood is assumed to act as Newtonian and non-Newtonian fluids. Further, blood flow through a constricted tapering region is also important from physiological conditions. To consider the flow of blood in the annular region, confined between an artificial catheter and a constricted tapering artery segment, is also equally important from medical and clinical aspects. It is already reported both theoretically and experimentally that blood while flowing through narrow blood vessels, leaves a cell poor region near the wall. As such two-layered blood flow, with peripheral plasma layer (ppl) and a core of red cell suspension, may be realistic from the physiological point of view. It may be recorded that plasma in the neighbourhood of vessel wall is represented by a Newtonian fluid while red cell suspension in the core region, is considered as a non-Newtonian fluid. In the ongoing analysis, two-layered blood flow in a tapering constricted artery, has been considered with applying a slip velocity condition at the interface of two layers. Flow situations for unidirectional flow, asymmetric stenosis formation and annular region, in the tapering regions for horizontal and inclined positions, have been developed.

1.5 Mathematical Models
In this present investigation, some mathematical models on blood flow have been put forward. In the ongoing analysis, some of the existing models on blood flow, have been included

1.5.1 Newtonian Models
A fluid is said to behave Newtonian if the shear stress versus rate of strain relation is linear. It is reported that body fluid blood behaves as a Newtonian fluid when it flows through larger arteries (tube diameter is about 1 mm above) at high shear rate (Taylor 1959, Fung 1981). Young has analysed the effects of stenosis on flow properties of blood by considering blood as a Newtonian fluid (Young 1969). The numerical analysis of steady generalised blood flow, by taking blood, like a Newtonian fluid, has been presented by Baojens et al. (1963).
A good many investigators have examined the blood flow in Catheterised artery by treating blood as Newtonian viscous fluid with no-slip boundary conditions (Kanai et al. 1970, Jayaraman and Tewary 1975). The importance of slip velocity at the flow boundaries, has been referred by many researchers both theoretically and experimentally (Vand 1948, Bloch 1962, Brunn 1975, Nubar 1967, Bugliarello and Hayden 1962, Bennett 1967). In their studies, blood is taken as Newtonian fluid model by Biswas and Chakraborty (2009. 2010).

1.5.2 Non-Newtonian Models

It is reported by some experimental works that in the vicinity of a stenosis, the shear rate of blood is low and therefore the steady and non-Newtonian character of blood in that section is important (Mishra et al. 2008). In view of above, many authors have assumed blood as a non-Newtonian fluid while dealing with the flow behaviour inside a stenosed artery. In our study, we shall deal with the models of blood flow where in blood flow will be assumed to act as Newtonian and non-Newtonian fluids.

1.6 Present Work

The present work addresses the mathematical modeling of blood flow inside constricted tapered and catheterized annular regions for horizontal and inclined vessels, in case of steady two-layered flow of blood with the introduction of a velocity slip at the interface of two layers, under the presence or absence of body force.

a. Outline of the thesis

In the ongoing analysis, physiological fluid blood is assumed to behave like both Newtonian and non-Newtonian fluids. Steady laminar flow is considered in the study, so that the involvement of several variables and their specific role as well as possible influence, could be dealt with. The study focuses on hydrodynamic forces that affect the flow of blood in a diseased arterial system. Theoretical investigations are conducted to analyze the flow parameters included viz, velocity slip, shape parameter etc.

b. Aim

The aim of the thesis is to study the behaviour of two-layered unidirectional blood flow through the stenosed, inclined, tapered and catheterised artery models. The influence of Newtonian and non-Newtonian nature of blood, steady behaviour on asymmetric stenotic field and other flow parameters, are examined.
c. **Objectives**

The objectives of the present effort have enlisted the following:

- To investigate the two-layered flow through the tapering stenosed geometry model, by considering different flow situations and conditions.
- To study the effects of stenosis size, location and shape parameter, slip velocity, artery inclination, annular region, tapering angle etc. on different flow variables.
- To compute the numerical work for the graphical representation of flow variables, in order to include the flow of blood both qualitatively and quantitatively.

**Methodology**

Apart from considering the basic equations governing of fluid flow, the constitutive equations for blood, behaving as Newtonian and non-Newtonian fluids, are dealt with. Integration of boundary value problems by usual method has been done in the work. In the computational work and for graphical representation relevant data for parameters are employed.

**Motivation**

The motivation behind this theoretical effort, in the midst of proposing different blood flow models, under separate flow situations, is to get an insight into the complex and complicated physiological situations, prevailing in human cvs.

**Thesis Structure**

The theoretical work that is performed here for dealing with the steady two-layered blood flow situations, inside asymmetric stenosed artery, may be organized with the following chapters and sections

- Chapter 1 includes a general introduction, detailing the different blood flow situations, relevant to this investigation.
- Chapter 2 presents the relevant and necessary review of existing literature.
- Chapter 3 deals with two-layered steady flow of blood behaving as a Newtonian fluid with different viscosities in a stenosed tapering artery. The flow of blood is considered axially symmetric, laminar and one-dimensional in
nature and, stenosis growth in an asymmetric form. To explain this unidirectional flow, velocity slip condition at the interface of layers is employed. Analytical expressions of different flow variables are obtained and their variations with parameters are presented graphically. Applications of this modeling to cvs diseases are included.

- Chapter 4 examines the two-layered blood flow of Newtonian fluid through an inclined tapering stenosed artery. The flow is assumed to be steady and one-dimensional and, slip velocity condition is used at the interface of fluids. The influences of slip velocity, stenosis shape parameter, artery inclination, tapering angle etc., are considered.

- Chapter 5 accommodates a two-layered annular flow of blood, enclosed between a catheter and stenotic wall/interface, through a tapering constricted artery, subject to velocity slip condition at the interface. Blood is assumed to act as a Newtonian fluid. The effect of slip parameter, shape parameter etc, on the annular flow, is studied. Physiological applications of this modeling are included.

- Chapter 6 deals with two-layered model of blood, behaving as Casson fluid inside a constricted tapering artery, with slip condition at interface of fluids. The influence of yield stress, shape parameter, velocity slip etc. on blood flow are recorded.

- Chapter 7 explains two-layered model of blood, acting as Bingham plastic fluid, through a tapering constricted artery with the employment of slip condition at the interface of fluids. The effect of shape parameters, slip velocity, yield stress etc, on the flow of blood, are discussed.

- References enlist a good deal of important, related and relevant mathematical models, experimental observations and other available literature on blood flow modeling.

- Summary of the work carried out in this theoretical investigation that includes different blood flow models, under different flow situations and conditions and, their possible improvement and, scope of further and future study, has been included at the end.

- In the Appendix, a list of communications, prepared form this investigation, has been included.
The survey of literature could play an important role in carrying out any investigation. It supplies recent and relevant information for helping and promoting the research work. In view of above, a review of recent and relevant literature, is dealt in next chapter2.