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Capillary rise in a circular tube with interfacial condensation process

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A B S T R A C T

In this work, we develop a theoretical model for the spontaneous imbibition process of a non-isothermal liquid body in a capillary tube. The imbibition front is in contact with a saturated vapor originating a direct condensation at the interface. In the mathematical model, the liquid phase has been coupled with the saturated vapor through the interfacial heat flux condition. The model predicts the evolution for the imbibition front being present the phase change occurring in the imbibition front at a constant rate, which is driven by a temperature difference at the interface between the liquid and the saturated vapor. The results shown a deviation from the Lucas–Washburn solution for the imbibition front, as a function of the dimensionless parameter involved in the analysis: the Jakob number, *Ja*; β representing the ratio of a characteristic equilibrium height to the characteristic thermal penetration, and ε, which depends on the physical properties of the liquid that penetrates the capillary tube.

1. Introduction

Due to the continued miniaturization of semiconductor devices, power electronics, biosensors and aerospace equipment, problems associated with overheating of these components have increased. Accordingly, the innovative cooling techniques are required to meet the demands of heat load removal from highly integrated electronic circuits and the electronic components of spacecraft designed for advanced long-term spacecraft missions. Those demands result in the rapid development of improved heat rejection techniques such as the interfacial vaporization and condensation heat transfer of thin liquid films. Closed two-phase devices such as heat pipes and thermosyphons have been and are being used successfully for the above application. Whatever configuration is used, the heat energy removed at the chip is transported away and rejected from the system by condensation at a remote location. Therefore, a fundamental understanding of the condensation process in minichannels and capillaries is important to optimize design considerations. In this direction, for possible use in electronic cooling applications, Begg et al. [1] developed a mathematical model of annular film condensation in a miniature tube. In this model, the liquid flow has been coupled with the vapor flow along the liquid–vapor interface through the interfacial temperature, heat flux, shear stress and pressure jump conditions. The model predicts the position of the liquid–vapor interface. The numerical results show that complete condensation of the incoming vapor is possible at comparatively low heat loads. L. P. Yarin et al. [2] present a quasi-one dimensional model of laminar flow in a heated capillary. In the frame of this model, the effects of channel size, initial temperature of the working fluid, wall heat flux and gravity on two phase capillary flow are studied. It is shown that hydrodynamical and thermal characteristics of laminar flow in a heated capillary are determined by the physical properties of the liquid and its vapor, as well as the heat flux at the wall. The effect of dimensionless parameters such as the Peclet, Jakob numbers, and dimensionless heat flux or Nusselt number on the velocity, temperature and pressure within the liquid and vapor domains has been studied. In addition, the above authors conducted an experimental analysis for showing that the flow in micro-channels appear to have to distinct phase domains. On the other hand, the theory of two-phase laminar flow in a heated micro-channels was presented by Yarin et al. [3] where they studied the thermohydrodynamic characteristics of a two-phase capillary flow with phase change at the meniscus, by using a quasi-one-dimensional model for the flow. It takes into account the principal characteristics of the phenomenon, namely, the effects of the inertia, pressure, gravity, friction forces and capillary pressure due to the curvature of the interface surface, as well as the thermal and dynamical interactions of the liquid and vapor phases. To describe the flow outside of the meniscus in the domains of the pure liquid or vapor, the one-dimensional mass, momentum and energy equations are used. The possible states of the flow are

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