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Particle movement with squeezing flow of liquid films

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ABSTRACT

The use of liquid chambers created with cover-slips on slides offers a very convenient means for particle and cell suspension handling. In this work, we demonstrate a simple approach of displacing suspended matter within such chambers by depressing one side of the cover-slip using piezoelectric translators to create a squeeze flow to move particles and to restore them close to their original position when translation ceased. In the system developed, the application of 60 V to a piezoelectric stack caused 60 μm of displacement. The transfer coefficient governing this ratio is largely dependent on the support stiffness in which we estimate here as $k = 22{,}000$ N/m. This value can be easily raised if required. The approach was also adapted to transfer particles and fluid between two cover-slip chambers sealed at all the edges except for a small air gap. During actuation, a liquid bridge was established between the two chambers to allow such transfer to occur. These findings constitute the first known successful attempt to use squeeze flow to manipulate particles.

1. Introduction

Particles and cells are typically suspended in fluid. The ability to move them within this fluid in a controlled manner is important in applications such as sorting [1], concentration [2], selection [3], mixing [4] or simply transport [5]. These capabilities are the building blocks for many microfluidic systems. In a small fluidic volume, particles can be moved optically [6], acoustically [7,8], or dielectrophoretically [9]. An alternative approach that applies modulation of liquid surface stresses is described in an extensive review [10]; but is applicable mainly in the context of droplets and liquid plugs. The driving of this modulation can come from environmental perturbations [11] or simply by geometry [12]. Chambers containing a known fluid volume trapped between a coverslip and glass slide (this fluid volume dictating the height of the chamber) have been used to investigate bacteria movements [13] and anisotropic Brownian motion [14]. Here, we develop a method of generating small flows within such chambers which can be used for particle displacement, contact line movement, and construction of fluid bridges. It is based on the controlled alteration of height of a liquid chamber at selected regions to give rise to what is commonly known as the squeeze flow of films.

The flow of liquid films squeezed between two flat plates has been widely investigated due to its use in lubrication [15] and viscometry [16]. This flow generating mechanism, although simple, has recently been used to demonstrate the deformation of entangled polymers in the context of nano-imprint embossing [17]. Here, we describe particle displacement schemes that are based on simple squeeze flow strategies. This has not been reported to the best of our knowledge.

2. Method

The basic system is illustrated in Fig. 1(A) wherein a liquid chamber containing particles is created between a cover-slip and slide held in place by a varnish seal at two edges (see Fig. 1(B)) these seals allow the cover-slip a degree of rotational freedom whilst preventing translational movement parallel to the focal plane. The application of a small downward piezoelectric displacement acts to depress the cover-slip at the left end will cause the cover-slip to rotate anti-clockwise (with reference to Fig. 1(A)) causing movement of the particles suspended in the fluid. There are three main physical effects which occur in this process, firstly the flow due to the reorientation of the glass surfaces, secondly the effect of contact angle hysteresis at free fluid edges, and thirdly the forces required to effect such a rotation of the coverslip. These will be discussed independently in order to ascertain the effect of each on the ability to displace particles.

When the surfaces realign, as shown in Fig. 2(A) a flow ensues within the chamber. A model has been developed [18] for such a flow between plates forming a wedge, if (i) the liquid is incompressible, (ii) the areas sufficiently large, (iii) the fluid remains constrained between the plates at all times, (iv) the wedge angle θ_w small, and (v) the inertia terms neglected, we have

$$\frac{\partial (rV_r)}{\partial r} + \frac{\partial V_\theta}{\partial \theta} = 0 \qquad (1)$$

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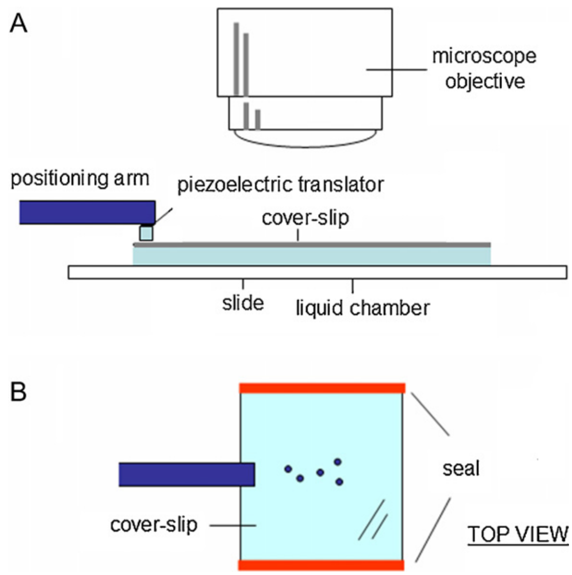

Fig. 1. Schematic of the squeeze flow particle location method, wherein in (A) the downward piezoelectric translation on the cover-slip causes it to rotate anticlockwise to produce a fluid flow that carries particles along to the right. The cover-slip was sealed along the edges shown from the top view (B).

where V_r and V_θ are the velocity components in the respective r and θ directions. If the flow in the chamber undergoes no slip, the boundary conditions may be specified as

$$\frac{\partial V_\theta}{\partial \theta} = 0, \qquad V_\theta = 0 \quad \text{at} \quad \theta = 0 \tag{2a}$$

$$V_r = 0, \qquad V_\theta = r\frac{d\theta_w}{dt} \quad \text{at} \quad \theta = \theta_w \tag{2b}$$

As the volume change due to squeezing is balanced by radial movement of the fluid, then [18]

$$V_r = -\frac{r}{2\theta_w}\frac{\partial\theta_w}{\partial t}(2\alpha_1 A + 3\alpha_2 A^2 + \cdots + (k+1)\alpha_k A^k) \tag{3}$$

where $A = [\theta_w - \theta]/\theta_w$ and α_k is a constant in which $(\alpha_k + \alpha_k + \cdots + \alpha_k) = 1$. Clearly the application of downward piezoelectric translation causes $\partial\theta_w/\partial t$ to be negative. This results in V_r acting towards the right to bring particles along with the flow.

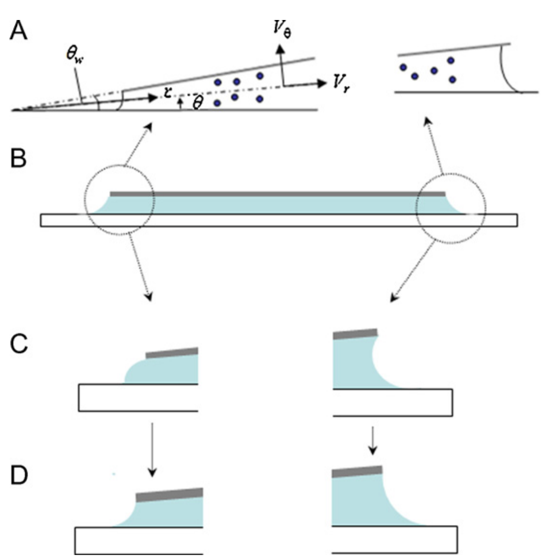

Fig. 2. A depiction of the flow occurring (A) from the realignment of the surfaces forming the chamber from the parallel state (B). A secondary flow causing effect occurs due to an adjustment of the free surface shape from momentarily (C) to a move stable case depicted in (D).

The second effect is that of the fluid free surface taking a shape dictated by the minimum of the surface energies of the liquid vapor interface and the solid liquid interface, and the line energy related to the movement of the contact line (during which the equilibrium contact angle, θ_0, undergoes hysteresis such that it may alter through a range between the receding angle, θ_R, and the advancing angle, θ_A). The associated change in energy for a droplet (changing the last term from a circumference to a line length renders the equation more widely applicable) deposited on a solid surface can be determined as [19]

$$\delta w = 0 = \gamma dA_{LV} + (\gamma_{SL} - \gamma_{SV})dA_{SL} - 2\pi k dr \tag{4}$$

where δw is the work change to cause the surface shape alteration, γ, γ_{SL} and γ_{SV}, are the surface energies of the interfaces between the liquid/vapor, solid/liquid and solid/vapor respectively, and k is the line energy of the contact line. The other variables are geometric, where dA_{LV} and dA_{SL} are the interface areas between the liquid/vapor and solid/liquid phases respectively, and r is the radius of the wetted area of the solid surface. In the general case, the fluid will seek to minimize surface areas and contact line lengths, though the contact line energy will restrict the motion required for this by its own resistance to motion. Indeed, contact angle hysteresis of the triple phase lines at the liquid free ends help to keep the liquid within the chamber. Such free surface alterations are depicted in Fig. 2(C) and (D), the former being an intermediary step prior to equilibrium being reestablished. This process will affect the flow through the chamber. In both depictions the contact line is assumed not to move. In relation to particle movement, this is supported by experimental findings presented here in which the particles are observed to move back closely to their original positions when the piezoelectric translator is switched off. This reversal in the direction of liquid flow indicates a clockwise rotation of the cover-slip. Such reversibility indicates that the contact line is unlikely to have moved. The effect on the distortion of the free surfaces is highly dependent on which sides are sealed. The sealing serves a few purposes; it (a) hinders translation of the coverslip, (b) lowers evaporative effects, and (c) can be used to guide motion – for example in the case of Fig. 1(B) where the motion is either predominately away from or towards the piezoelectric actuator. If a second actuator applies a force at the lower edge (with reference to the image) of the system shown in Fig. 1(B), there will be a component of motion away from (or towards) the actuator. There will also be perpendicular motion due to change of the free surfaces. Motion is also achievable in the case of sealing all edges; however the forces required will be greater, which relates to the third main effect when we apply the piezoelectric stack actuation.

Whilst the realignment of the glass surfaces causes a flow that is affected by the sealing of the edges, the distance that the fluid (and thus particles) moves is largely related to the forces in the system. Piezoelectric stacks tend to be characterized by displacement versus voltage (4.6 μm at the maximum 100 V for the system used). The extent that this displacement is able to create an ensuing deflection on the liquid chamber is related to the stiffness of the system itself and the forces which the stack can exert. Squeeze film forces have been well described in an early description by Kuzma [20] for parallel circular plates, in which the force required to change the distance between the plates, h, is given by

$$F = -\frac{\pi R^4}{4}\left(\frac{6\mu\dot{h}}{h^3} + \frac{3\rho\ddot{h}}{5h} - \frac{15\rho\dot{h}^2}{14h^2}\right) \tag{5}$$

where R is the radius of the plates, μ is the viscosity and ρ is the fluid density. As might be expected, the resulting force is dependent on the velocity and acceleration of the contraction or expansion of