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Mass transport across porous wall of a microtube: A facile way to diagnosis of diseased state

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ABSTRACT

Mass transport characteristics of a neutral solute in a Casson fluid through a microtube with porous wall under the influence of both pressure and electric field are attempted in this work. The velocity and concentration fields were derived from first principles analytically. The expression of Sherwood number was obtained and impact of rheological parameters on Sherwood number was quantified. Influence of system parameters on solute transport characteristics in terms of permeation flux and concentration was established in detail. Finally, a theoretical method was developed to identify the diseased state by detecting the stagnation point in the microfluidic platform without any chemical reagents.

1. Introduction

Microfluidics and nanofluidics are the engineering fields attracting immense focus of the research community in last two decades [1]. The main reason is introduction of miniaturized fluidic devices and their immense applicability in medical science and other fields [1]. These microfluidic devices have changed the outlook of engineering replacing big scale plants by smaller seized equipment, e.g., power plant on a chip [2]. Large volume reactors are substituted by arrays of micro reactors having greater efficiency and control of performance. Lab on chip technology has become an alternative to whole pathological laboratory by a small chip having potential for diagnosis of biofluids [3].

Physiological fluids are gaining importance in microfluidic research. These fluids have widely varied rheological characteristics and composition. They carry the signature of pathogens in diseased conditions of the body. Virus and bacteria propagate by these fluids from one location of the body to another. Malignant cells are transported from its source to a new destination within the host body and this phenomenon is known as metastasis leading to cancer [4]. Continued research efforts are undertaken in this area and microfluidics can contribute in better understanding of underlying transport phenomena substantially. Blood and Lymph are two most abundant physiological fluids of human body and in terms of volume percentage, blood is the most important one [5]. Blood not only transports oxygen and essential nutrients to the cells but also works as the body coolant playing a critical role in body defence mechanism [6]. Upon infection by pathogen, blood is the first medium to be contaminated and one can diagnose the exact disease by its analysis. Blood viscosity, threshold shear stress, hematocrit level are some factors which are immensely important for maintaining a stable health condition in a human body. If one of these parameters is changed by any means, that may be fatal. On the contrary, estimation of these parameters gives an idea about any anomaly present in the body. Threshold shear stress of blood changes depending on hematocrit level, concentration of triglyceride, etc. Polycythemia is a diseased condition when blood hematocrit level exceeds 50 and threshold shear stress (τ_c) increases to 0.0183 Pa [7]. Hyperfibrinogenemia is a rare disease when τ_c increases to 0.006 Pa [7]. Diabetic blood apparently does not show any rheological abnormality but if the same blood possesses an enhanced hematocrit level, the detection of blood glucose level becomes difficult due to strong interference of hematocrit with the diagnostic procedure [8]. Crohn's disease is characterized by critical symptoms, like, fistulae or stenoses and patients with these symptoms generally need to undergo surgery. However, these diseases can be detected by measuring the blood hematocrit level which is not only easy but cost effective as well [9]. Rheological changes in blood have an influence on platelets activation and thrombus growth in the artery facilitating the fatal and life threatening phenomenon of arteriole thrombosis [10]. Sepsis and septic shocks are the major causes of (40%–50%) mortality rate in intensive care units. Rheology of red blood cell is altered during the sepsis shocks in body that is responsible for change of the microcirculation system leading to multiple organ failure and

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Notations

A	coefficient defined in Eq. (12)
A_1	coefficient defined as, $A_1 = \frac{1}{4}\left(Re \cdot Sc \cdot \frac{d}{L}\right)\frac{1}{G}A(\kappa R, G, \tau_c)$
B	coefficient defined as, $B = \frac{3\overline{Pe_w}}{8(A_1)^{1/3}}$
c	concentration of solute, kg/m^3
c^*	non-dimensional concentration
c_0	initial concentration
c_p	permeate concentration, kg/m^3
c_w	wall concentration, kg/m^3
c_w^*	non-dimensional wall concentration
d	diameter of the tube, m
D	diffusivity, m^2/s
e	charge of an electron, 1.6×10^{-19} C
E_x	axial electric field, v/m
G	ratio between shear stress velocity and Smoluchowski velocity
I	integral constant defined as, $\int_0^\infty \exp\left(-\frac{\eta^3}{9} - B\eta\right)d\eta$
I_1	Bessel function of first kind
I_0	zeroth order Bessel function
k	mass transfer coefficient, m/s
k_B	Boltzmann constant, 1.38064852 $\times 10^{-23}$ m^2 kg s^{-2} K^{-1}
k_1	constant defined in Eq. (C8)
k_2	constant defined in Eq. (C9)
L	length of the tube, m
L_p	permeability of the tube wall, m/Pa s
n_∞	Avogadro's number, 6.023×10^{23}
p	applied pressure, Pa
Pe_w	Peclet number
$\overline{Pe_w}$	length averaged Peclet number
r	radial co-ordinate, m
r^*	non-dimensional radius
R	radius of tube, m
Re	Reynolds number
R_r	real retention
s	flow consistency index, s^{-1}
Sc	Schmidt number
$Sh(x^*)$	axially varying Sherwood number
$\overline{Sh_L}$	length averaged Sherwood number
T	temperature, K
u	axial velocity, m/s
u_{HS}	Helmholtz-Smoluchowski velocity, m/s
u^*	non-dimensional axial velocity
u_e	electro-osmotic velocity
u_p	Poiseuille velocity
$u_{\tau c}$	shear stress velocity, m/s
$u_{\tau w}$	normal stress velocity, m/s
v	y-directional velocity, m/s
v_w	permeate velocity, m/s
x	axial co-ordinate, m
x^*	non-dimensional axial co-ordinate
y	longitudinal co-ordinate, m
y^*	non-dimensional longitudinal co-ordinate
z	valency of ions

Greek symbols

α_1	osmotic pressure coefficient, m$^{3.5}$ kg$^{-0.5}$ s^{-2}
α_2	osmotic pressure coefficient
β	constant term defined as, $\beta = L_p \Delta P_w \frac{d}{D}$
δ^*	non dimensional thickness of mass transfer boundary layer
ΔP_w	trans wall pressure drop
ε	dielectric constant of the medium, C/V.m
η	similarity parameter
κ	inverse Debye length, m^{-1}
κR	scaled Debye length
τ_c	threshold shear stress, Pa
τ_w	wall shear stress, Pa
ξ	wall potential, V
ψ	surface potential, V

death [11]. Therefore, monitoring of blood rheology can be an easy tool to detect these diseases. Blood contains two main components, plasma and corpuscles [6]. Blood plasma obeys the Newtonian model of viscosity but when corpuscles are suspended within it, the overall fluid exhibits non-Newtonian characteristics [12]. Many attempts have been made to model rheological behaviour of blood but each model has its own shortcomings. Appanaboyina et al., have considered blood as an incompressible Newtonian fluid in their study [13]. Power law fluid has been used to model the rheology of blood many times but detailed investigation reveals that there exists a threshold shear stress for blood to flow, negating the power law as a valid rheological model [14,15]. Chakravarty and Mondal [16] have reported blood to be non Newtonian fluid with complex viscosity relationship but the threshold shear stress is missing. Quemada model is another model depicting the rheological behaviour of blood in a realistic manner. Both Casson and Quemada model give similar stress behaviour with shear rate in the range of 10–100 s^{-1} [17]. Very few modeling approaches are found considering blood as a Casson fluid [18]. This rheological model is more pragmatic in capturing the flow behaviour of blood successfully as it incorporates both nonlinearity and threshold shear stress.

Study of heat transfer and flow characteristics in case of micro and nano channels under the influence of combined pressure and electric field is a well explored area. However, the study of mass transfer has not received much attention of the research community. Mass transport characteristics of transport of neutral macrosolute in a micron sized conduit with porous wall is reported considering Newtonian rheology under the effect of combined pressure and electric field in case of a power law fluid [19,20]. The extended version of these works with power law rheology is also available [21]. Shear dispersion in capillary tube with porous wall has been studied but with Newtonian rheology [22,23]. Mass transport characteristics of Power law fluid under combined electroosmotic and Poiseuille flow are reported in microreactors with impervious wall [24]. Chen et al., have studied mass transport in a microchannel bio-reactor with porous wall using Newtonian rheology [25]. Dey and Raja Sekhar have studied the hydrodynamics and mass transport in a microchannel considering a wall with an asymmetric deformable lining under Newtonian flow conditions [26]. However, in that work, the channel wall was not considered porous. Apart from this, the more realistic Casson rheology that is the closest for the blood was not attempted.

In the present work, effort has been made to bridge this gap, considering Casson rheology for the fluid and flow through a microtube with porous wall under combined pressure gradient and electric field. Detailed study has been done to estimate the combined velocity profile and Sherwood number. The parametric variation of different variables represents various diseased conditions and pathological states. An interesting analysis to predict the permeation flux and permeate concentration has also been presented that will be useful in real life modeling of mass transport of neutral solutes in blood and to identify the diagnosis of diseased state.