NANO/MICRO JETS IN THIN FILMS FOR BIOMATERIAL MANIPULATION AND CHARACTERIZATION

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ABSTRACT

This paper presents a liquid jet caused by a laser-induced cavitation bubble in thin films (height varies from micro to nanometers). The dynamics is highly depending on the thin film's dimension and viscosity. The penetrating axial jet can be enhanced by increasing the laser energy or decreasing the distance between the laser focus and the targeted gas bubble surface. In the microchannel, strong shear stress ruptures part of the gas bubble and Rayleigh-Plateau instability further shattered it into small bubbles. While in the nanochannel, the nanojets can accelerate femtoliter liquids with thickness of hundreds of nanometers.

KEYWORDS

Nano/micro jets, thin films, cavitation, bubble

INTRODUCTION

Jetting caused by a cavitation bubble is widely used in biomedical applications, such as drug delivery, cell poration and microsurgery [1-3]. The jet formation associated with bubble collapsing near a solid boundary is well studied [4, 5]. An expanding bubble can also cause an outward normal jet at the free surface [6, 7]. The power of cavitation can be released upon asymmetric collapse in the form of liquid jet and already used in biomedical treatment. However, the understanding of jet dynamics and its properties in various environments still remains uncertain. Given the trend of miniaturization, it is a broad interesting subject of the bubble dynamics and liquid jets on increasingly small scales, where the viscosity effect eventually becomes important. In this paper, jetting is studied in the thin films whose height is changed from microscale to nanoscale. The dynamics are highly depending on the thin film's dimension and viscosity.

PHYSICAL MODELS

Figure 1(a) shows the schematic illustration of high speed jets created by focusing a laser pulse in a liquid filled capillary [8]. The laser pulse results in the formation of a vapor bubble accompanied by a pressure wave, which is reflected at the free surface and forms a jet. With the decreasing channel height, the effect of shear stresses from the channel wall plays a more important role on the jet dynamics. Fig. 1(b) shows the jet dynamics in a microchannel. Due to the shear stress, the gas near the wall moves much slower than that in the center of the channel. This results in the rupture of a part of the gas and a small bubble is formed. On the other hand, in nanochannel (see Fig. 1(c)), the significantly stronger shear stress fixes two sides of the bubble near the wall, and only a very thin jet sheet can penetrate into the gas bubble and rupture into two liquid columns.

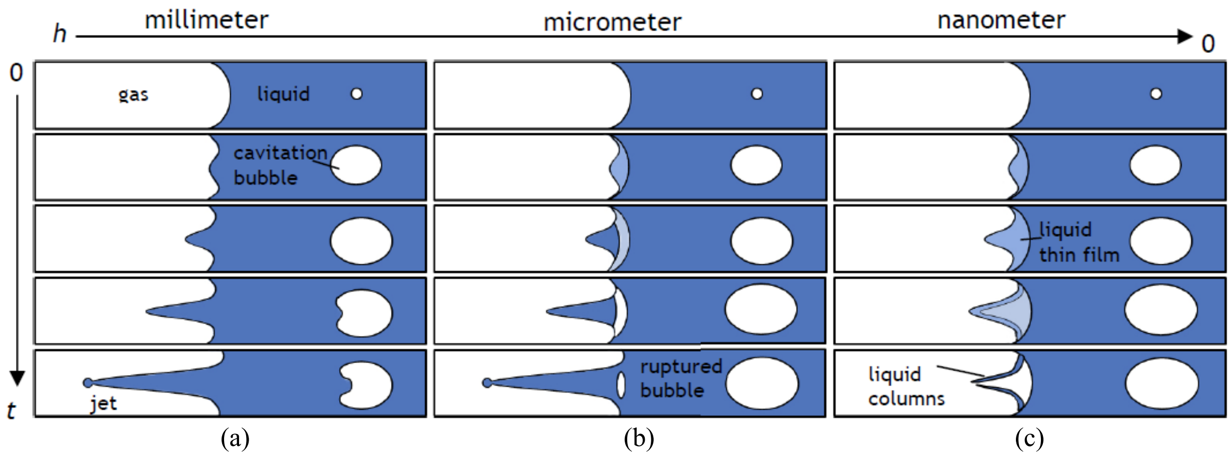

Figure 1: Schematic illustration of the jetting caused by a cavitation bubble in different confined environments: (a) capillary tube, (b) microchannel and (c) nanochannel.

EXPERIMENTAL AND DISCUSSIONS

Standard lithography and wet chemical etching techniques are used to fabricate micro/nanostructure onto a borosilicate glass substrate. The channel width is 100 µm, and the height varies from 5 µm to 550 nm. The optical setup to create a laser-induced cavitation bubble includes a pulsed laser (532 nm, 6 ns) and an inverted microscope. The images are captured by a high-speed camera ((SA-1.1, Photron). The bubble dynamics is recorded at 300 000 frame per second (fps). The exposure time for each frame is 370 ns. By gradually shifting the

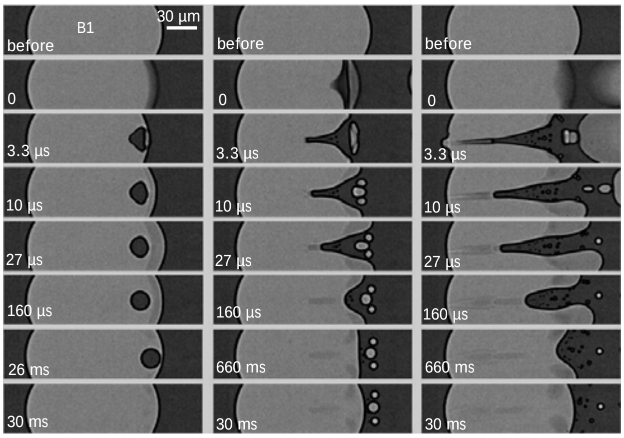

Figure 2: (a) Evolution of gas bubble (B1) after shooting a bubble (B2) on the left with a distance of (a) 142, (b)110 and (c) 78 µm in the microchannel.

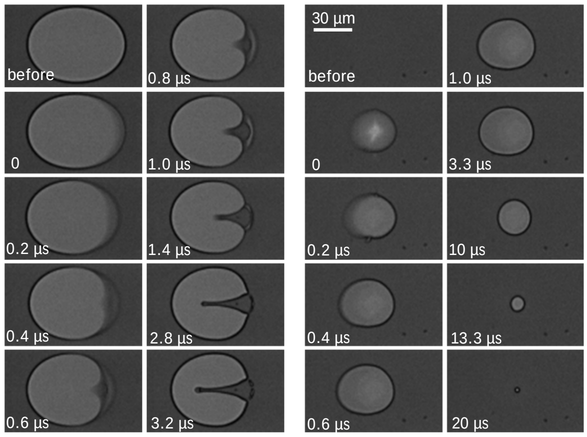

Figure 3: Snapshot of (a) jet evolution and (b) bubble growth after laser shooting in the microchannel.

triggering time of the camera, the dynamical evolutions of the bubble are studied in detail.

Figure 2 shows the temporal evolution of the gas bubble (B1) after shooting a bubble (B2) on the left with different distances in a 5-µm channel. The impact strength of the jetting is increased by decreasing the distance between the two bubbles, as well as increasing the energy (not shown here). The former increases the initial impact, which is affected by the fast attenuation of shock wave. The latter increases the pressure and the speed of the cavitation bubble-induced flow front, and the total duration of bubble expansion [8]. Fig. 3 shows more detailed evolution of the bubble and the jet. The growth time of the jet is much shorter than that in a capillary tube (i.e. 300 µs). The jet reaches its maximum length in the microchannel in approximately 3 µs. The cavitation bubble ends its expansion in 1 µs, and then collapses into a small remaining gas bubble within 20 µs. It is interesting to observe that some small bubbles are ruptured during the jetting, which has not been reported in other bubble-bubble interaction or jetting studies. In a relatively shallow channel, the viscosity effect becomes dominant and the high shear stress hinders the movement of gas near the channel walls. It results in the rapture of the front part of the gas bubble. As shown in Fig. 3, the raptured part shrunk into a cylindrical thread within 2 µs. The Rayleigh-Plateau instability causes the breakup of a long fluid cylinder into small bubbles [9].

Figure 4 shows the evolution of the jet length, which is corresponding to Fig. 3(a). The jet tip travels from the gas bubble surface into the center with a speed of 20 m/s. After reaching its maximum length, the liquid are slowly pushed back. Fig. 5 shows the jet velocity as a function of the laser energy with different distances between the laser focus and the bubble surface. As noted before, the experimental results suggest that the velocity is proportional to the pressure of the shock wave. The slope of the data is larger for shorter distance. Thus, for the same laser energy, the jet speed increases with decreasing inter-bubble distance. Here, the jet velocity reaches 65 m/s.

Figure 6 shows that the jetting in the nanochannel is much milder due to the viscous effects. In Fig. 6(a), a laser spot generates a nanobubble (B2) 9 µm away from a static gas bubble (B1). Instead of a surface concave towards the center of the bubble and hundreds microseconds jetting acceleration process as in the microchannels, a fast change of the gas bubble is observed in the frame at $t = 0$. Some dark regions forming a triangle shape near the proximal side of bubble B1 are observed. This indicates a propagating thin liquid jet, which is parallel to the glass channel

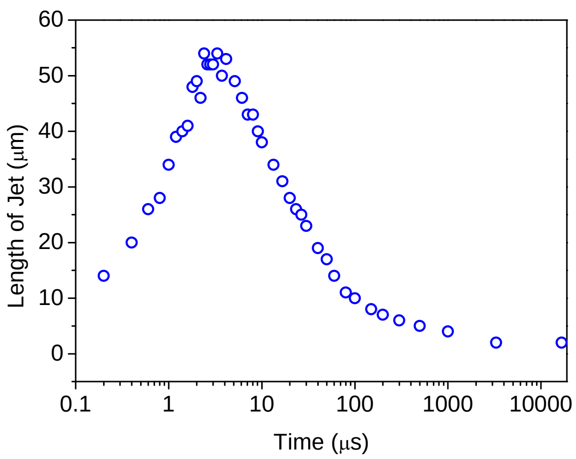

Figure 4: (a) Evolution of jet length in the microchannel.

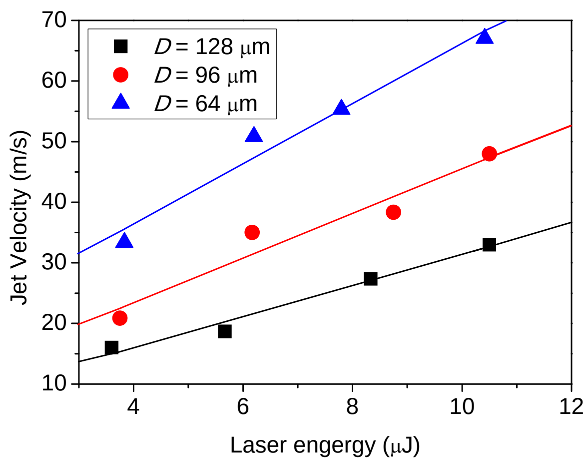

Figure 5: Jet velocity as a function of the laser energy with different distances between the laser focus and bubble surface.

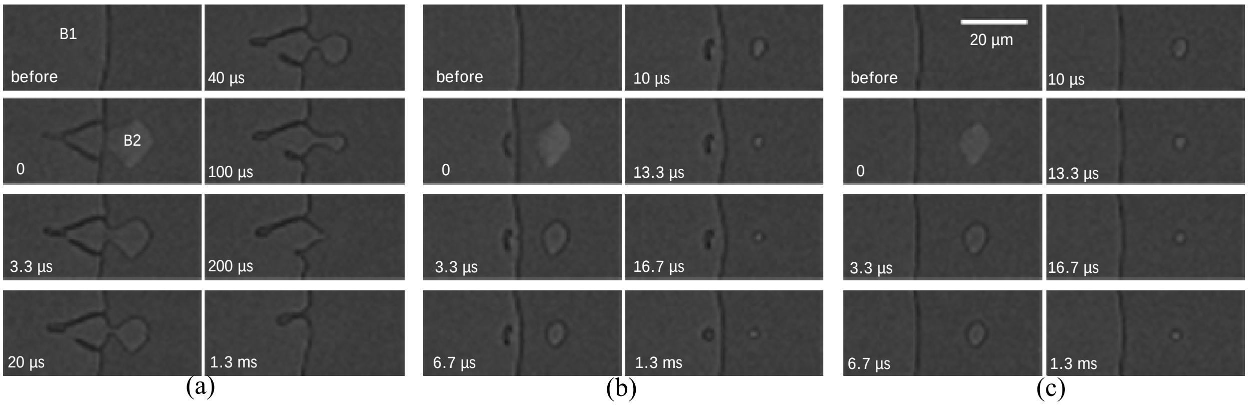

Figure 6: Evolution of nanojet and nanobubble with different distances between laser focus and bubble surface: (a) 9 µm, (b) 12µm and (c) 19 µm.

walls. The shock induced fast jetting creates a thin triangular liquid jet sheet. Capillary forces at the edge cause the drainage of the film, which eventually ruptures and leaves two liquid columns on its edges. This process happens in 370 ns, and is not resolved due to the limited framing speed. It indicates a fast jet at velocity of more than 30 m/s. A homogeneous jet thickness of 200 ± 30 nm is estimated. After the first frame, the dynamics becomes slow. Surface tension further minimizes the surface area, thus the liquid cylinder connected with the outside liquid slowly retracts. The power of the jetting attenuates faster with increasing distance. When the distance is 12 µm (Fig. 6(b)), the nanojet penetrates only into the bubble by 5 µm and contracts into a droplet (6 femtoliter). No obvious effect can be observed when the distance is increased to 19 µm as shown in Fig. 6(c). Although the nanobubble caused jetting is much milder due to the viscous effect, the nanobubbles offer more precise control over the jetting location with high speed velocity.

CONCLUSIONS

In conclusion, the cavitation-induced jetting in thin films with nano/micrometer height is studied. Although surface forces dominate in the confined regions, rapid fluid mechanics (jet velocity of 10~65 m/s) are still observed. The jet velocity increases with increasing laser energy and decreasing inter-bubble distance. The nanojets can be as thin as 1/3 of the channel height. The demonstration of jetting on the micro/nanoscale offers possibilities for precision fluid handling, nanodroplet generation as well as biomaterial characterization.

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