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MAGNETICALLY MANIPULATED SAMPLE HANDLING SYSTEM ON DIGITAL MICROFLUIDIC PLATFORMS

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ABSTRACT

“Biofunctionalized” ferrofluid droplets carrying a measured volume of analytes or reagents can be manipulated magnetically on a flat microfluidic platform, executing key tasks of a micrototal analysis system (μ-TAS). Precise control of these ferrofluid droplets can be achieved using on-chip miniaturized magnetic coils which require delicate combination of operating parameters, e.g., magnetizing current and timing of switching, fluid viscosity, droplet size, etc. Herein we present a proof of concept demonstration of magnetic manipulation of an immiscible, microliter-scale ferrofluid droplet over a thin aqueous film on a solid substrate, using an array of square electromagnets. The droplet can be moved in a zigzag or a less meandering path over an active substrate area by sequential switching of the electromagnet array with adjusting the operating parameters, e.g., fluid viscosity, current in the coil, and the droplet volume. The transport is broadly classified into a viscosity-dominated regime and an inertia-influenced one. Transport time of the droplet for the viscous regime is expressed in terms of a generalized group-variable involving the operating parameters. This magnetically manipulated ferrofluid droplets handling system offers a promising tool for miniscule sample handling in lab-on-chip devices.

DROPLET-BASED MICROFLUDICS

- ❑ Extremely small amounts of reagent required (nanoliters to microliters)
  - Reduced cost of chemicals
- ❑ Reduced bioanalytical reaction time
- ❑ Ability to handle measured volumes
- ❑ Immune to surface contamination
- ❑ Versatile applications such as molecular detection, imaging, drug delivery, diagnostics, cell biology etc.

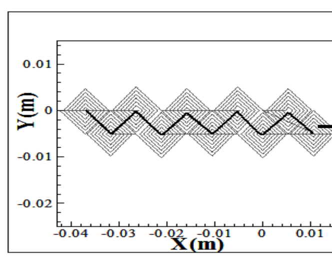
Why ferrofluid droplets?

- ❑ Effectively carry a measured volume of analyte or reagents
- ❑ Precisely manipulated on microfluidic platform by magnetic force
- ❑ Can be individually transported, mixed and analyzed
- ❑ Nanoparticles can be biofunctionalized for specific applications

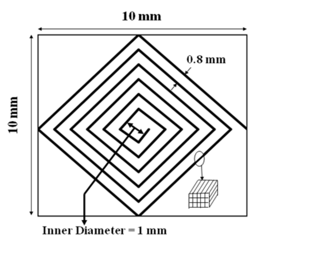
OBJECTIVES

- Design of a ferrofluid droplet-based microfluidic platform to transport microliter sized , oil based ferrofluid droplets.
- Developing a numerical model to analysis the controlled manipulation of the ferrofluid droplets on the liquid film atop the substrate using periodically switched array of electromagnetic micro-coils
- Experimental validation of predicted motion of ferrofluid droplet under the influence of electromagnetic micro-coils
- Parametric analysis to characterize the influence of the salient design and operating parameters like the coil current, ferrofluid droplet size, and fluid viscosity on the ferrofluid droplet transport

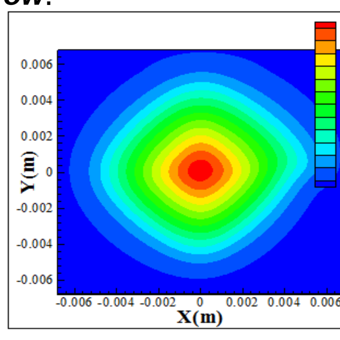
Micro-electromagnets



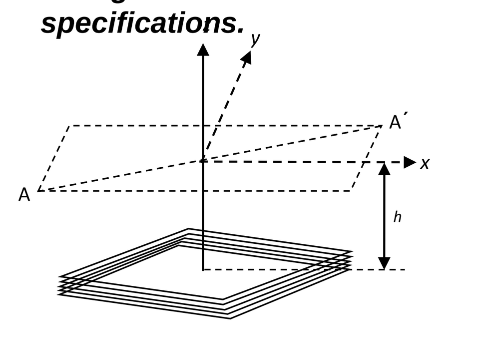
Array of the square coils arranged in double row.



A single coil is shown with its specifications.



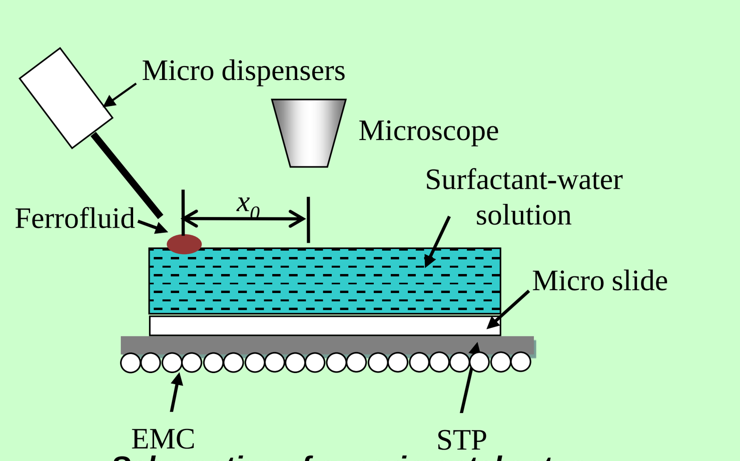
Contour plot of |B| (T) at a plane AA´ located at h = 2 mm above the coil for I = 2.5 A.



The corresponding schematic arrangement showing the relative positions of the coil and the AA´ plane.

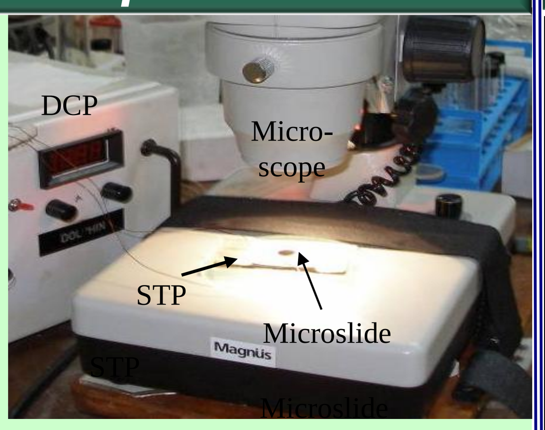
EXPERIMENT

Validation of the droplet transport model

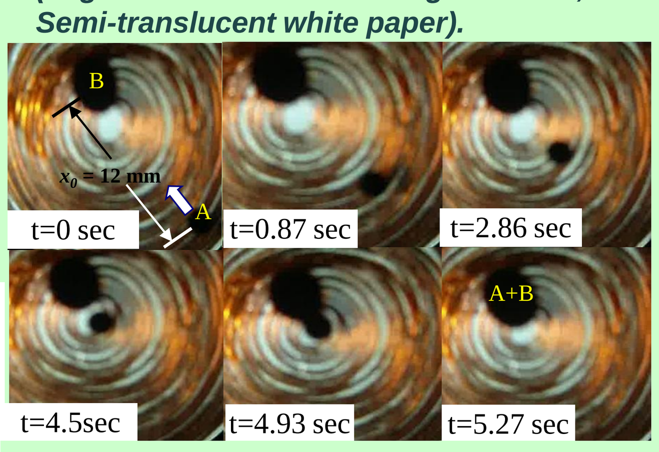


Schematics of experimental setup

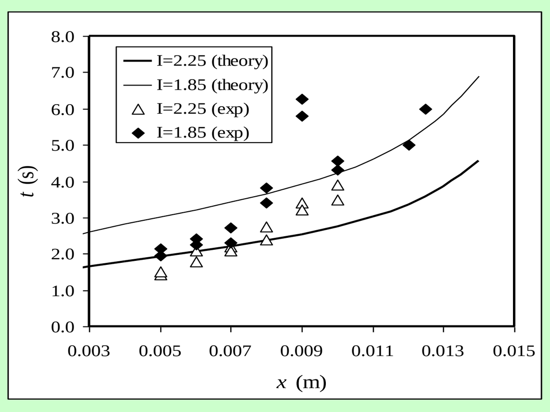
(Legend: EMC = Electromagnetic coil, DCP = DC power supply unit for EMC, STP = Semi-translucent white paper).



The actual experimental setup under the microscope.

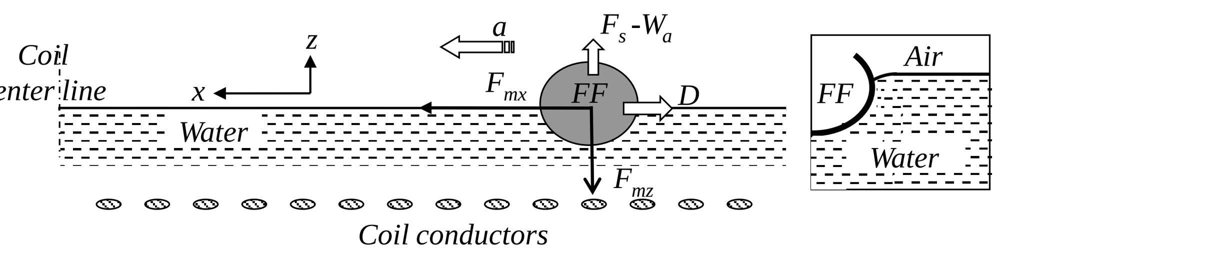


Experimentally observed trajectory of ferrofluid droplet under the influence of the circular spiral coil carrying 1.85 A current. Legend: A- the moving ferrofluid droplet; B - ferrofluid accumulation from previously transported droplets



Variation of the predicted time-of-flight of ferrofluid droplets validation between theoretical and experimental results.

THEORETICAL FORMULATION



Magnetic force on ferrofluid droplet within the magnetic field :

$$\vec{F}_{mag} = \mu_0 3\frac{\mu_r - 1}{\mu_r + 2}\int (H.\nabla)H d^3r \approx \frac{1}{2}\mu_0 V_{FF}\chi_m \nabla(|H|^2)$$

The *x* and y components of magnetic force on a ferrofluid droplet are

$$F_{mx} = \mu_0 \frac{4}{3}\pi R_{FF}^3 \chi_{eff} \frac{\partial}{\partial x}\left(\frac{1}{2}H^2\right) \qquad F_{my} = \mu_0 \frac{4}{3}\pi R_{FF}^3 \chi_{eff} \frac{\partial}{\partial y}\left(\frac{1}{2}H^2\right)$$

The equations of motion for the droplet in terms of the *x* and *y* components :

$$m_{FF}\frac{d^2x}{dt^2} = F_{mx}(x,y,z) + D_x \qquad m_{FF}\frac{d^2y}{dt^2} = F_{my}(x,y,z) + D_y$$

Along the *z* axis, the surface tension-induced reaction force is capable of nullifying the *z* component of magnetic force and the buoyancy force, i.e.

$$0 = F_s - F_{mz}(x,y,z) - W_a$$

Drag force for half-immersed ferrofluid droplet to be

$$D_y = -\pi R_{FF}\eta\left(\frac{2+3\varsigma}{1+\varsigma}\right)\frac{dy}{dt} \qquad D_x = -\pi R_{FF}\eta\left(\frac{2+3\varsigma}{1+\varsigma}\right)\frac{dx}{dt}$$

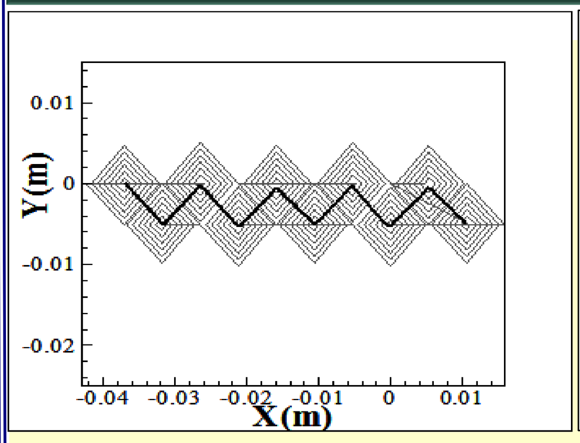
The equations of motion of the ferrofluid droplets

$$\frac{d^2y}{dt^2} + \frac{3}{4}\left(\frac{2+3\varsigma}{1+\varsigma}\right)\frac{\eta}{R_{FF}^2\rho_{FF}}\frac{dy}{dt} - \frac{\mu_0\chi_{eff}}{\rho_{FF}}f(y) = 0 \qquad \frac{d^2x}{dt^2} + \frac{3}{4}\left(\frac{2+3\varsigma}{1+\varsigma}\right)\frac{\eta}{R_{FF}^2\rho_{FF}}\frac{dx}{dt} - \frac{\mu_0\chi_{eff}}{\rho_{FF}}f(x) = 0$$

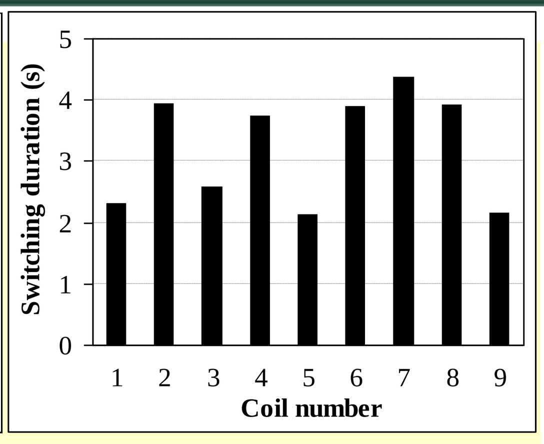
Here $f(x) = \frac{\partial}{\partial x}\left(\frac{1}{2}H^2\right)$ and $f(y) = \frac{\partial}{\partial y}\left(\frac{1}{2}H^2\right)$

RESULTS

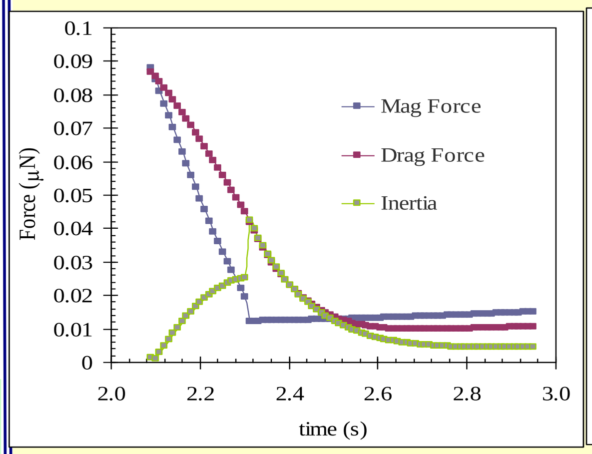
Ferrofluid droplet trajectory (Base case)



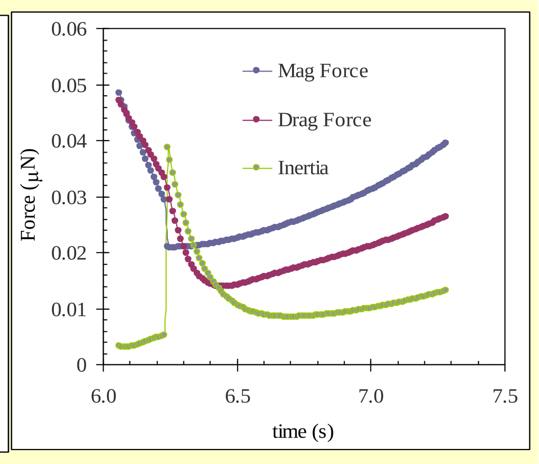
Trajectory of a 1.7 mm diameter ferrofluid droplet on the AA´ plane



The corresponding switching durations (for which the relevant coil was at “switched on” states) of coil C1 through C9 which are turned ‘on’ and ‘off’ in sequence.

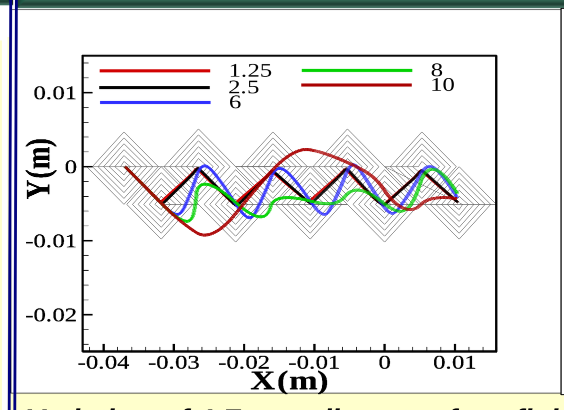


Magnetic, drag and inertial forces on the droplet at the instants first switching (C1 turns off, C2 turns on)

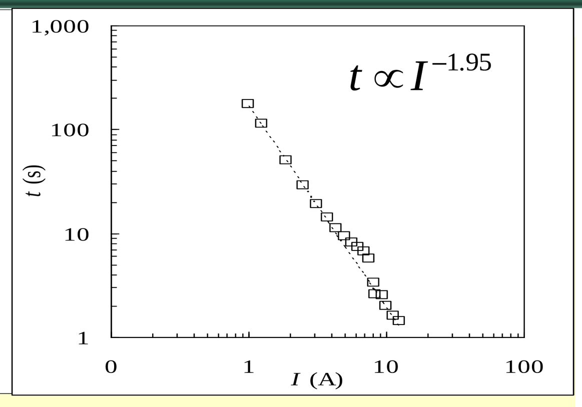


Magnetic, drag and inertial forces on the droplet at the instants second switching (C2 turns off, C3 turns on).

Effect of variation of field current

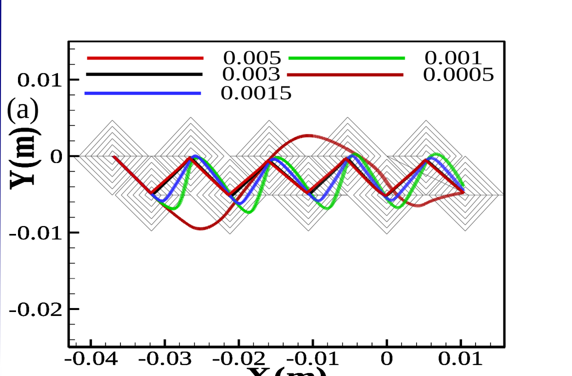


Variation of 1.7 mm diameter ferrofluid droplet trajectories on the AA´ plane for different values of current in the coil (in terms of percentage of the base current of 2.5 A)

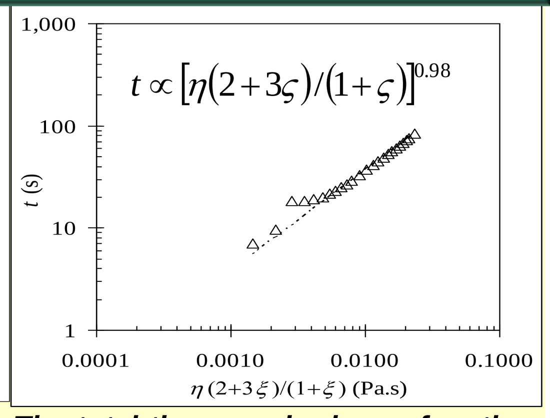


The total time-of-flight required decreases with increasing current in the coils(□ simulation results, - - - trend line $t \propto I^{-1.95}$).

Effect of variation of host fluid viscosity



Variation of 1.1 mm diameter ferrofluid droplet trajectories on the AA´ plane for different values of host fluid viscosity (expressed in Pa.s).

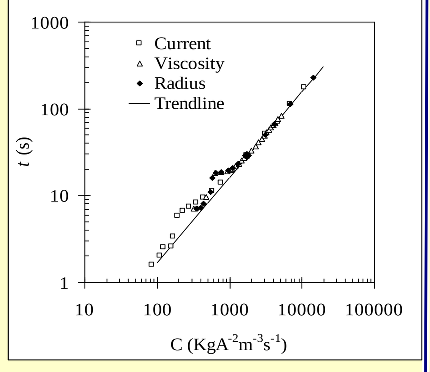


The total time required as a function of the parameter (Δ simulation results, - - trendline $t \propto [\eta(2+3\varsigma)/(1+\varsigma)]^{0.98}$.

Scaling analysis

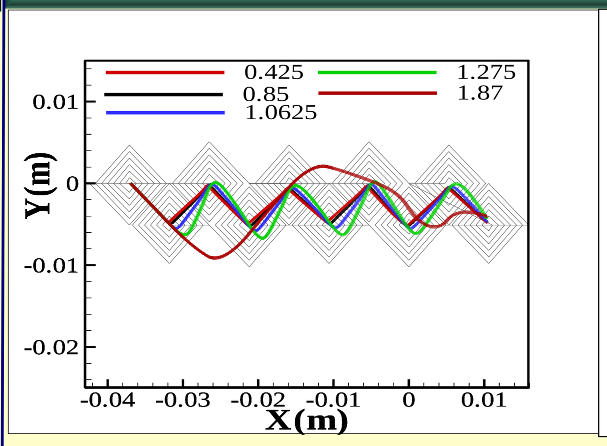
- For small droplet size and low viscosity inertial effect negligible
- Magnetic force $F_m \approx I^2$
- Moment balance $\frac{dx}{dt} \approx R_{FF}^2 I_2 \Big/ \eta\left(\frac{2+3\varsigma}{1+\varsigma}\right)$
- Therefore $t \approx \left(\frac{2+3\varsigma}{1+\varsigma}\right)\frac{\eta}{R_{FF}^2 I^2}x$
- Dimensional group variable

$$C = [\eta(2+3\varsigma)/(1+\varsigma)] \big/ [I^2 R_{FF}^2]$$

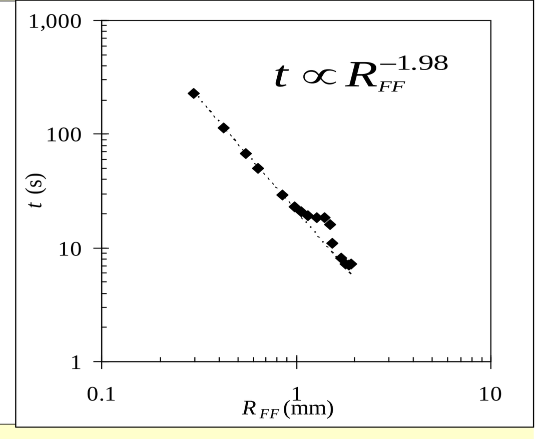


Combined plots of droplet transport time as function of the group-variable .

Effect of ferrofluid droplet size



Variation of ferrofluid droplet trajectories on the AA´ plane for different values of radius RFF of the droplet.



The total time required decreases with increasing radius of the droplet (♦ denotes simulation results, - - - denotes the trendline $t \propto R_{FF}^{-1.98}$

Conclusions

- Controlled transport of a microliter-size ferrofluid droplet over a thin aqueous film on a flat substrate is demonstrated at a proof-of-concept level.
- A numerical model is used to characterize two-dimensional manipulation of the ferrofluid droplets
- Predictions of the magnetic force field and the resulting transient transport of ferrofluid droplet are validated experimentally in a single-coil configuration.
- Ferrofluid droplet motion induced by the micro-coil array is subsequently analyzed for different values of field current, fluid viscosity and droplet size.
- Overall, the droplet transport time over the coil-array length is found to scale linearly with a group-variable $C = [\eta(2+3\varsigma)/(1+\varsigma)] \big/ [I^2 R_{FF}^2]$ for the viscosity-dominated regime but for inertia-dominated transports this scaling relationship slightly exceeds due to inertia-driven over-travels in the positive and negative y-directions

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