Sensors and Actuators B 236 (2016) 367–377

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

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

Magnetically actuated transport of ferrofluid droplets over micro-coil array on a digital microfluidic platform

Debiprasad Chakrabarty, Susovan Dutta, Niladri Chakraborty, Ranjan Ganguly*

Department of Power Engineering, Jadavpur University, Kolkata 700098, India

A R T I C L E I N F O

Article history:
Received 8 February 2016
Received in revised form 17 May 2016
Accepted 1 June 2016
Available online 2 June 2016

Keywords:
Ferrofluid
Digital microfluidics
Droplet manipulation
Magnetic field
Micro-coil array

A B S T R A C T

Magnetic manipulation of liquid droplets in microfluidic environment offers a promising tool for sample handling in lab-on-chip devices. Biofunctionalized ferrofluid droplets can effectively carry a measured volume of analytes or reagents on a flat microfluidic platform, executing key tasks of a micrototal analysis system (μ-TAS). However, achieving precise control using on-chip miniaturized magnetic coils is challenging and requires delicate combination of operating parameters, e.g., magnetizing current and timing of switching, fluid viscosity, droplet size, etc. Here we present a numerical analysis of magnetic manipulation of an immiscible, microliter-scale ferrofluid droplet over a thin aqueous film on a solid substrate using embedded micro-electromagnet coils. The numerical model is first validated against the experimentally observed droplet trajectory in a simple, single-coil configuration. Subsequently, two-dimensional manipulation of the ferrofluid droplets on the liquid film is predicted numerically when the magnetic field is produced by a sequentially switched array of square spiral microelectromagnets. By adjusting the operating parameters, we show that the droplet can be moved in predefined meandering path over an active substrate area. The transport is broadly classified into viscosity- and inertia-influenced regimes. Transport time of the droplet for the viscous regime is expressed in terms of a generalized group-variable involving the operating parameters. The study is important for selecting the design bases for a magnetically manipulated sample handling system for digital microfluidic platforms.

1. Introduction

Microfluidics is the enabling technology of handling fluid flow in diminutive amounts, typically ranging from nanoliters to microlitres, in micro total analysis systems (μ-TAS). These devices are capable of performing varied bioanalytical tasks, which are normally carried out in a lab, like sample preparation, purification, separation, reaction, transport, immobilization, labeling, biosensing and detection on a chip [1]. These devices offer advantages over the conventional bioanalytical protocol through reduced biochemical reaction time, enhanced efficiency and mobility and reduced sample and reagent consumptions. Small reactor volumes are also favored where the analyze sample is available in extremely small amount, e.g., in case of a forensic detection. The key generic steps in any MEMS-(Microelectromechanical Systems) based bioanalytical device (e.g. a biosensor) involves sample handling for mixing, reaction and separation. Active microfluidics refers to the defined manipulation of the working fluid by active (micro) components such as micropump or micro valves. There has been a recent shift of sample handling strategy from the continuous-flow to the droplet-based system, where sample droplets can be stored and manipulated in an immiscible liquid. Samples and reagents can be confined in an immiscible carrier in spherical droplets which are dispersed in another immiscible fluid that is flown through the channel. Droplet-based microfluidics is relatively free from the common problems of flow-through microfluidics like sample dilution and cross-contamination [2,3]. Several useful applications of droplet-based microfluidics, e.g., protein purification [4], biosensor [5], immunoassays [6], DNA-replication [7], cell-based assays [8], bio-molecular extraction [9] etc. have underscored the importance of on-chip droplet manipulation [10,11]. Magnetic force offers a viable alternative for the manipulation of microdroplets. Functionalized magnetic nanoparticles, either in the form of ferrofluid droplets or magnetic microspheres offer a facile tool for micromanipulation on microfluidic platform. Magnetic force is used widely for handling magnetic beads [12,13] in microchannels and capillaries in the context of active mixing [14] and immunomagnetic separation in microfluidic devices [15], or in studies related to magnetic drug targeting [16,17]. Ganguly et al. [18] provides an insight into the transport of ferrofluid and magnetic microspheres

* Corresponding author.
E-mail addresses: ranjan@pe.jusl.ac.in, rgangu2@yahoo.com (R. Ganguly).

http://dx.doi.org/10.1016/j.snb.2016.06.001
0925-4005/

for droplet-based microfluidics and presents a review of their applications in microscale devices. The Kelvin body force on the magnetic nanoparticles is proportional to both the gradient of the magnetic field and the field strength [19]. Thus, on a microfluidic platform, it is possible to create strong localized magnetic force-fields by using active device like miniaturized permanent magnet or electromagnet coils [20–23] or by passive device (e.g., macroscale biasing magnet in conjunction with an active electromagnet [24]). More recent applications have shown better on-chip maneuverability; lower power consumption and high throughput using sequentially switchable multiple-coils and arrays [25]. Deng et al. [26] demonstrated the controlled movement of superparamagnetic microbeads along a magnetic track generated by a combination of microfields produced by small wires and a superimposed external field. A new dynamic and compact technology by Fulcrand et al. [27] demonstrated simultaneous manipulation of microbead batches in continuous flow along controlled spatial pathways by synchronizing the injection of beads in the channel and the actuation of micro-coils. A novel magnetic repulsion-actuated microfluidic technique capable of achieving on-demand manipulation of nano- to pico-litre volumes of water droplets without involving complicated manufacturing processes and bulky external control facility have also been reported [28]. While most of these above techniques used magnetic microbeads (micron sized polystyrene beads containing superparamagnetic nanoparticles), similar manipulation of ferrofluid droplets have not been undertaken widely.

Ferrofluids are colloidal suspension of superparamagnetic ferrous nanoparticles in a nonmagnetic liquid. The nanoparticles are stabilized (either by surfactant or ionic charges on the particles) in the host liquid so that they exhibit continuum behavior even under strong magnetic fields. On-chip transport of ferrofluid droplets have primarily been carried out by the group of Nguyen et al. [29], who reported a system for magnetic manipulation of ferrofluid droplets by an array of PCB-based planar coils in conjunction with permanent magnets. Tan et al. [30] presented a technique of generation and manipulation of ferrofluid droplets in a confined T-shaped microchannel. For effective magnetic fluid droplet manipulation in a microfluidic device the imposed magnetic field should be strong enough to overcome the viscous resistance, but at the same time should not lead to particle aggregation and droplet splitting. Probst et al. [31] have developed an optimal control of a single droplet of ferrofluid in the plane by 4 electromagnets. Studies on manipulation of magnetic particle-laden droplet on superhydrophobic substrates have provided an insight of the relevant operating regimes [32,33]. Nguyen et al. have also investigated the fluid dynamic aspect of ferrofluid droplet manipulation on an open substrate that is covered with an immiscible liquid [34,29] or a superhydrophobic coating [35]. While these works have nicely portrayed the controllability of the ferrofluid droplets in one or two dimensions on the substrates through controlling the excitations in the field-producing coils, ferrofluid transport behaviors using multiple-coil arrays have not yet been studied. Assadsangabi et al. [36] have demonstrated the possibility of using microcoil array to achieve two-dimensional control of magnetic force on a thin ferrofluid layer and control the ferrofluid motion on substrate in a different context (creation of deformable mirrors), but their study did not focus on the motion of an isolated ferrofluid droplet.

Complex, two-dimensional manipulation of liquid droplets on a surface microfluidic platform warrants the use of arrays of periodically switched micro-coils. Such devices will have several practical use. For example, periodic zigzag motion of a droplet may be effectively deployed to promote shear-induced chaotic mixing inside the droplet [37]; droplets may be magnetically actuated back and forth over the hot and cold regions of a differentially heated substrate (overcoming the thermocapillary force) to offer thermal cycling [38] of the liquid content of the droplet; periodic switching of liquid droplets is also essential for sorting droplets and increasing the throughput of downstream processes on a droplet-based microfluidic device [39]. Design of these ferrofluid droplet-based microfluidic platform would require a systematic characterization of the droplet trajectory and the switching sequence and timing for the field-producing microcoils.

Here we present a numerical model to analyze controlled manipulation of immiscible ferrofluid droplets on a liquid film spread atop a solid substrate. Magnetic manipulation of the ferrofluid droplets is achieved using periodically switched array of electromagnetic micro-coils. First, the field produced by an individual micro-coil is simulated. Next, the predicted motion of a ferrofluid droplet under the influence of a single magnetic coil is validated against an in-house experiment, where an oil-based ferrofluid droplets is transported over a thin aqueous film over a flat substrate using a substrate-embedded circular microcoil. Finally, the numerical analysis is extended to predicting the 2-dimensional zig-zag motion of ferrofluid droplet under different modes of periodic switching of a micro-coil array. Square coils are chosen for this, since they offer better packing density (thus minimizing the dead space between the neighboring coils) than circular coils in an array. Influence of the salient design and operating parameters like the coil current, ferrofluid droplet size, and fluid viscosity is also studied. Ferrofluid droplet transport time over the length of the active substrate is characterized in terms of a group variable that can serve has the basis of a general design criterion for similar ferrofluid droplet-based micro-manipulation devices.

2. Configuration

2.1. The coil array and the magnetic field

Fig. 1(a) shows the arrangement of a planar square coil of 10 mm × 10 mm size in a double-stranded array ten coils placed under a 18 mm × 60 mm flat substrate (dimension typical of a microfluidic chip) on which a thin (2 mm) film of aqueous solution renders mobility of the ferrofluid droplet. Fig. 1(b) shows a single square coil with detail specification. Each square spiral consists of 6 turn of conductors at 800 μm pitch. The conductors have 800 μm × 800 μm square cross section. Each conductor of the planar coils is considered as composed of a bundle of 5 × 3 slender of current-carrying wires (see the inset of Fig. 1(b)). Fig. 1(c) shows the magnetic field (Tesla) computed at the aqueous film surface (i.e., at $z = 2$ mm, see Fig. 1(d)) for a coil carrying current 2.5 A. The magnetic field is computed using Biot-Savart law [40] following the approach of Santra et al. [41] for each slender conductor segment in a coil and then by superposing the resulting fields. As can be seen from Fig. 1(d) the magnetic field peaks at the center of the spiral and it drops sharply towards the periphery. From magnetic field plot of Fig. 1(c) it is observed that maximum flux density occur at center of the coil i.e. 0.0026 T and it decreases gradually towards outer periphery of the coil.

2.2. Magnetic force on a ferrofluid droplet

The information of the local magnetic force field is important for predicting the magnetic manipulation of the microliter volume ferrofluid droplet. Considering each ferrofluid droplet of volume V_{FF} to have homogeneous magnetization **M** induced due to an imposed field **H**, the magnetic force on such a droplet within the magnetic field is calculated from the general expression [38]

$$\mathbf{F_m} = \mu_0 \int (\mathbf{M}.\nabla)\mathbf{H} d^3 r = 3\mu_0 \frac{\mu_r - 1}{\mu_r + 2} \int (\mathbf{H}.\nabla)\mathbf{H} d^3 r \approx \mu_0 V_{FF} \chi_m \nabla(\frac{1}{2}|H|^2) \qquad (1)$$

Here, H denotes the field in the absence of the magnetic object, i.e., it does not consider the demagnetization effect caused by the