NANO-NOZZLE FOR FLUID INJECTION DRIVEN BY CAVITATION BUBBLE-INDUCED JETTING FLOW

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ABSTRACT

In this paper, a micro/nano-nozzle driven by cavitation bubble-induced jetting flow is proposed and demonstrated. A microfluidic chip with a micro-nozzle is designed and fabricated. A cavitation bubble created using a pulsed laser system close to the boundary of the micro-nozzle. Since the effect of the solid boundary, a jetting flow is introduced by the asymmetrical collapse of the bubble and the testing microbeads are projected by the jet through the connection channel between fluid chamber. The mean velocity of the jet is up to 1.2 m/s. This technique is easy to be integrated to other nano/microfluidic system and it has great potential in single cell analysis and high throughput cell sorting.

KEYWORDS: Nano-nozzle, Particle/fluid Injection, Cavitation Bubble, Jetting Flow

INTRODUCTION

Cavitation bubbles often introduce damages to ship propeller blades and hydraulic structures [1]. Recent years, cavitation bubbles have been applied in many biomedical approaches, such as the treatment of kidney stones by shock wave lithotripsy and ultrasound driven drug and gene delivery [2]. The development of the nano/micro-fluidics provides more opportunities of the application of cavitation bubbles, such as micropump [3] and droplets manipulation [4]. For cavitation bubbles, different boundaries will make different effects on the bubble collapse [5, 6]. For a bubble close to a solid rigid boundary, the bubble migrates toward the boundary and a jet will be created in the bubble collapse phase. The jet will piersce the opposing side of the bubble and may strike the boundary.

In this paper, a micro/nano-nozzle driven by cavitation bubble-induced jetting flow is demonstrated. A microfluidic chip with a micro-nozzle is designed and fabricated. A cavitation bubble is created close to the nozzle. Since the solid boundary effect, the bubble collapses asymmetrically and a jetting flow is introduced. The jetting flow can drive the testing microbeads to flow in the micro-nozzle. The developed nano/micro-nozzle fluid injection technique has great potential applied in various nano/microfluidic systems.

WORKING PRINCIPLE

The schematic of the testing microfluidic structure is shown in Fig. 1(a). Two fluid chambers are connected with a microchannel and its width and length are 5 µm and 50 µm, respectively. The bubble is created at location closes to the rigid boundary and its collapse is affected by the rigid boundary [5, 6]. When the bubble collapses and the jet is formed, the testing microbeads will be projected from the fluid chamber into the nano/microchannel with the flow of the jet. Fig. 1(b)

Figure 1: (a) The schematic of the microfluidic chip with nano-nozzle. (b) The mechanism of the formation of a jet (E) induced by a cavitation bubble collapse near a rigid boundary.
presents the mechanism of the collapse of a cavitation bubble near a rigid boundary. When a cavitation bubble is created close to a rigid boundary (A), the collapse of the bubble is affected by the rigid boundary. The bubble does not collapse symmetrically with the presence of the rigid boundary and it collapses asymmetrically (B and C). The asymmetrical collapse of the bubble develops a jet directed towards the rigid boundary and it pierces the opposing side of the bubble to flow into the nozzle structure (C, D, and E). The jet towards the wall can be used to drive fluid or other materials in the fluid (particles, etc) to flow towards the nozzle structure.

EXPERIMENTAL SETUP AND CHIP FABRICATION

The experimental setup for the cavitation bubble creation is shown in Fig. 2. It includes a pulsed laser, optical components, and an inverted microscope to create the bubbles and image the coalescence process. The Nd:YAG laser (Orion, New Wave Research, Fremont, CA) creates a single laser pulse at a wavelength of 532 nm with a duration of approximately 6 ns and 100 µJ energy. The illumination light from the microscope condenser propagates through the dichroic mirror of the microscope (IX-71, Olympus). With the increasing of the laser energy, the radii of cavitation bubbles increase linearly as shown in Fig. 2(b). Images are recorded with a high-speed camera ((SA-1.1, Photron) at 552 000 frames per second with an exposure time 1 µs.

The microfluidic chip is fabricated using standard soft-lithography techniques. A 15-µm thick layer of SU8 master structure is fabricated first. Then, the mixture of poly(dimethylsiloxane) (PDMS, Sylgard 184, Dow Corning) prepolymer and curing agent (10:1) is poured over the master, degassed, baked for 2 hours at 75 ºC and then peeled off. After manually punching inlets and outlets, the PDMS devices are exposed to air plasma for 15 s using a corona treater (BD-25, Electro-Technic Products) to bond it with a PDMS coated glass substrate.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The selected images of the oscillation of the displacement of the microbeads is shown in Figure 3 (a). The 2-µm diameter polymer microspheres (Duke) suspended in the refill ink for inkjet printer (red, Maxtec) with dynamic viscosity 2 mPa·s are pumped into the microfluidic chip as the testing microbeads. The width of the micro-nozzle is 10 µm. A cavitation bubble is created with a laser energy 315 µJ and the distance between the center of the bubble and the PDMS boundary is 72 µm. The maximum of the radius of the bubble is 59 µm. The image with bubble collapse completely is defined as time \( t = 0 \) and the solid boundary is defined as \( y = 0 \). The microbead oscillated during the bubble expansion (- 11.4 µs, - 7.8 µs and - 1.9 µs) and retreat (0 µs) and the distance between the microbead and the solid boundary varies from 4 µm, 11 µm to 8 µm.

Since the effect of the solid boundary, the bubble collapses asymmetrically as shown in the image \( t = -1.9 \) µs in Fig. 3 (a). After the cavitation bubble collapses (start from 0 µs), a jetting flow is formed since the effect of the solid boundary on the collapse of the bubble. Even the jetting flow cannot be observed directly, the projecting of the microbead into the micro nozzle as shown in Fig. 3(b) proves it. The microbead (circled line) is projected to 22 µm, 26 µm and 29 µm at 7.6 µs, 11.4 µs and 19 µs, respectively. In the total 19 µs, the microbead is projected as far as 21 µm. The displacement of the microbead as the function of time is plotted in Figure 3(c). Error bars represent exemplarily the measurement error of ±1 pixel accuracy.
Figure 3: (a) oscillation of the microbead (circled) driven by the expansion and collapse of the cavitation bubble. (b) The high speed images of the displacement of one microbead driven by a cavitation bubble collapse. The scale bar is 10 µm. (c) The displacement vs. time of the microbead.

At 19 µs, the net displacement is up to 21 µm and the mean velocity of the testing microbead is up to 1.2 m/s. The displacement of the microbead is affected by several factors. One factor is the strength of the jet flow, which depends on two parameters: the distance between bubble and solid boundary, and the size of the bubble [5,6]. Decreasing the distance and increasing the size of bubble both can enhance the strength the jet flow. Another factor is the properties of the fluid and microbeads, such as viscosity and density of the fluid and the density of microbeads. Smaller viscosity of the fluid and smaller density of the microbeads both can enhance the displacement of the microbeads.

CONCLUSIONS

In conclusion, a nano/micro-nozzle for fluid injection based on the cavitation bubble asymmetric collapse-induced jetting flow is developed. A microfluidic chip with a micro-nozzle is designed and fabricated. A cavitation bubble created using a pulsed laser system collapses asymmetrically with the effects of rigid boundary. A jet flow is created by the asymmetrical collapse of the bubble and the testing microbeads are projected by the jet through the connection channel between fluid chamber. The mean velocity of the jet is up to 1.2 m/s. This technique is easy to be integrated to other nano/microfluidic system and it has great potential in single cell analysis and high throughput cell sorting.

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