International Communications in Heat and Mass Transfer 38 (2011) 1340–1343

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Effect of gradient wetting surface on liquid flow in rectangular microchannels driven by capillary force and gravity: An analytical study ☆

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ARTICLE INFO

Available online 29 July 2011

Keywords:
Flow-front
Rectangular microchannel
Capillary flow
Wetting gradient
Contact angle
Driving force

ABSTRACT

A model is presented for predicting liquid flow velocity in a rectangular microchannel driven by capillary force, gravity and an extra driving force due to the surface wettability gradient. The nth power function, $\cos\theta_x = \cos\theta_0 + (\cos\theta_L - \cos\theta_0)\left(\frac{x}{L}\right)^n$, for the cosine of contact angle (CA) with typical n order of 0.5, 1 and 2 is applied to analyze how the inner surface wettability gradient of the microchannel affects the flow velocity. Flow simulations revealed that the velocity of liquid flow decreases with the length of microchannel and the wettability gradient (e.g. from 80° to 2°) on channel surface will accelerate the motion of liquid when the flow-front approaches to the end of the microchannel although the gradient surface may decrease the initial motion of liquid due to the great CA at channel entrance in comparison to the uniform CA channel (with respect to the lowest CA of 2°). The linear function (n = 1) of wetting gradient profile may achieve relatively more stable and higher flow velocity than the other n power functions. The analysis of driving force along the moving path matches well with the flow velocity predicted by the model.

1. Introduction

Recently research on liquid flow in microchannels driven by capillary force and gravity is particularly active because of its variety applications including microelectronics cooling, lab-on-a-chip, underfilling of flip chip and biochemical analysis. Actually early study on capillary wetting phenomenon can be traced back about 90 years ago to the first basic understanding of the laws of capillarity developed by Lucas [1] and Washburn [2]. While the equations (such as the Lucas-Washburn equation) established in their original studies or some variant thereof are still of practical interest [3]. Modification of these equations was presented by Staples and Shaffer [4] to describe the capillary flow in tubes irregularly shaped along their primary axis. The classical Lucas–Washburn equation and its modified forms usually hold for describing the fully developed laminar flow (ignoring the end effects) in microchannel. In more recent years Waghmare and Mitra [5] developed a transient capillary flow equation including the effects of inertial force and entrance pressure field by integral momentum balance, which may be capable of predicting the initial stage of capillary flow process. Furthermore study of capillary flow extended in rectangular microchannel has also received much attention [5–8]. Jong et al. [6] developed a mathematical model of capillary flow in rectangular microchannel from the Navier–Stokes equations, and the predicted flow times in microchannels agree well with their experimental results.

On the other hand, fabricating a wettability gradient along a solid surface for actuating droplet motion or accelerating liquid flow is currently one of the most attractive research topics, which has potential applications in enhancing the process performance of heat and mass transfer [9–13]. Chaudhury and WhiteSides [9] created a spatial gradient in its surface free energy capable of causing drops of water placed on it to move uphill. The resulting surface displayed a gradient of water contact angle(CA) changing from 97° to 25°over a distance of 1 cm and a drop moving velocity toward the hydrophilic side of 1 to 2 mm per second on the gradient surface with inclination angle of 15°. Isaksson et al. [11] reported an electrochemically induced wettability gradient to control water movement on a polyaniline surface. Zhu et al. [12] fabricated a surface with wettability gradient on a treated silicon chip by using CVD technique with dodecyltrichlorosilane as a source of silanization to investigate the motion behaviors of water and ethylene glycol droplets on it, and found the liquid droplets were self-propelled to move horizontally or uphill from hydrophobic zone to hydrophilic zone. To our best knowledge, however, there is little report to date on quantitative influence of wettability gradient of a microchannel inner surface on liquid flow in the channel. It is the goal of this work to develop a mathematical model on the basis of Jong's research [6] to predict quantitatively the enhancement of liquid flow inside a microchannel arising from the wettability gradient of the channel inner surface.

☆ Communicated by P. Cheng and W.-Q. Tao.
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0735-1933/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.icheatmasstransfer.2011.07.011