Abstract

Droplet based Digital Microfluidics (DMF) has emerged as a promising enabling technology for a wide range of applications in the areas of low-cost biosensors and molecular diagnostics. In an Open-surface Magnetic Digital Microfluidics (OMDMF) nano-liter to micro-liter sized, magnetically responsive droplets, containing samples and reagents can be manipulated on a liquid-film coated or a hydrophobic surface, executing key tasks of a micro-total analysis system (μ-TAS). An OMDMF platform uses magnetic forces to transport droplets, presenting a few exclusive benefits over the conventional digital microfluidic platform. Effective deployment of such OMDMF would warrant precise manipulation of the magnetically responsive droplets – usually a stable suspension of magnetic nanoparticles dispersed in a nonmagnetic liquid – using chip-embedded miniaturized magnetic coils that are electrically insulated from the liquid medium. The driving magnetic force should, in one hand be strong enough to overcome the capillary pinning and viscous forces, while on the other hand it has to be spatially and temporally resolved with sufficient accuracy to engender directional transport; such action-at-a-distance is challenging and requires delicate combination of operating parameters, e.g., magnetizing current and timing of switching of the chip-embedded coils, fluid viscosity, droplet size, etc. Unlike microchannel-based fluidics, in magnetic OMDMF system, multiple droplets can be steered concurrently using sequentially switched array of chip-embedded micro-coils; at the same time strategic manipulation of droplets can be attained using such design. Here, two magnetic force-based droplet manipulation strategies have been proposed where an array of planar electromagnetic micro-coils embedded in a substrate provides the motive force. In the first scheme a numerical analysis is performed where the manipulation of an immiscible, microliter-scale ferrofluid droplet over a thin aqueous film on a solid substrate, using embedded micro-electromagnet coils, is performed. The numerical model is first validated against an experimentally observed droplet trajectory in a simple, single-coil configuration. Subsequently, simulation of the ferrofluid droplets transport on a liquid film is carried out under a magnetic field that is produced by a sequentially-switched array of square-spiral micro electromagnets. Guided transport of the droplet in predefined meandering path over an active substrate area is achieved through precisely tuning the operating parameters. The droplets clearly display two distinct regimes of transport – one dominated by viscosity and the other by inertia. In the viscous-regime, the time-of-flight of a given ferrofluid droplet over the magnetic actuator section is found to scale with a generalized group-variable involving the operating parameters, viz., the field current, droplet size, and the viscosities of the magnetic fluid and the film-liquid. The second strategy demonstrates two distinct transport models of a spherical-cap ferrofluid droplet that is manipulated on solid surface. The first transport model proposed a microliter-volume droplet manipulation in a sequence of rectilinear paths using an array of double-layer electromagnetic micro-coils embedded in the substrate. Appropriate sequence of coil energization for attaining the desired trajectory of the droplet is described. The study paves the foundation of developing an OMDMF platform for more complex digital microfluidic manipulations that are pertinent to different bio-microfluidic applications. The second transport model proposes a concept of several two-dimensional multi-droplet manipulations, such as multiple droplets sorting, sequential merging as well as pooling on a solid hydrophobic surface by the sequentially switched array of electromagnetic micro-coils. By applying appropriate sequences of micro-coil switching multiple droplets can be manipulated simultaneously and various droplet operations can be attained. Results of the study lead to the formulation of design bases for magnetically manipulated, configurable, multi-tasking open-surfaced, digital microfluidic platforms.