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Sensors and Actuators A 140 (2007) 145–155
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Thermocapillary actuation of liquid plugs using a heater array

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Received 12 January 2007; received in revised form 20 June 2007; accepted 21 June 2007
Available online 27 June 2007

Abstract

With the aim toward realizing polymerase chain reaction (PCR) of deoxyribonucleic acid (DNA) in plug-based capillary platforms, this paper reports the theoretical and experimental results of thermocapillary actuation for temperature cycling with an arbitrary ramping function. Two concepts were investigated: (a) actuation and spatial temperature cycling with three heaters and (b) actuation and temporal cycling with two heaters. The paper first describes the analytical models of both concepts. The model considers the spatio-temporal heat transfer effects, which is coupled with the surface tension driven movement of the plug. In the experiments, both temperature field and plug motion were measured and evaluated. The temperature field was captured by an infrared thermal tracer camera. The position of the plugs was automatically captured and evaluated with a CCD camera. Finally, analytical and experimental results are compared and discussed.

Keywords: Droplet microfluidics; Capillary-based; Lab on chip; Thermocapillarity; Temperature cycling

1. Introduction

Recently, droplet-based microfluidics has been emerged as an alternative for continuous-flow microfluidics. Microdroplets formed in microchannels can be used as a vehicle for reagent transport as well as a platform for chemical reactions. Large droplets that touch the channel wall are referred to in this paper as microplugs. The emerging field of droplet-based microfluidics leads to the need of effective manipulation and control of droplets and plugs in microchannels [1]. In these continuous-flow platforms, both immiscible liquid phases are driven by pressure. Active control of microdroplets can be achieved by pressure difference. Link et al. utilized the channel length at a bifurcation to control the pressure difference and to split droplets [3]. Ting et al. used temperature dependency of interfacial tension and viscosity to switch droplets at a bifurcation [4]. In contrast to droplet-based continuous microfluidics, droplet-based digital microfluidics handles individual droplets using electrostatic forces [2,5], magnetic forces [6] or thermocapillary forces [7,8]. Electrowetting utilizes electrostatic forces at the solid/liquid/liquid or solid/gas/liquid interfaces to manipulate the interfacial energy and subsequently the motion of droplets. Gradients of surface stress can also be induced by a temperature gradient. A temperature gradient can move droplets on a flat surface [7,8]. Previously, our group reported an one-dimensional (1D) analytical model for the transient behaviour of a liquid plug in a capillary which is heated at one end [9]. This 1D model agreed well with the measured results. Recently, we reported a theoretical model and experimental results of the motion of a liquid plug between two heaters, which are alternately activated. The concept allows the reciprocating motion of the liquid plug between the two heaters [10].

Microdroplets are often generated in a microfluidic device and stored as liquid plugs in a glass capillary for storage and post processing [11]. Deoxyribonucleic acid (DNA) processing systems based on liquid plugs in glass capillary was previously reported by Fiedman and Meldrum [12]. In this capillary-based platform, mixing inside a liquid plug is an important task. Evensen et al. used pressure induced by an external piezoelectric actuator to move a liquid plug in a capillary [13]. Improved mixing inside the liquid plug was observed as it is driven back and forth in the capillary. The plug motion is important for mixing in liquid plugs of capillary-based platforms. The coupling between heat transfer in the capillary wall and the motion of the plug presents a source of a chaotic behaviour [14]. Thus, flow reversal could disturb the symmetric stream lines in the straight capillary leading to improved mixing inside the liquid plug.

In this paper, we combine thermocapillary driven motion with thermal cycling using an array of heaters. Temperature cycling

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doi:10.1016/j.sna.2007.06.025

was realized spatially with three heaters or temporally with two heaters. In the first concept, three heaters are activated sequentially propelling the liquid plug through three temperature zones. Repeating this process in the reverse direction allows thermal cycling and mixing inside the liquid plug. In the second concept, two heaters are used for realizing the reciprocating motion of the plug, while temporal ramping of the heater's temperature with a given function enables thermal cycling. First, the concept of these two methods are described analytically. Subsequently, details on the experimental setup and results are reported. Measurement results of plug positions and plug velocities are finally compared with the theory.

2. Actuation concept

2.1. Spatial cycling with three heaters

Fig. 1 shows the schematic concept of thermocapillary actuation and spatial cycling. The basic actuation concept can be described by a transient model for each heater with corresponding boundary conditions and initial conditions. The temperature distribution in a hollow cylindrical capillary can be described with the transient 1D heat conduction equation [9]:

$$\frac{\partial \theta}{\partial t} = \alpha \frac{\partial^2 \theta}{\partial x^2} - \frac{2hR_\mathrm{o}}{\rho c(R_\mathrm{o}^2 - R_\mathrm{i}^2)}\theta \tag{1}$$

where θ is the temperature difference relative to the ambient temperature, R_o and R_i the outer diameter of the capillary and α, ρ and c are the thermal diffusivity, density and specific heat capacity of the capillary material, respectively. Heat radiation is neglected in this model because of the relatively low temperature of the outer capillary surface. The transient boundary conditions of the heater are:

$$\begin{aligned} t = 0: &\quad \theta(x) = \theta_0(x) \\ t > 0: &\quad \begin{cases} x = 0, & \dfrac{\mathrm{d}\theta}{\mathrm{d}x} = \dfrac{-q''}{k} \\ x = L_\mathrm{c}, & \theta = 0 \end{cases} \end{aligned} \tag{2}$$

where L_c is the length of the capillary, k the thermal conductivity of the capillary material, q'' the heat flux inside the capillary and $\theta_0(x)$ is the initial temperature. For simplicity, we assume the same heat flux for all three heaters in both the analytical analysis and the later experimental investigation.

Introducing the dimensionless variables $t^* = t/(L_\mathrm{c}^2\alpha)$, $x^* = x/L_\mathrm{c}$ and $\theta^* = \theta k/(q' L_\mathrm{c})$ lead to the dimensionless heat conduction equation:

$$\frac{\partial \theta^*}{\partial t^*} = \frac{\partial^2 \theta^*}{\partial x^{*2}} - \beta^2 \theta^* \tag{3}$$

with $\beta = \sqrt{2hL_\mathrm{c}^2 R_\mathrm{o}/k(R_\mathrm{o}^2 - R_\mathrm{in}^2)}$. The corresponding dimensionless boundary conditions are:

$$\begin{aligned} t^* = 0: &\quad \theta^*(x^*) = \theta_0^*(x^*) \\ t^* > 0: &\quad \begin{cases} x^* = 0, & \dfrac{\mathrm{d}\theta^*}{\mathrm{d}x^*} = -1 \\ x^* = 1, & \theta^* = 0 \end{cases} \end{aligned} \tag{4}$$

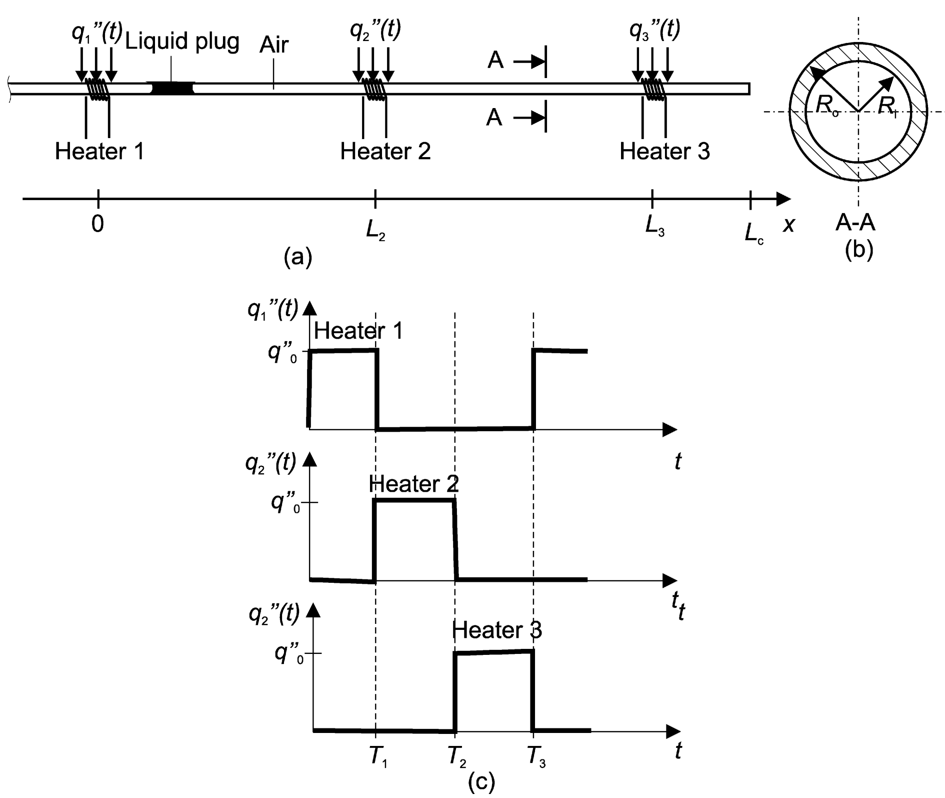

Fig. 1. Model of the concept with thermocapillary actuation and spatial cycling: (a) heater arrangement, (b) capillary cross-section and (c) heating schemes of the three heaters.