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Numerical study of the migration of a silicone plug inside a capillary tube subjected to an unsteady wall temperature gradient

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ABSTRACT

In this study, the movement of a silicone plug is actuated by the application of heat flux to one end of a capillary tube. The transient motion of the plug is investigated in a numerical simulation. The finite element method with the two-phase level set technique, developed by Comsol Multiphysics, is used to solve the incompressible Navier–Stokes equations coupled with the energy equation. The results show that the flow motion is affected by the thermocapillary effect generated by the temperature gradient along the gas–liquid interface near the receding side and the capillary force caused by the temperature difference between the ends of the liquid plug. For a longer migration time, the flow mainly moves horizontally from the hot side to the cold side near the tube wall and then returns to the hot side near the center of the tube due to the capillary force effect. There is a smaller clockwise circulation near the receding contact angle caused by the thermocapillary convection. The flow motion causes significant distortion of the isotherms inside the silicone plug. The temperature gradient along the tube is enhanced by the flow motion inside the capillary tube. The liquid plug accelerates rapidly in the initial stage and then decelerates after it reaches the maximum speed. During the migration process, the receding contact angle is always greater than the advancing one. An increase in the input heat flux leads to a higher migration velocity due to the higher temperature gradient along the tube wall. When the initial contact angle is smaller, the migration velocity moves faster due to the higher capillary force. A liquid plug with a lower viscosity moves faster owing to the lower viscous force. The numerical simulation results are in good agreement with the results from previous experiments.

1. Introduction

In recent years, the transport behavior of multiphase flows has received enormous attention because of potential applications in heat transfer and microfluidic devices [1–4]. The motion of a fluid in a microchannel can be driven by thermal [5], electrical [6], magnetic [7] or photic [8] actuating force. In the present study, we pay attention to the motion of a liquid plug in a capillary tube actuated through the application of a heat flux.

The contact angle (CA) φ is set when the liquid droplet or plug comes into contact with a solid and a gas. The balance of forces at the interface is described by Young's equation [9]:

$$\sigma_{sg} = \sigma_{sl} + \sigma_{lg} \cos\ \varphi, \tag{1}$$

where σ (N/m) indicates the surface tension between the two phases; subscripts s, g, and l represent a solid, gas, and liquid, respectively. The solid surface is hydrophilic if the value of CA is less than 90° or hydrophobic if it is greater than 90°. For a liquid moving over a solid surface, the CA can be altered from its value at rest, called the dynamic contact angle (DCA). During the movement of a liquid plug inside a capillary tube, there is a difference between the advancing and receding dynamic contact angles of the two menisci which is usually called the contact angle hysteresis (CAH) [10]. Chen et al. [11], based on the method developed by Ford and Nadim [12], using the height of a droplet obtained from the experiments, showed that the actuation velocity is more significantly influenced by the CAH than the slip length. In a capillary tube, fluid motion can result from the pressure difference induced by the net capillary force between the front and the rear of the liquid [13,17]. The net capillary force is generated by a change in the thermal conditions and pushes the liquid plug from a higher temperature gradient (hot side) to a lower temperature (cold side).

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The motion of a liquid drop in a microchannel driven by capillary actuation has been previously investigated in several studies [5,10,13–20]. Research work has been carried out on microchannels with various cross-sectional areas including circular microtubes [14], trapezoidal microchannels [15] and rectangular microchannels [13,16]. Recently, Bajpai and Khandekar [10] analyzed the heat transfer in a single isolated liquid plug such as glycerin and water inside a dry capillary tube. The results indicate that variation in the dynamic contact angle leads to an enhanced heat transfer coefficient in the moving liquid plug and that the local fluid circulation is affected by menisci deformation. The heat transfer coefficient in the flow of an isolated plug depends on the length of the liquid plug. Glockner et al. [17] investigated the movement of a plug in a closed microchannel subjected to the influence of a temperature field using an analytical model and a numerical simulation. Their results indicate that the plug motion is strongly dependent on the thermal conditions of the microchannel wall. Nguyen et al. [18–20] studied the thermocapillary effect on a liquid plug in a long capillary tube subjected to a transient temperature gradient, which was generated by heating the capillary tube. For a small diameter tube, the liquid plug is mainly actuated by the capillary force and the gravitational force is relatively insignificant. Their results indicate that a silicone plug moves faster with less viscosity or in a smaller capillary tube. Their analytical model predicts a higher migration velocity for a smaller viscosity plug than that obtained from the experiments, but a lower velocity for a higher viscosity plug.

This study extends the numerical simulation scheme developed by Le et al. [21] and Nguyen and Chen [22–24] to investigate the thermocapillary actuation behavior of a silicone liquid plug inside a capillary tube when heat is applied to one end of the tube wall. The conservative level set method [25,26] and the arbitrary Lagrangian Eulerian (ALE) technique developed by Comsol Multiphysics are used to track the liquid/gas interface and ensure good resolution near the free interface. Two forces are considered at the liquid/gas interface, the capillary force acting in the normal direction due to the interface curvature and surface tension and the thermocapillary force acting in a direction tangential to the free surface. The finite element method is employed to solve the Navier–Stokes equations coupled with the energy equation to obtain the transient temperature distribution in the capillary tube and the transient velocity and temperature patterns inside/outside the plug during the migration process. The effects of the magnitude of the input heat flux, initial static contact angle, and viscosity are also considered. The numerical simulation results are also discussed and compared with previous experimental results.

2. Physical problem

A liquid plug is placed inside a glass capillary tube with a length L_c, inner radius r_i, and outer radius r_o (Fig. 1). The plug has a static contact angle φ and length L. First, a constant heat flux q'' is applied at one end of the tube wall in the region W. The distance from one end of the tube to the initial position of the liquid plug is set to Z_0. In the present study, silicone oil is chosen. The properties of the glass capillary tube, air and liquid are listed in Table 1.

The effect of gravitational force as the liquid plug migrates inside a small capillary tube is relatively insignificant. The axial-symmetric equations of the conservation of mass, momentum, and energy for an incompressible and Newtonian fluid are written as

$$\left[\frac{1}{r}\frac{\partial}{\partial r}(ru_r)+\frac{\partial(u_z)}{\partial z}\right]_i=0, \tag{2}$$

$$\rho_i\left[\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+u_z\frac{\partial u_r}{\partial z}\right]_i=-\frac{\partial p_i}{\partial r}+F_{SVr}+\mu_i\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right)-\frac{u_r}{r^2}+\frac{\partial^2 u_r}{\partial z^2}\right]_i, \tag{3}$$

$$\rho_i\left[\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+u_z\frac{\partial u_z}{\partial z}\right]_i=-\frac{\partial p_i}{\partial z}+F_{SVz}+\mu_i\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{\partial^2 u_z}{\partial z^2}\right]_i, \tag{4}$$

$$\rho_i C_{Pi}\left[\frac{\partial T}{\partial t}+u_r\frac{\partial T}{\partial r}+u_z\frac{\partial T}{\partial z}\right]_i=k_i\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}\right]_i, \tag{5}$$

where u_{ri} and u_{zi} are velocity components in the r- and z-directions, respectively, p_i is the pressure, ρ_i is the fluid density, μ_i is the dynamic viscosity, C_{Pi} is the specific heat, k_i is the thermal conductivity, and T is the temperature. The subscripts i = "l" and i = "a" denote liquid and air, respectively. F_{SVr} and F_{SVz} are the surface tension force in the r- and z-directions, respectively.

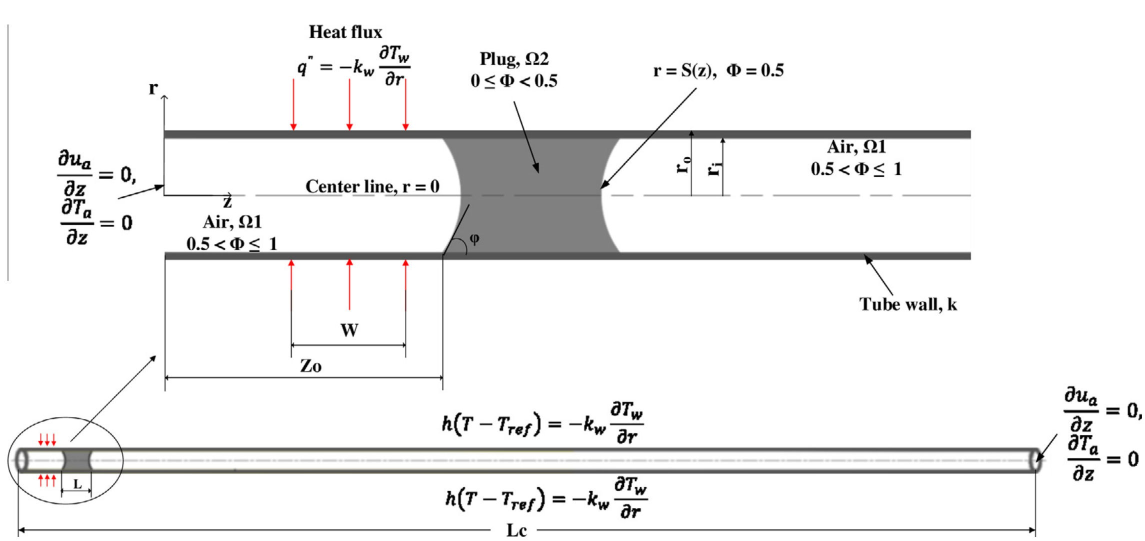

Fig. 1. Schematic diagram of the physical system. The value of the level set function Φ is equal to 0.5 at the plug/air interface. The air phase (subdomain Ω_1) and the liquid phase (subdomain Ω_2) are represented by $0.5 < \Phi \leqslant 1$ and $0 \leqslant \Phi < 0.5$, respectively.