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THERMOCAPILLARY MIGRATION OF LIQUIDS ON PATTERNED SURFACES: DESIGN CONCEPT FOR MICROFLUIDIC DELIVERY

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Abstract

We present a novel method of fluidic transport on the open surface of a chemically patterned substrate using thermocapillary actuation. Our experimental and numerical studies provide the desired correlations between the microstream flow rate and tunable parameters like the liquid sample volume, microstream width, and magnitude of the applied thermal gradient.

Keywords: thermocapillary transport, micropatterned surfaces, free surface flow

1. Introduction

Studies have shown that thin liquid films subject to a thermal gradient will flow toward the colder end due to thermocapillary migration [1]. The thermal gradient, dT/dx, along the solid substrate produces a positive thermocapillary stress, $d\gamma/dx$, along the air-liquid interface which causes the film to spread. On homogeneous surfaces, the advancing film can undergo lateral break up into a series of regularly spaced fingers with characteristic period λ. Stable spreading and flow control can be attained by confining the flow to hydrophilic stripes whose width $w \ll \lambda$. Using optical lithography, we have patterned a network of hydrophilic stripes on glass or silicon substrates treated with hydrophobic monolayers. Integrated sub-surface heaters are electronically controlled to maintain the desired temperature distribution which determines the magnitude and direction of the volumetric flow rate. Advantages to this method of fluidic transport include no moving mechanical parts, low operating voltages, no micro machining, no restriction to ionic or highly conductive liquids and accessibility to reaction products for further analysis. Present drawbacks include evaporation, which can be reduced by encapsulation and saturation of the ambient environment, and sensitivity to surface defects within hydrophilic regions, which requires refinement of substrate processing techniques.

2. Theory

Figure 1 represents the geometry of interest. The liquid is confined to the hydrophilic regions (square pad and connecting stripe) by an exterior hydrophobic coating. The stripe contains imbedded heating resistors which in this study subject the overlying liquid to a constant surface shear stress $\tau = d\gamma/dT \cdot dT/dx$.

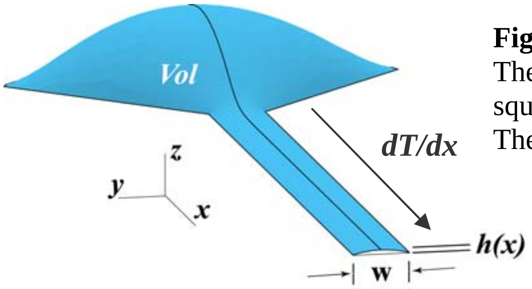

Fig. 1: Schematic diagram of the flow geometry. The liquid sample is extracted from the isothermal square pad onto a differentially heated microstripe. The microstream apex height is designated by *h(x)*.

To optimize our experimental system, we have solved the governing hydrodynamic equation in the lubrication limit for thermocapillary driven flow along a hydrophilic microstripe to obtain the interfacial profile, *h(x,t)*, the volumetric flow rate, *Q(x,t)*, and the front speed, *V(x,t)*. The variation of the liquid surface tension and viscosity, γ and μ, with temperature are included in these computations. The capillary terms $\gamma\nabla^2 h$ represent flow caused by surface curvature variations, which induce slow spontaneous spreading even under isothermal conditions.

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\left[\frac{\tau h^2}{2\mu}+\frac{h^3}{3\mu}\frac{\partial}{\partial x}\left(\gamma\,\nabla^2 h\right)\right]+\frac{\partial}{\partial y}\left[\frac{h^3}{3\mu}\frac{\partial}{\partial y}\left(\gamma\,\nabla^2 h\right)\right]=0 \qquad (1)$$

3. Experimental Results and Discussion

We have fabricated samples for thermofluidic transport on silicon and glass surfaces using standard micro-electronic techniques. The surfaces are hydrophobized using self-assembled monolayers [3]. To minimize evaporative problems while first exploring the physical and geometrical mechanisms controlling the flow, we have used non-volatile organic liquids like polydimethylsiloxane and tetraethylene glycol which are well confined to the microstripe by the hydrophobic exterior. The small sample volumes and stripe widths used in this study generate rivulets whose thickness is in the tens of microns range. The resultant small Biot number ensures that the temperature at the air-liquid and liquid-solid interface is the same. We have calibrated the linearity of the thermal profile, T(x), in the absence of liquid by direct measurement with fine thermocouples. Measurements of the streaming velocity reveal the functional dependence on the stripe width (see Fig. 2c), the applied temperature gradient and sample volume deposited [4]. The volumetric flow rate always increases with increasing w, dT/dx or sample volume. The experimental measurements compare favorably with numerical solutions of Eq. (1) and can therefore be used to optimize device performance.

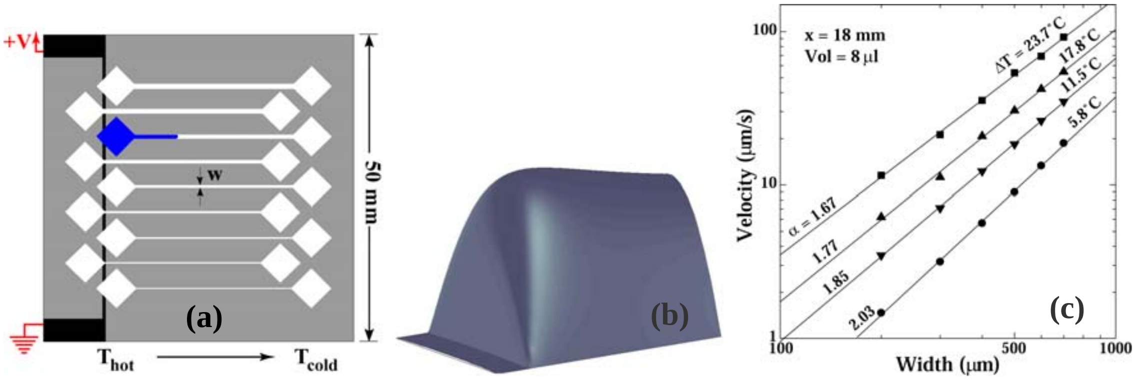

Figure 2 (a) Experimental layout: grey=hydrophobic area, white=hydrophilic area. The black vertical line is the heating resistor which is connected to external contact pads. We have studied the flow for various heater positions. (b) Numerical simulation of liquid rivulet with w=200 µm, dT/dx=14.4°C/cm and inlet height h=7.5µm. Heater was located at stripe entrance x=0. (c) Experimental results for the liquid speed at downstream position x=18 mm as a function of w and ΔT for a total path length Δx=28.4 mm and liquid sample volume 8 µl. The α values denote the fitted power law exponent $V \sim w^{\alpha}$.

4. Conclusion

The thermofluidic concept described above provides a new method for routing liquid microstreams along desired segments of hydrophilic pathways. We have so far achieved a flow speed of 600 µm/s for µ=5 mPa·s, dT/dx=14.4°C/cm and w=800µm, making this a viable technique for microfluidic dosing applications. Applying larger thermal gradients to liquids of lower viscosity and higher dγ/dT will produce higher speeds. In addition to holding or releasing liquid samples dynamically via manipulation of thermal gradients, it is also possible to apply thermal maps to initiate or quench chemical reactions. We are presently studying the use of thermal gradients to enforce micro mixing as well. The application of temperature distributions for routing, reacting and mixing ultra small liquid samples is a unique and attractive feature of our device.

Acknowledgements

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