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General

Linear concentration of microscale samples under an ultrasonically vibrating needle in water on a substrate surface

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ABSTRACT

We show a method of concentrating microscale samples in a film of aqueous suspension on a stationary substrate (not in vibration), which employs the acoustic streaming generated by an ultrasonically vibrating needle parallel to and above the stationary substrate. Concentrated yeast particles with a diameter of 4–6 μm may form a series of lobed zones on the stationary substrate if the position of the vibrating needle has no change during the sonication, and form a continuous linear line if the vibrating needle is moved back and forth along a linear trajectory. Smaller objects such as AgNWs with a length of 30–40 μm and diameter of 300 nm, and ZnO particles with a diameter of about 1 μm, can also be concentrated by the method. For the yeast and ZnO microparticles, boundaries of the concentration zones are very distinct.

1. Introduction

Controlled concentration of small samples has potential applications in high-sensitivity sensing of biological substances, crystal growth, culture of artificial tissues, separation and filtering process, etc. Controlled ultrasound provides a very effective method to concentrate small samples. The ultrasonic standing-wave field, in which microscale objects are pushed to the nodes or anti-nodes of sound pressure by the acoustic radiation force [1–4], provides an effective way to concentrate microscale samples [5–10]. Ultrasonic field in a droplet at the center of an ultrasonic stage can be used to concentrate nanoscale samples in the droplet [11], in which the acoustic streaming is used to push the samples on the surface of the ultrasonic stage to the center of the droplet. In the former technique, an ultrasonic standing-wave field is needed, and the concentration position is within the field. In the latter one, an ultrasonically vibrating substrate is needed. In many practical applications, it is desired that the mechanism to excite the ultrasonic field is simple, compact and reliable, and microscale samples in aqueous suspension are concentrated on a common substrate such as a glass slide or silicon substrate, which is not in vibration. It is still a challenge for the existing ultrasonic techniques to meet these requirements.

In this paper, we report an acoustic streaming induced concentration of microscale samples in an aqueous suspension film (a water film with micro objects suspended inside) on a stationary substrate. The concentration is realized by an ultrasonically vibrating needle inserted into the aqueous suspension film. Concentrated micro samples in our method may form a series of lobed patterns along the length direction of the vibrating needle, which are under the vibrating needle on the surface of the stationary substrate. And the concentrated microscale samples can also form a linear line if the needle is linearly moved back and forth along a linear trajectory. The concentration zones, formed by micro or smaller samples, have a very clear boundary.

2. Experimental setup, phenomena and principle

Fig. 1 shows the experimental setup for concentration of yeast particles under an ultrasonically vibrating needle. A layer of aqueous suspension film with a thickness of about 2.5 mm is dispersed on a silicon substrate, and a stainless steel needle is inserted into the suspension film horizontally, as show in Fig. 1(a). The suspension is formed by deionized water with dispersed yeast particles. During the concentration process, the silicon substrate is stationary (not in vibration), and the stainless steel needle vibrates in the parallel direction to the substrate. The suspension film and lobed patterns were observed by a microscope (VHX-1000E, Keyence). The device used in our experiments is composed of a piezoelectric transducer and the stainless steel needle which is bonded to the radiation surface of the piezoelectric transducer with a resonance frequency of 74.5 kHz, as show in Fig. 1(b). In this piezoelectric transducer, four piezoelectric rings are aligned and pressed together by two cylindrical aluminum covers with a bolting

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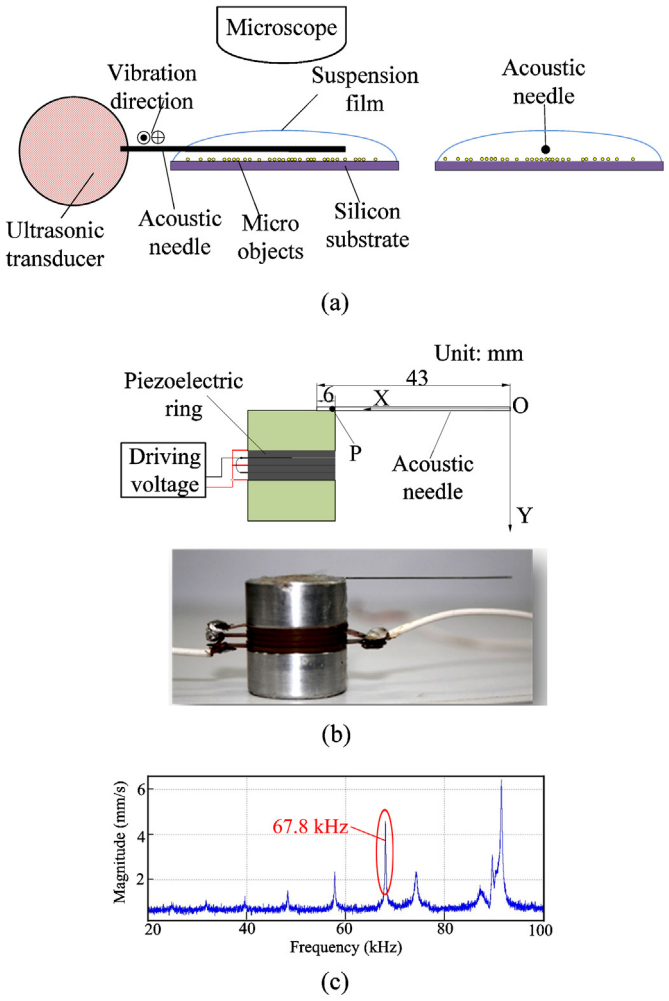

Fig. 1. Experimental setup for generating the lobed concentration patterns in aqueous suspension film of yeast particles on a silicon substrate. (a) Schematic diagram. (b) Construction of the ultrasonic transducer. (c) Vibration magnitude vs. operating frequency of the needle.

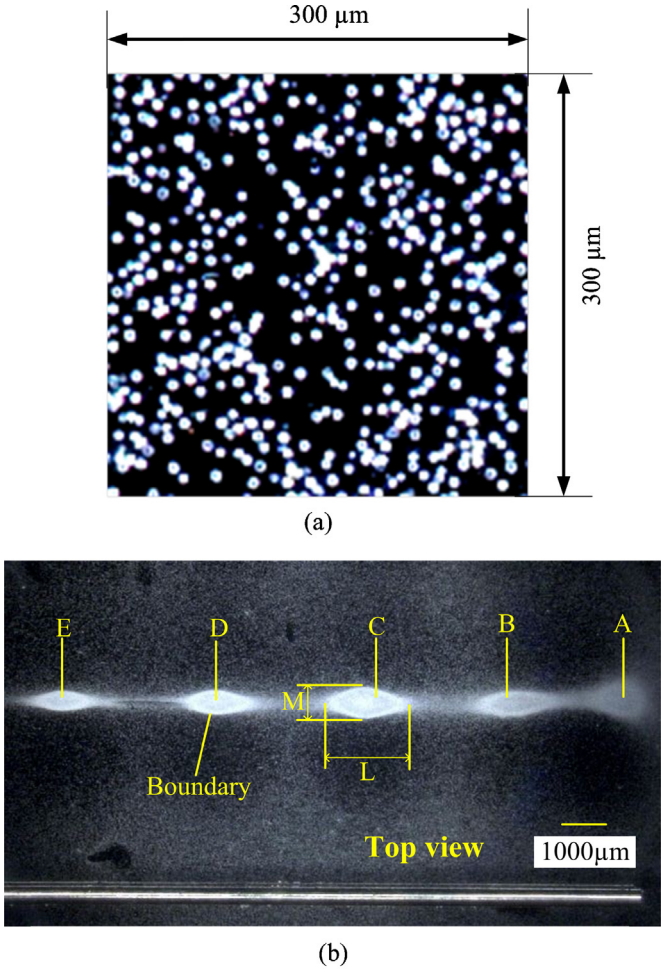

Fig. 2. (a) Aqueous suspension of yeast particles used in the experiments. The real size of the image is 300 μm × 300 μm. (b) Lobed patterns in aqueous suspension film of yeast particles on a silicon substrate, generated by ultrasonic vibration of the fine stainless needle. The vibration displacement of the needle at point *P* [Fig. 1(b)] is 180 nm. The separation between the needle and substrate is 1.5 mm, the needle length inserted into the water is 20 mm.

structure, with the poling directions and electrode configuration shown in Fig. 1(b). The outer diameter, inner diameter and thickness of each piezoelectric ring are 20 mm, 6 mm and 1 mm, respectively. The electromechanical quality factor Q_m, piezoelectric coefficient d_{33}, and relative dielectric constant $\varepsilon_{33}{}^{T}/\varepsilon_0$ of the piezoelectric ring are 2000, 325 × 10^{-12} m/v and 1450, respectively. Each cylindrical aluminum cover at the two ends of transducer has a diameter of 20 mm and thickness of 10 mm. The stainless steel needle has a total length of 45 mm, and uniform diameter of 0.35 mm. The length of the needle bonded onto the piezoelectric transducer is 7 mm. The driving voltage is sinusoidal, and the transducer woks at resonance frequency of the needle (=67.8 kHz), as shown in Fig. 1(c). The piezoelectric transducer shown in Fig. 1(b) utilizes the vibration of piezoelectric stack to excite a flexural vibration mode in the needle in the *XY* plane; thus in Fig. 1(a), the needle vibration is perpendicular to the page and parallel to the suspension film.

House hold baking yeast particles (*Saccharomycescerevisiae*) are the main samples used in the experimental aqueous suspension. Yeast particle concentration is 0.048 mg/ml and the diameter of yeast particles is 4–6 μm. Fig. 2(a) shows the yeast particles dispersed in the suspension before sonication. The average number of yeast particles in a 300 μm × 300 μm square is about 400 with a standard deviation of 27. Fig. 2(b) shows the observed concentration pattern in an aqueous suspension film of yeast particles on a silicon substrate under the ultrasonically vibrating needle with a 180 nm vibration amplitude at point *P* (see Fig. 1(b)) at 67.8 kHz. In the experiment, the separation between the needle and substrate is 1.5 mm. In the pattern, there are four lobed concentration zones which are termed lobes *B*, *C*, *D* and *E*, and an end zone *A* which is like the end of a match stick. In experiments, it takes 2–3 min to form the patterns after the sonication onset, and after this time duration, length *L* and width *M* of the patterns become stable as well as the yeast particle concentration beyond the lobed and end zones. The pattern is two dimensional and symmetric about the axis of the needle.

Fig. 3 gives the zoom-in images of the suspension around the boundary of zone *A* in the stable state at different vibration displacement. Fig. 3(a) shows the location where the images are taken, and Fig. 3(b) gives images b1–b6 at the vibration displacement of 80 nm, 100 nm, 120 nm, 140 nm, 160 nm, and 180 nm, respectively. It shows that the boundary becomes quite clear as the vibration increases. The size of the squares in Fig. 3(b) is 300 μm × 300 μm.

Our experiments in this work also show that whether the concentration process can occur under the vibration needle depends on the distance between the needle and substrate. When this distance is less than 0.5 mm, micro particles could hardly concentrate under the vibrating needle. Actually in this case a series of clear