ABSTRACT

Fundamental insight into evaporation and condensation over small scales is important for developing applications such as high performance electronic systems, and lab-on-a-chip based biofluidic devices. Over such small scales, there are several unresolved issues which are yet to be answered. In the present study, we have identified some of those issues like evaporation of w ater droplet in an unconfined environment, evaporation of water confined in a cylindrical nanopore, and film condensation over vertical surfaces as well as horizontal tubes with varying radius of curvature. The working fluid encountered in various applications may range from simple pure water to more rheologically complex biological fluids like blood. Accordingly, we have also instigated the evaporation dynamics of blood in a narrow fluidic channel. Below, we give a brief summary of the problems considered in the present thesis.

First, a comparative study of purely diffusion controlled and kinetic models is presented for the predictions of evaporation characteristics of water droplet in a quiescent ambience of air with varying vapor concentrations at different pressures and temperatures. The comparison is made in perspective of benchmark empirical results for varying initial droplet sizes. The purely diffusion controlled model is based on the consideration of phase equilibrium at droplet surface, which is considered to be impermeable to non evaporating species. The kinetic model is based on the matching of molecular fluxes under thermodynamic non-equilibrium condition at droplet surface with diffusion fluxes in the hydrodynamic region beyond the Knudsen layer. The instantaneous droplet surface temperature is evaluated to determine the vapor concentration at droplet surface and hence in the evaporative mass flux. This is found out from the solution of coupled conservation equations of mass, energy, and species of the gas phase along with conservation of energy of the droplet phase in consideration with the droplet as a lumped parameter system.

Next, a mathematical model is developed for characterizing transport phenomena in thin evaporating liquid films inside nanopores. The mathematical model is based on the conservation equations for mass, momentum and energy transport in the liquid phase linked to the vapor phase through the interfacial equilibrium constraints. Augmented Young-Laplace equation is used for predicting the pressure difference, due to capillary and disjoining pressure, between vapor and liquid at the liquid-vapor interface. Mass transfer across the liquid-vapor interface is governed by the interfacial thermo-kinetic constraints. The implications of electrostatic component of disjoining pressure on interfacial transport of evaporating liquid with interfacial slip are studied in particular, to predict the interface shape and, in turn, the rate of evaporative mass transfer on evaporation of thin liquid films for various pore sizes, wall temperatures and ambient vapor pressures.

The evaporation dynamics of blood in a microfluidic channel is next analyzed, considering typical rheological characteristics of blood. A semi-analytical mathematical model based on the conservation equations for mass, momentum and energy transport in the liquid and vapor phases is developed with the consideration that the rheology of blood (a non-homogenous, anisotropic dispersion of colloids and polymers) is influenced by the shear rate, degree of aggregation and the mechanical response of cells towards the incipient flow. Emphasis is laid on capturing the influence of the factors affecting blood rheology like the hematocrit fraction and total

serum protein minus albumin fraction (TPMA) and the degree of superheat. The methodology proposed in this study may be of immense consequence towards optimizing the performances of lab-on-a-chip based biofluidic devices.

An analytical investigation is next executed to determine the role of wall slip towards heat transfer enhancement in laminar film condensation on a vertical surface. The governing equations of mass, momentum and energy conservation in the liquid phase are solved analytically, to yield a physically-insightful yet mathematically-simple closed form expression for the condensate film thickness and the local Nusselt number that may potentially act as a design basis for microfluidic systems involving film condensation.

The interplay between variable radius of curvature and interfacial slip is next studied by a comprehensive and systematic semi-analytical methodology for characterization of thermal performance in film condensation over horizontal tubes with varying radius of curvature. A polar surface comprising a segment of an equiangular spiral curve, generated symmetrically on a vertical chord, is considered. In the first of the study, condensation of pure vapor (devoid of any non-condensable species in the bulk mixture at free stream) is studied. The governing equations of mass, momentum and energy conservation in the liquid phase are solved to predict the local Nusselt number and the average Nusselt number in terms of key operating parameters. The study is further extended to account for the presence of non-condensable species in the bulk mixture at free stream.