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Thermophoretically driven capillary transport of nanofluid in a microchannel

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ABSTRACT

We investigate the interplay of thermophoretic force and interfacial tension on the capillary filling dynamics of a Newtonian nanofluid in a microchannel. In our model, we also consider an intricate thermofluidic coupling by taking the temperature dependence of viscosity aptly into account. This, in turn, determines the evolution of the viscous resistive force as the capillary front progresses, and presents an involved inter-connection between the driving thermophoretic force and the viscous resistive force. The two distinct regimes of particle transport in a fluid medium, delineated by particle size, are expounded to peruse the impact of imposed thermal gradients and particle size on particle retaining propensity of the nanofluid. Additionally, we witness a significant reduction in particle bearing proclivity of the nanofluid with enhancement in a thermal gradient. The results demonstrate the efficacy of the thermophoretic actuation towards the filling of narrow capillaries under the influence of a thermal gradient.

1. Introduction

Capillary-driven systems are ubiquitous in this physical world, with implications in diverse applications ranging from the transport of blood in the cardio-vascular pathways to the ascent of sap in plants occurring through the xylem and phloem tissues. Capillary transport has also been a widely pursued problem in the field of microfluidics [1–7]. Microfluidic transport has widespread importance, encompassing biomedical engineering [8–11] to flow-modulated cooling of electronic components [12,13] and also in chemical engineering [14,15]. Pressure-driven microfluidic transport has several disadvantages which include the paucity of precise experimental control, high pumping power requisites, and ample dispersion. This has led to the emergence of various other modes of transport which include electrosmosis [16–19], electrocapillarity [20], and electrokinetics [21]. Various state of the art models is available in this regard with an attempt to understand the physics of flow of Newtonian [22–25] as well as Non-Newtonian fluids [16,17]. Because of the immense diversity of the environments where capillary flows prevail, they are subjected to different physical forcing conditions arising from their surroundings. In this context, the detailed analysis of the physics of capillary flows attains paramount importance as it not only provides extremely useful theoretical insights to intricacies of the physical phenomenon by eliciting valuable scientific implications but also leads to the development of devices with widespread practical applications.

When there is a temperature gradient in a particle-laden fluid subjected to capillarity, the particles suspended in the fluid experience a force on account of thermophoresis, as expounded by Talbot et al. [26]. This thermophoretic force has been a driving factor behind the deposition of particles in a gaseous medium leading to commonly observed phenomena like blackening of a lantern. Based on particle sizes, different particles will experience different forces in presence of thermal gradients in a given flow field. As a consequence, thermophoresis results in varied migration rates of the particles, as delineated by Malvandi and Ganji [27], Guha and Samanta [28]. Hence, such thermal gradients which are prevalent in most of the modern day lab-on-a-chip devices may be pertinently utilized to regulate the resultant capillary dynamics. Additionally, temperature gradients existing in a system can be employed to separate different particles in a suspension. In the context of such systems, migration of nanoparticles eventually results in their preferential deposition determined by existing thermal fields. The separation of nanoparticles attains utmost importance not only in the context of achieving homogeneous suspensions but also in the design of

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particle retrieval systems essential for minimizing operational costs.

Choi and Eastman [29] coined the term “nanofluid” as a dilute mixture of particles, varying in size from 1 nm to 100 nm, suspended in a base fluid. Compared to base fluids, nanofluids inimitably possess superior thermophysical attributes like thermal conductivity [29]. Previously, Malvandi et al. [30] studied thermophoretic effects in nanofluids with a motivation to explore critical heat fluxes in boiling condition. Shiekholeslami et al. [31] delineated magnetohydrodynamic effects on natural convection with Cu-water nanofluid. Additional studies [32–34] have been conducted to expound intricate and interesting physics of nanofluids. Furthermore, researchers have investigated the enhancement of heat transfer in the convective flow of nanofluids in different geometries [35–37]. In microscale engineering systems like heat pipes and cooling components of electronic devices, where appreciable thermal gradients prevail, nanofluids can be utilized for their enhanced thermophysical properties. Consequently, the study of thermophoretic effects on the capillary transport of nanofluids in microfluidic confinements becomes immensely important.

This paper deals with the effects of thermophoresis on the capillary filling dynamics of nanofluids. The primary focus is to mathematically investigate the dynamics of capillary flow of nanofluids in the presence of thermal gradients, using a reduced order model, addressing the following: (a) effect of particle size, (b) influence of thermal gradient. Furthermore, the work is motivated by the requirement to achieve nanoparticle separations accompanied by a critical exegesis of the influence of pertinent parameters on nanoparticle deposition in microfluidic confinements. To the best of authors’ knowledge, no comprehensive study thus far has been conducted to explore capillary dynamics in presence of thermophoretic effects. The present theoretical findings are expected to impel the researchers in performing experiments with nanofluids to explicate thermophoretic effects in microscale confinements. In the following section, the mathematical model used to illustrate the above-mentioned physical aspects is discussed in detail, along with the relevant fundamental parameters that implicitly influence the interaction of the various important facets controlling the physics of flow.

2. Mathematical formulation and numerical procedure

2.1. Physical problem

We consider parallel plate microchannel geometry, with the two plates being separated by a distance h which is equal to 500 μm. The channel is assumed to have a width b perpendicular to the plane of the diagram, such that $b \gg h$. The fluid has initially traversed a perfectly insulated section which is long enough for the flow to become hydro-dynamically fully developed. We set our origin at the center of the channel in the beginning of the non-insulated section (see Fig. 1), with y axis running along the transverse direction and x axis along the length of the channel. The static contact angle at the solid-liquid-gas (air) interface is denoted by ϕ. There will be a transition of the fully developed velocity profile to a meniscus traction regime near the interface via a transition region. However, the length of the meniscus traction regime is very small compared to the length of the fully developed region and hence, is neglected in this model.

At the inlet of the non-insulated section, we have a uniform temperature (T_I), concentration (C_o) and fully developed velocity field. The walls are cooled to a constant temperature (T_w). The nanofluid under consideration conceived as a suspension of nanoparticles comprises two discrete phases-1) The liquid phase (water) 2) The particle phase (SiO_2). One of the most important considerations of the present model is that there is uni-directional coupling (i.e. the particle motion is determined by the flow field not the other way around) and there will be no mutual interaction between the particles. A similar model has been adopted by Guha and Samanta [28], Chein and Liao [38]. The potency of this assumption is attributed to the fact that we will be dealing with nanofluids of extremely dilute concentrations ($C \sim 10^{-3}$ M) and nanoparticles of sizes ($d \sim 1$ nm), resulting in low volume fraction ($\varphi \sim 0.001\%$). In the current study, gravity, inter-particle forces, magnetic and electrostatic forces on the particle are all neglected. The temperature dependence of viscosity is suitably taken into account in the present model through its dependence on the mean temperature at a given cross-section. Consequently, it is a function of the axial coordinate (x) only. Except for viscosity, other thermo-physical properties of the fluids are evaluated at the average of the maximum and minimum temperatures. The temperature dependence of thermophysical properties of the fluid is given by Eqs. (A.1)–(A.4). The thermophysical property of a given nanofluid like thermal conductivity, heat capacity, dynamic viscosity was computed as a function of the particle volume fraction (φ) by He et al. [39]. Later, Ganguly et al. [31] incorporated established models to obtain pertinent thermophysical properties of the nanofluids in their study. However, in the limit of low volume fractions, the thermophysical property of a nanofluid becomes equivalent to the corresponding property of the fluid phase. Hence, in the present analysis, the nanofluid properties have been replaced by the analogous properties of the fluid phase.

Here, we apply a reduced order model [40] that is commonly used for evaluating the capillary filling distance as a function of time. This model has its inception from the early works of Lucas [41] and Washburn [42]. By dynamics of the capillary transport following this model, what we intend to study is the average position (x) of the capillary front at a time t. The equation of motion for the capillary advancement taking the appropriate direction of the forces, following Newton’s second law of motion, may be expressed as (neglecting inertial forces consistent with a microfluidic paradigm):

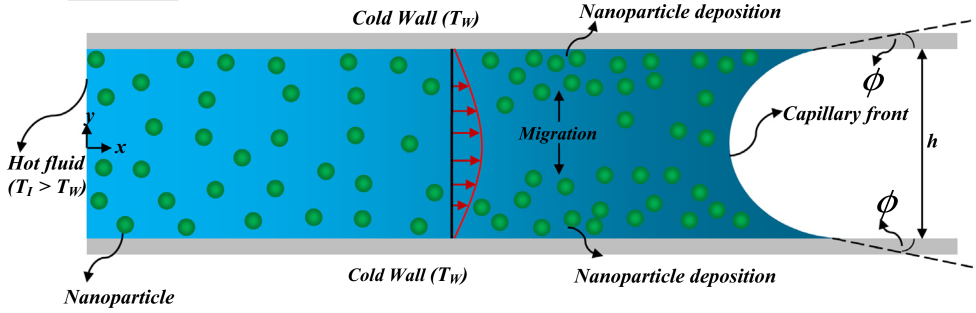

Fig. 1. Physical model depicting the layout of the two-dimensional microchannel and the coordinate system.

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