Abstract

This dissertation explores the interfacial thermocapillary-driven transport phenomena in multi-layer thin liquid films in microfluidic domains. This study thoroughly investigates the individual role and the interplay of the periodic thermal stimuli and wettability patterns at the microchannel walls on the transport characteristics. The coupled energy and momentum equations are solved semi-analytically to understand the thermal Marangoni effect in immiscible multifluid systems. The study is performed under the assumptions of negligible Reynolds (Re), Marangoni (Ma), and Capillary (Ca) numbers and a quasi-deformed fluid-fluid interfaces at low gravity environments.

The author first explores how mixing performance and discharge rate of the liquid layers in a binary-liquid system can be morphed by altering the applied thermal stimuli and the wall slip patterns. The discussion is then extended to the ternary-liquid systems, where mixing enhancement in the present configuration is compared with the fully developed laminar flow (Poiseuille flow) by numerically solving the species transport equation in COMSOL Multiphysics. The improved mixing observed in the present model is attributed to the circulatory vortices, which are absent in a fully developed laminar flow. The circulations created due to patterned wall conditions cause the convection of the solute particles across the microchannel axis.

Next, the author studies the thermo-capillarity induced thermo-fluid dynamics in an immiscible binary-liquid microscale film system, which rests on a wavy contoured hot substrate and is open to air at the top. This flow type is seen in liquid film coatings on patterned surfaces, which are widely used in MEMS (micro-electromechanical systems)/NEMS (nano-electromechanical systems) applications (Weinstein & Palmer, 1997; Palacio & Bhushan, 2008). The thin film lubrication theory is used to theoretically solve the coupled momentum and energy balance problem. Asymptotic solutions up to the second correction terms are presented for the temperature and flow fields. While the leading order solutions are obtained by considering pure vertical diffusion, the convective transport is considered in higher order correction terms. As a result, while the substrate temperature controls the leading order temperature field, the source and sink terms (due to viscous dissipation) determine the correction terms for higher order thermal solutions.

Further, the author presents the interplay of microchannel walls' patterned topography, temperature, and surface wettability to produce thermocapillary flow in confined binary-liquid systems. The periodic nature of wall conditions causes fluid circulations in the flow domain. The thermocapillary effect generates vorticity at the interface, which then diffuses throughout the entire liquid domain via diffusion and convection mechanisms. The author also performs the parametric study to optimize the present configuration and produce a strong thermocapillary action. The influence of the relative thermal conductivity of the liquid layers (λ), film thickness ratio (r), and system's Biot number (Bi) on the strength of the interfacial thermo-capillarity is explored by the OFAT (one factor at a time) method. Lastly, the author discusses the thermocapillary transport of a single liquid layer open to air over a topological substrate with periodic wall wettability and surface temperature as a special case.

Keywords: film hydrodynamics; thermocapillary effect; Marangoni advection; mixing; periodic thermal stimulus; wettability; patterned substrate; interfacial tension; binary-liquid; ternary-liquid; microfluidics.