DIRECTED PRECIPITATION OF SUSPENSION PARTICLES ONTO BLANK SUBSTRATES USING MARANGONI CELLS

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ABSTRACT

The directed precipitation of suspension particles in a thin layer of fluid (≤ 1 mm) onto a featureless glass substrate by Marangoni flows is presented. A millimeter-sized heat source is suspended above the fluid in close proximity ranging from 0.1-2 mm to create surface tension gradient along the fluid surface, generating Marangoni flow cells harnessed for particle precipitation in the bulk fluid. The resultant pattern and accumulation level depend on factors such as the number of active heaters and type of fluid used.

KEYWORDS: Marangoni flow, thermocapillary convection, surface tension gradient, precipitation, programmable microfluidics

INTRODUCTION

The accumulation and precipitation of suspension particles are important for environmental monitoring and biochemical analysis [1]. Thermocapillary (Marangoni) flow, the flow of liquids induced by temperature gradient at a liquid-gas interface, has been utilized to perform droplet actuation by programmable manipulation using a 128-pixel heater array suspended 0.1-2 mm above the liquid surface [2]. This paper describes the directed precipitation of suspension particles in a fluid onto a featureless glass substrate by Marangoni flows. By activating a particular resistor of the heater array, a temperature gradient is created on the surface of a thin liquid layer directly below the resistor [3]. This results in surface tension gradient, which generates Marangoni flows capable of directing particles to precipitate at desired locations on a blank glass substrate in a contactless manner.

THEORY

When a small heat source is suspended above a thin fluid layer in close proximity, the heat travels through the air gap and increases the fluid surface temperature directly below the heat source. A temperature gradient is created at the fluid surface, resulting in a surface tension gradient. The corresponding thermocapillary shear stress, τ_s, is proportional to the temperature gradient, ∇T_s, [3,4]:

$$\tau_s = \mu \frac{d\vec{u}_s}{d\vec{N}} = -\sigma_T \nabla T_s \tag{1}$$

In this equation, μ is the dynamic viscosity of the fluid, $\vec{u}_s$ is the tangential surface velocity vector, $\vec{N}$ is the surface normal vector and $\sigma_T = \partial\sigma/\partial T$ is the surface tension temperature coefficient. The direction of shear stress and flow are from a region of low surface tension (high temperature) to a region of high surface tension (low temperature). Therefore, Marangoni flow is directed away from the heat source at the fluid surface. This motion along the surface results in subsurface flows towards the heat source in the bulk. The surface and subsurface flows together form the Marangoni cell, transporting suspended particles in a toroidal pattern and sweeping those settled on the glass substrate to an area below the heater. This sweeping action assists in the localization of the precipitate, regardless of whether it is caused by gravitational forces or particle-substrate interaction.

When a power supply of 0.6 W is applied to the resistor, the temperature of the resistor measured by thermocouple and infrared thermometer is 117°C. The air gap distance between the heater and fluid surface is approximately 700 µm. Simulation result shows that the surface temperature of the fluid immediately below the resistor rises proportionately as the heater temperature is increased or the air gap distance is decreased. Surface and subsurface flows are generated within the liquid, forming Marangoni flow cells as shown in Figure 1.

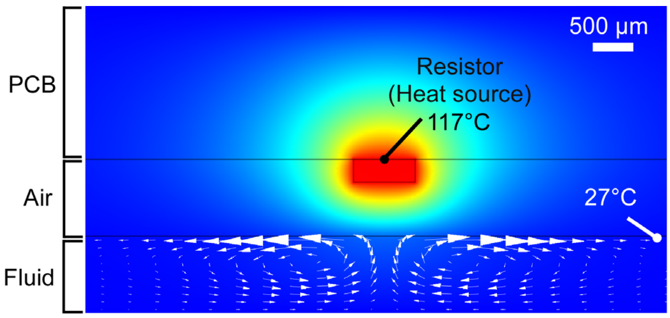


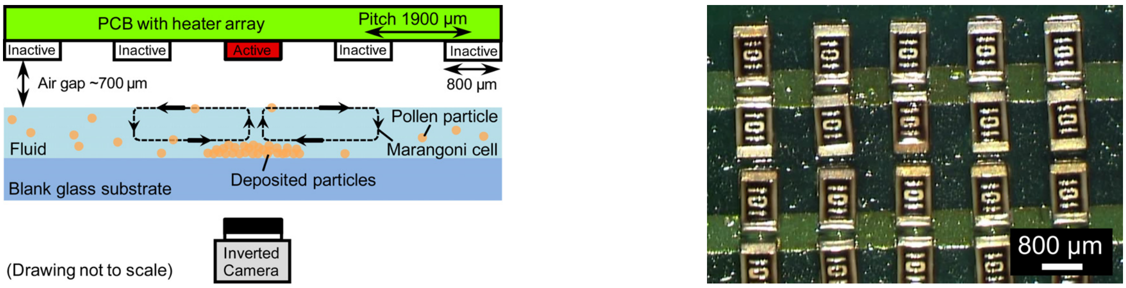
Figure 1: Simulation result showing temperature distribution profile and generated Marangoni flow cells.

EXPERIMENTAL SETUP

A 16 x 8 heater array is used to generate Marangoni flows in a thin layer of fluid. The heater array consists of #0603 surface-mount resistors (100 Ω, each of size 1 x 0.8 x 0.3 mm^3) placed at 1.9 mm pitch on a PCB [2]. These resistors are suspended ~700 μm above the fluid surface, and when activated, create a local temperature increase on the fluid surface and corresponding decrease in surface tension. This generates Marangoni flows which can be utilized to collect particles on a blank substrate. The liquid is not removed in this process. An inverted camera is placed underneath the glass substrate to observe particle precipitation as shown in Figure 2(a). Figure 2(b) shows part of the 128-resistor heater array captured by the camera. The precipitation of 25-30 μm diameter weed pollen (*Kochia scoparia*, Sigma-Aldrich) is investigated. Three kinds of liquids are used, namely silicone oil DC-550 (Dow Corning), DC-704 (Dow Corning) and Fluorinert FC-3283 (3M). Some of their properties are listed in Table 1 [2].

Table 1. Material properties of the three liquids used.

Properties at 25°C	Liquids		
	DC-550	DC-704	FC-3283
Density (kg/m^3)	1070	1070	1820
Viscosity (kg/m.s)	0.134	0.042	0.0014
Thermal conductivity (W/m.K)	0.13	0.16	0.066

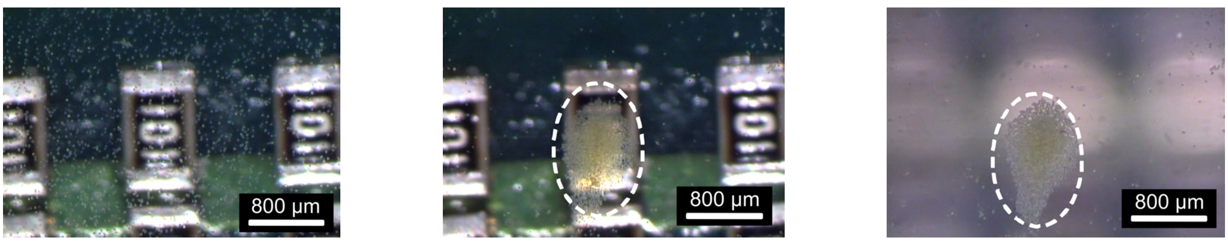


(a) *(b)*

Figure 2: (a) Schematic diagram of experimental setup (side view). (b) Top view of part of the 16 x 8 heater array.

RESULTS AND DISCUSSION

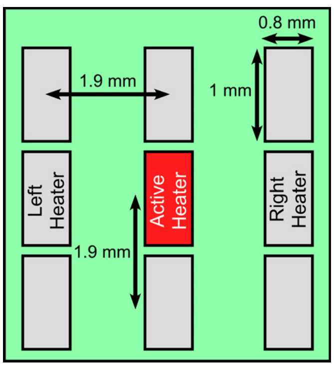
Figure 3 shows temporal sequence of particle precipitation starting with random distribution of 25-30 μm weed pollen immersed in silicone oil DC-704 with initial approximate concentration of 3-5 particles per 5 x 10^6 μm^3. Figure 3(c) shows the resultant precipitation pattern of the pollens in the fluid on the glass surface. The approximate number of pollens collected directly under the active heater and also below adjacent heaters per 100 x 100 μm^2 is listed in Table 2.



(a) *(b)* *(c)*

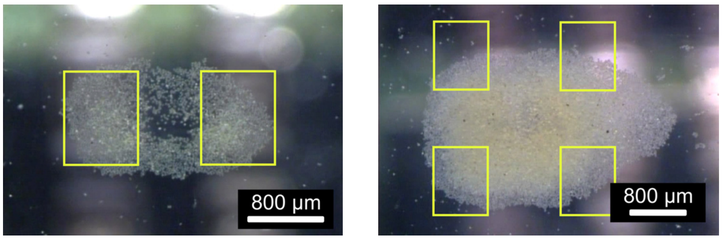
Figure 3: Precipitation in DC-704. (a) Initial random distribution of particles immersed throughout the liquid with approximate concentration of 3-5 particles per 5 x 10^6 μm^3. (b) Particle precipitation after 4 minutes. (c) Particle precipitation after 12 minutes. Before taking the image, the suspended heater is raised but the liquid is not removed.

Table 2. Number of suspension particles (25-30 μm weed pollen) accumulated below center active heater, the heater to the left and to the right. More and more particles are accumulated below the center active heater as time increases.



	Number of particles (per 100 x 100 μm^2)		
Time (s)	**Below left heater**	**Below center active heater**	**Below right heater**
0	4	3	3
15	4	5	3
30	4	6	3
45	3	8	2
60	4	11	3
75	4	15-19	3
90	3	> 20	3

The resultant pattern and accumulation level can be controlled. Figures 4(a) and 4(b) show that different precipitation pattern and amount of collected particles can be attained by activating different number of heaters simultaneously. Each heater is supplied with 0.6 W, and the fluid used is DC-704. More particles are collected when more heaters are active with the same initial concentration of suspension particles. The yellow rectangles in Figure 4 identify the initial location of the suspended heaters during the experiment.



(a) *(b)*

Figure 4: Formation of different patterns and amount of precipitation in DC-704 after approximately 15 minutes by: (a) 2 heaters; (b) 4 heaters. Each heater is supplied with 0.6 W. The liquid is not removed. The yellow rectangles identify the original location of the suspended heaters before they are raised.

The type of fluid used also affects precipitation. In this set of experiments, the concentration of the suspension particles is kept constant. One heater is activated at a power of 0.6 W. The thickness of the fluid layer is in the range of 500-1000 μm. Figure 5(a) shows the resultant precipitation in DC-550. In this fluid, particle movement is very slow, typically ~600 μm/s at 1 mm offset from the center of the heat source. Particle collection is limited to a small area below the heater. Those particles not trapped in the Marangoni cells settle to the bottom of the fluid. It is difficult to sweep particles along the glass substrate, and the final pattern of particles seems scattered. Figure 5(b) is particle precipitation in DC-704. The particle speed is relatively higher, > 1000 μm/s. More particles are collected from a larger area and form a more focused pattern. In Fluorinert FC-3283, the particles easily settle on the glass, and those that remain suspended move at a very high speed away from the heat source. No precipitation occurs.

(a) *(b)* *(c)*

Figure 5: Particle precipitation in three different fluids. (a) Precipitation in DC-550. Particle collection is limited to a small area below the heater. (b) Precipitation in DC-704. More particles are collected from a larger area. (c) No precipitation occurs in FC-3283. The suspended heater is not raised before taking the image.

CONCLUSION

This work shows that an array of millimeter-sized heat sources can be used to generate Marangoni flow in the bulk fluid for the purpose of spatially localized precipitation of small suspension particles. This method can effectively generate various precipitation patterns by imposing appropriate conditions. Such technique can have potential applications in environmental science and biology.

ACKNOWLEDGEMENTS

The authors sincerely thank Dr. Amar Basu for the meaningful discussions, guidance in modeling, as well as the development of the 128-pixel heater array. E.H. is grateful for the graduate student fellowship support from the Department of Electrical Engineering and Computer Science of the University of Michigan, Ann Arbor.

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