A particle manipulation method and its experimental study based on opposed jets

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A particle manipulation method was presented in this paper based on opposed jets. In such a method, particles were trapped near the stagnation point of the flow field and moved by controlling the position of the stagnation point. The hold direction of the flow to the particle was changed by changing the orientation of the opposed-jet flow field where a particle is trapped. Subsequently, the directional and quantitative movement of the particle in any direction was achieved. Taking micron particles as examples, we analyzed the control mechanism of particles based on opposed jets and evaluated the influence of jet velocity, inner diameter, distance of end face, radial error, and position of capillaries on the particle control performance by simulations. The feasibility of the proposed method was proved by a great number of experiments, and the results demonstrated that particles with the arbitrary size and shape can be trapped and moved directionally and quantitatively by constructing an opposed-jet flow field. The trapping and position control of particles can be manipulated without any contact with proper flow field parameters. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5020600>

I. INTRODUCTION

The trapping and movement of particles are the key points of the micromanipulation technology, which are widely used in microassembly, disease diagnosis, biomedical engineering, and other fields. The manipulation methods for particles can be broadly classified into contact-based and noncontact methods. Particles are operated directly using the microtools in contact-based methods, which requires advanced skills for operators. Moreover, mechanical damage of particles may happen.^{1–3} For noncontact methods, mechanical damage caused by the improper operations can be avoided or reduced, which is becoming the mainstream approaches in current research studies. A diverse set of noncontact methods based on optical,^{4–6} electrokinetic,^{7–9} magnetic,¹⁰ acoustic,^{11,12} and microfluidic^{13–19} technologies have been developed to manipulate particles. However, due to the unclear effects of the optical, electrostatic, magnetic, and acoustic forces on living cells, the microfluidic methods have attracted more attention for their security and operability.

In microfluidic methods, Pawashe *et al.* controlled the micro-magnetic robot to move around particles to drive the fluid flow. The viscous force of the flowing fluid is utilized to drive the particles to move.¹³ Tanyeri *et al.* designed a microfluidic device with a cross-slot channel geometry, which can produce a hydrodynamic trap to confine a single particle for a long time.¹⁴ However, this method is strictly limited to trapping and manipulation of single particles. Shenoy *et al.* built a microfluidic device with multiple channels. In such a device, the position of the hydrodynamic trap can be adjusted by controlling the flow rate of each channel, and as a result, the position of particles can be controlled.¹⁵ However, in the case of multi-channels, the control

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algorithms are complicated. Aoyama *et al.* utilized a vibrated pipette to drive the fluid flow in three-dimensional space, which is able to avoid mechanical damage. However, it is difficult to adjust the vibration parameters when the cell size and fluid parameters change.¹⁶ References 17–19 proposed a microfluidic-based particle manipulation method that used the fluid pressure at the surface of the particle to clamp the particle. In this method, the trap and movement of micron particles in the axial direction of the capillaries can be achieved. Based on the above research, we further proposed a method that can steadily move a particle along any direction, which can be realized by changing the orientation of the two capillaries to change the direction of the opposed-jet flow trapping the particle. The control mechanism of particles based on opposed jets will be analyzed, and the influencing factors such as capillary parameters, relative position, and jet velocities of capillaries on the manipulation performance of the particle will be quantitatively evaluated. The feasibility of the proposed method will be demonstrated by simulations and experiments in this work.

II. PARTICLE MANIPULATION BASED ON OPPOSED JETS

Two capillaries with the same specifications are placed on both sides of a particle symmetrically. The fluid pressures on both sides of the particle are the same, when the two capillaries' jet fluid are at the same velocity. As shown in Fig. 1, the particle will be trapped between the two capillaries under the symmetrical fluid pressure.

Under the situation that a particle is stably trapped between two capillaries, if the two capillaries move slowly along the axis direction, the particle will follow the capillaries and stabilize at a new pressure balance position between the capillaries as shown in Fig. 2(a). When the two capillaries change their orientation synchronously, the direction of opposed jets will also change, and the particles can still be stably trapped as shown in Fig. 2(b). Rotating the capillaries that trap a particle and then moving the capillaries along their axis direction, movement of the particles in different directions can be achieved. Since the fluid can be flexibly deformed, particles with the arbitrary size and shape can be trapped and moved in any direction.

III. MECHANISM ANALYSIS

A. Flow generation and mathematical model

An opposed-jet flow can be generated by two capillaries' jetting fluid in opposite directions, as shown in Fig. 3. The characteristics of the flow field are symmetrically distributed around the center O of the two capillaries. The velocity in point O is zero, which is the stagnation point of the flow field. A coordinate system $\sum xoy$ is established with the origin located at

FIG. 1. Trapping of a particle.

FIG. 2. Schematic diagram of a trapped particle manipulation based on opposed jets formed by capillaries: (a) Particle followed the capillaries moving in the x direction. (b) Rotating the capillaries that trapped a particle and then moving the capillaries in their axis direction. White arrows denote the moving direction of capillaries, and gray arrows denote the moving direction of the particle.

point O . The x direction is the same as the jet direction. The velocity potential function and streamline function near the point O are described as²⁰

$$\phi = \frac{k}{2}(y^2 - x^2), \quad \varphi = kxy, \quad (1)$$

respectively, where k is a constant relative to the flow field.

FIG. 3. Schematic diagram of the opposed-jet flow field. D is the inner diameter of capillary. L is the distance between two capillaries and v is the jet velocity. O is the stagnation point of the flow field. The dotted circle area is the low velocity region of the flow field.

The streamlines near the stagnation point O are hyperbolas approaching x and y axes. The component fluid velocities near the stagnation point O can be obtained by the partial derivative of the velocity potential function

$$v_x = -kx, \quad v_y = ky. \quad (2)$$

The resultant velocity is

$$V = k\sqrt{v_x^2 + v_y^2}. \quad (3)$$

Substituting Eq. (2) into the two-dimensional incompressible Navier-Stokes equations

$$\begin{aligned} v_x \frac{\partial v_x}{\partial x} + v_y \frac{\partial v_x}{\partial y} - \nu \nabla^2 v_x &= \frac{-1}{\rho} \frac{\partial P}{\partial x}, \\ v_x \frac{\partial v_y}{\partial x} + v_y \frac{\partial v_y}{\partial y} - \nu \nabla^2 v_y &= \frac{-1}{\rho} \frac{\partial P}{\partial y}, \end{aligned}$$

we can get the pressure distribution near the stagnation point O

$$P = -\frac{\rho k^2}{2}(x^2 + y^2) + C = -\frac{\rho V^2}{2} + C, \quad (4)$$

where v_x and v_y are the velocities of the flow point (x, y) in x and y directions, ν is the kinematic viscosity of fluid, ∇^2 is a Laplace operator, ρ is the fluid density, and P is the fluid pressure.

At the stagnation point O , $V=0$, assuming the pressure at the stagnation point $P=P_0$. By substituting these parameters into Eq. (4), the pressure distribution can be expressed as

$$P = -\frac{\rho V^2}{2} + P_0. \quad (5)$$

The pressure and velocity distributions in the flow field are shown in Fig. 4. The pressure and velocity distributions are symmetrically distributed around the stagnation point O . Compared with the whole flow field, the fluid pressure is the highest and the flow velocity is the smallest near the stagnation point O . Within the flow field between the two capillaries, away from the stagnation point O , the pressure gradually weakens and the velocity gradually increases. The maximum velocity appears at the exit of the capillaries. The area near the stagnation point O is a low velocity region with large pressure, where the particles can be trapped and controlled, and such a region is called the trap area. The larger low velocity region causes the less velocity disturbance to the particle. The stronger the pressure results in greater the fluid pressure on the particles. Thus, the smaller velocity and the greater pressure in the area make it easier to trap and manipulate the particle quickly and stably.

FIG. 4. Characteristics of the opposed-jet flow field: (a) Contour plots of pressure. (b) Contour plots of velocity.

Assume P_m is the minimum pressure required to clamp the particles and V_m is the maximum velocity in the low velocity region. In the vicinity of the stagnation point O , the size of the region where the fluid pressure is greater than P_m is expressed as the average radius R_p ; the size of the region where the fluid velocity is less than V_m is represented as the average radius R_v , as shown in Fig. 4. Larger R_p and R_v make the particle trapping easier. Parameters R_v and R_p change with the flow field parameters.

B. Analysis of the factors affecting the manipulation performance

In order to quantitatively analyze and evaluate the influence of flow field parameters on the trap area, the models are established in ANSYS ICEM and imported into ANSYS Fluent software. The external boundary conditions of the models adopt the pressure outlet. Two capillaries have the same flow rate. The Reynolds number $Re = \nu d / \nu < 20$, and thus, a Laminar flow model is used. The medium is water. Atmospheric pressure is used as a reference pressure. We set $P_m = 0.2 \text{ Pa}$ and $V_m = 0.01 \text{ m/s}$.

In the following analysis, D is the inner diameter of the capillary, L is the distance between the two capillaries, v is the jet velocity of the capillary, Q is the flow rate of a single capillary, and d is the particle diameter.

The inner diameter D of the capillary and the distance L between two capillaries remain unchanged, when the flow rates of the capillaries change, and the R_p and R_v are shown in Fig. 5. We can find that as the flow rate Q increases, the average radius R_p of the high pressure region becomes larger and the average radius R_v of the low velocity region becomes smaller. Although the R_p increases, the R_v decreases sharply. If the flow velocity becomes larger, the particle near the stagnation point will be disturbed easier, and vortexes are easily generated on both sides of the capillaries, which increases instability and against to the trap of the particle.

The flow rates of the capillaries and the distance L between the two capillaries remain unchanged. When the inner diameter D of the capillary increases, the R_p decreases slowly and the R_v increases, as shown in Fig. 6.

The flow rates of the capillaries and the inner diameter D of the capillary remain unchanged. When the distance L between the two capillaries increases, the R_p decreases slowly and the R_v increases, as shown in Fig. 7.

If the two capillaries are parallel to each other, there is a radial deviation Δy in the y direction. When the inner diameter D , the distance L , and the flow rates remain the same, both R_p and R_v decrease as the deviation increases, as shown in Fig. 8. We can find that the existence of Δy will affect the size of the trap area.

If the capillaries are unparallel, there is an angle error $\Delta\theta$ between the two capillaries. As $\Delta\theta$ increases, the changes of R_p and R_v are shown in Fig. 9. Both R_p and R_v decrease with the increase in $\Delta\theta$ between the capillaries.

FIG. 5. Relationship between the R_p , R_v , and the flow rate Q of capillary ($L = 600 \mu\text{m}$ and $D = 600 \mu\text{m}$).

FIG. 6. Relationship between the R_p , R_v , and the inner diameter D of capillary ($L = 600 \mu\text{m}$ and $Q = 15 \text{ ml/h}$).

FIG. 7. Relationship between the R_p , R_v , and the distance L between two capillaries ($D = 600 \mu\text{m}$ and $Q = 15 \text{ ml/h}$).

FIG. 8. Relationship between the R_p , R_v , and the radial error Δy between two capillaries ($L = 600 \mu\text{m}$, $D = 600 \mu\text{m}$, and $Q = 15 \text{ ml/h}$).

From the simulation results as shown in Figs. 8 and 9, we can find that a relative position error between the capillaries will reduce the trap area, the success rate of trap, and the anti-disturbance ability, which is not conducive to the trap the particle.

From the above analysis, we can found that the magnitudes and distributions of pressure and velocity within the trap area in the opposed-jet flow field are related to the parameters such as the inner diameter of the capillary, the distance between the capillaries, the jetting velocities of the capillaries, the radial error, and the angle error between the capillaries. When the

FIG. 9. Relationship between the R_p , R_v , and the angle error $\Delta\theta$ between two capillaries ($L = 600 \mu\text{m}$, $D = 600 \mu\text{m}$, and $Q = 15 \text{ ml/h}$).

pressure between the two capillaries in the trap area is large enough and the velocity is low, the particles can be stably trapped. The change of the parameters of the flow field can adjust the size of R_p and R_v , which is beneficial to the realization of the particle trap and manipulation. If the R_p is large and the R_v is small, the trapped particle is easily disturbed by the flowing fluid and escape the trap area. Therefore, it is easy to trap a particle by selecting the appropriate parameters of the flow field according to the particle parameters to ensure a large fluid pressure and a big low velocity region.

C. The particle force in the opposed-jet flow field

The particles in the opposed-jet flow field are subjected to the force F_x , F_y , as shown in Fig. 10 (particles 1, 2, and 3).

The F_x points to the stagnation point along the x direction and drives the particle into the vicinity of the stagnation point (trap area). The F_y points away from the stagnation point in the y direction and drives the particle to escape from the trap area. When a particle enters the low velocity region near the stagnation point O , the particle is not easily subjected to velocity disturbance. If the fluid pressure on the particle is large enough to overcome the effect of F_y , the particle can be trapped. If the fluid pressure on the particle is small, the particle is easily

FIG. 10. Forces acting on the particles in the flow field.

disturbed and may escape from the trap area. The ideal trapped state is that the center of the particle just coincides with the stagnation point and the resultant force on the particle is zero, as particle 3 in Fig. 10. Therefore, it is very important to adjust the flow field according to the particle parameters, so that the particles can easily enter the trap area.

When there are multiple particles in the flow field, only the target particle (particle 3) entering the low velocity region can be stably trapped. Other particles (such as particles 1 or 2) will easily escape from the trap area under the action of F_y , so the excess of particles have no effect on the manipulation of the target particle.

D. Particle manipulation

When a particle is at the stagnation point, the pressure and velocity distributions of the flow field are shown in Fig. 11. When the particle is near the stagnation point, the flow field has good symmetry and a pressure containment surface is formed on the surface of the particle; the force acting on the particle in the jet direction is the largest. If the fluid pressure on the particle is large enough, the particle can be trapped and fixed. The trapped particle in the low velocity region near the stagnation point is not easily disturbed by the flowing fluid, which is beneficial to confine the particle for a long time.

When two capillaries move slowly along the axis direction of the capillaries (x direction) at the same time, the position of the stagnation point O of the flow field also follows their movements and the fluid pressure on both sides of the particle will be changed. The resultant force of F_x is no longer equal to zero. The particle will offset the original stagnation point O due to the pressure difference. As a result, the particle will follow the capillaries in the same direction and stabilize at the new stagnation point between the two capillaries.

When the two capillaries rotate slowly around their center synchronously, the jet direction will also change. However, the resultant force acting on the particle is still equal to zero.²¹ Therefore, the position of the stagnation point will not be affected by the direction change of the opposed jets, and the position of the particles will also remain unchanged. Rotating the capillaries with a trapped particle and then moving the capillaries along the axis direction, the quantitative and directional movement of the particle in any direction in the plane can be realized.

IV. EXPERIMENTS

A. Experimental principle

The capillaries used in the experiments are glass capillaries. The two selected capillaries are the same. The experimental principle is shown in Fig. 12. A medical pump (WZ-50C66T) equipped with a 50 ml syringe is used to control fluid flow. The flow regulation range of the pump is 0–1200 ml/h, and its minimum resolution is 0.01 ml/h. The fluid supplied by the pump is diverted equally to both sides by a T-joint. The capillaries are placed on both sides of the particle, and their positions are adjusted by the mobile platforms. The movement speed and the movement distance of the platforms can be controlled by manual fine-tuning knob or by

FIG. 11. Particle in the flow field. (a) Contour plots of pressure. (b) Contour plots of velocity.

FIG. 12. Schematic diagram of the experiment principle. 1. T-joint. 2. Silicone tube. 3. Capillary. 4. Particle. 5. Microscope.

computer. The mobile platforms have the mobile range of 0–3 mm and the speed range of 0.01–0.24 mm/s. The entire operation process is displayed on the computer *via* a digital microscope, which is convenient for the operators to carry out real-time manipulation. The particles used in experiment are shrimp eggs (diameter = 100–300 μm and density = 1.02 g/cm³) and silica particles (diameter = 100–550 μm and density = 2.3 g/cm³). The medium is water.

B. Experiment results and discussions

Figure 13 shows that two capillaries trapping a shrimp egg move in the x direction. The process that the particle follows the movement of capillaries is divided into three stages as shown in Fig. 14. In stage I, the shrimp egg is stably trapped. In stage II, the capillaries clamp the shrimp egg and move in the x direction. In stage III, the capillaries stop moving and the shrimp egg gradually stabilizes at the new stagnation point. The diameter of the shrimp egg used in this experiment is about 120 μm . Since the density is similar to that of the water, the shrimp eggs are suspended in the water. In the experiment, the shrimp egg is easily subjected to random forces and fluttered around the stagnation point. Due to the viscous resistance of the fluid, the movement of the shrimp egg will be behind the capillaries; however, the shrimp egg will follow the capillary movement and finally be stable in an updated and balanced position.

Figure 15 shows that two capillaries clamp a shrimp egg and rotate it around their center. In the rotation, the shrimp egg is affected by random forces and fluttered around the stagnation point without leaving the trap area. Figure 16 shows the histogram of displacements of the trapped shrimp egg during the capillary rotation. The standard deviations of the displacements in x and y directions are $\sigma_x = 15.46 \mu\text{m}$ and $\sigma_y = 38.14 \mu\text{m}$, respectively. The standard deviation of the displacements in the y direction is slightly larger than that in the x direction because

FIG. 13. The shrimp egg follows the capillaries moving in the x direction. White arrows denote the moving direction ($d = 120 \mu\text{m}$, $L = 800 \mu\text{m}$, $D = 600 \mu\text{m}$, and $v = 0.0147 \text{ m/s}$).

FIG. 14. Trajectories of the capillaries and the shrimp egg when the shrimp egg follows the capillaries moving in the x direction.

FIG. 15. Rotation of the capillaries that trapped a shrimp egg. White arrows denote the direction of rotation ($d = 130 \mu\text{m}$, $L = 800 \mu\text{m}$, $D = 600 \mu\text{m}$, and $v = 0.0147 \text{ m/s}$).

FIG. 16. Histogram of displacements of the trapped shrimp egg from the trap center. (a) Histogram of displacements in the x direction. (b) Histogram of displacements in the y direction.

of the random forces acting on the particle. In addition to the random forces and the incomplete symmetry of the flow field, the fluttering range of the particle is also affected by the deviation between the center of the two capillaries and the center of the rotation. These factors may also result in the flutters of the stagnation point. However, the shrimp egg usually can be well stabilized in the vicinity of the stagnation point. During the experiment, the particle may deviate from the center of two capillaries. The reason is that the parameters of two capillaries and the jet velocities are difficult to be guaranteed exactly the same, which cause an offset of the stagnation point.

Figures 17 and 18 show the trap and movement of irregular silica particles when there is a radial error Δy and angle error $\Delta\theta$ between two capillaries, respectively. The experiments show

FIG. 17. Manipulation of an irregular silica particle with radial error Δy between two capillaries ($d = 300 \mu\text{m}$, $L = 650 \mu\text{m}$, $D = 600 \mu\text{m}$, and $v = 0.0147 \text{ m/s}$).

FIG. 18. Manipulation of an irregular silica particle with angle error $\Delta\theta$ between two capillaries ($d = 300 \mu\text{m}$, $L = 500 \mu\text{m}$, $D = 600 \mu\text{m}$, and $v = 0.0147 \text{ m/s}$).

that the particle can also be manipulated when there are relative position errors within a certain range between two capillaries.

V. CONCLUSIONS

In this work, the shrimp eggs and silica particles are used as the experimental particles to display the particle manipulation based on opposed jets. A large number of experiments show that particles can be trapped and controlled by constructing an opposed-jet flow field. The control performance of particles will be affected by jet velocity, inner diameter, distance of end face, radial error, and position of the capillaries. Particles with an arbitrary size and shape can be trapped and moved directionally and quantitatively with proper flow field parameters. By the proposed method, trapping and position control of particles can be achieved without any contact. Because there is no limitation of microchannels, the proposed method in this work has more flexibility, better real-time performance, and wider applicability in particle manipulation compared with other existing methods. Therefore, it can be used more conveniently in micro-manipulation such as particle screening, particle directional assembly, and so on.

Our future work will focus on studying the dynamic characteristics of manipulating particles and the way to manipulate particles in three dimensional space and the applications in nanoparticles.

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