STUDY OF NANO/MICRO JETS GENERATED BY LASER-INDUCED BUBBLES IN THIN FILMS
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ABSTRACT
The paper presents a liquid jet in thin films (height varies from micro to nanometers) and the study of its dynamics under the effects of the film’s dimension and viscosity. Furthermore, the penetrating jet velocity is investigated in terms of the laser energy and 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. On the other hand, in the nanochannel, the nanojets accelerate liquids with thickness of hundreds of nanometers.

INTRODUCTION
Liquid jets generated by cavitation bubbles are extensively investigated as a key role in the damaging mechanism behind erosion of hydraulic machinery for decades [1, 2]. Recently, with the prosperous ultrasonic and laser technologies, the concentrated energy of the liquid jets has been used in biomedical engineering, such as mixing in enzyme-catalyzed reaction [3], membrane disruption [4] and cell lysis [5].

The asymmetric collapse of a vapor bubble near a rigid boundary is always companied with a high-speed liquid jet directed towards the boundary [6, 7]. On the contrary, the jet directed away from a free surface [8, 9]. It is been demonstrated that the movement of the liquid jets depends on the physical properties of the boundary [8-10]. Because of the similarity to human tissue and cells, some studies focus on the bubble growth and collapse near an elastic material, e.g. polyacrylamide gel [11] and gelatin surface [12]. These research results can be used to simulate the jets penetrating the biomaterials. The jet generated by bubble-bubble interaction also attracts attentions due to its rich phenomena and its similar dynamics as jet close to an elastic boundary. The mutual interaction between two laser induced bubbles associated with jetting, fragmentation and entanglement were addressed in a thin liquid layer [13]. The coupled oscillation of two bubbles could lead to directional microjets which were used for single-cell membrane poration [14]. However, the thoroughly understanding of the dynamics and well control of all parameters still remains a significant challenge, especially on confined small scale.

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 MODEL
Optical breakdown leads to plasma formation by the absorption of a focused laser pulse in the liquid. Plasma formation is accompanied with the generation of shock wave and cavitation bubble expansion. To characterize the shock wave propagation, we investigated the pressure amplitude at the shock front. It is can be find that the pressure amplitude decreases inversely with the distance and proportional to the laser energy.

The pressure wave travels through the liquid and reflects on the surface of the gas bubble. The reflections of the pressure wave on the gas/liquid interface result in a pressure gradient ∆P between the laser-induced bubble and the surface of the gas bubble. After the liquid is set into motion, the sudden change in the velocity is transmitted to all fluid particles. Each fluid particle acquires a velocity U_p before reaching the gas bubble surface. As shown in Fig. 1(a), the jet focusing can be produced by the concave surface between liquid and gas, which converges the liquid towards the center of the curvature.

Figure 1: Schematic illumination of (a) the jet formation and (b) experimental setup.
In the case of jetting caused by the reflection of a shock wave from the gas/liquid interface, the initial velocity of the liquid jet $U_{jo}$ is twice the particle velocity $U_p$. The pressure wave strength $\Delta P$ can be estimated as

$$\Delta P = \frac{1}{2} \rho c U_{jo}$$

where $c$ is the speed of sound in the liquid, $\rho$ is the density of the liquid.

With the decreasing channel height, the effect of shear stresses from the channel wall plays a more important role on 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 a nanochannel, 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. Besides, the jet strength is weakening with the decreasing channel height.

**EXPERIMENTAL RESULTS**

Standard lithography and wet chemical etching techniques were used for fabricating the micro/nanostructure onto a 25 × 45-mm borosilicate glass substrate with thickness of 0.7 mm. The channel height varies from 5 µm to 550 nm. Inlets and outlets are drilled at the ends of channels for injecting liquids. Another piece of borosilicate glass was thermally bonded with the etched substrates. The chip was fixed in a home-made chip holder and connected to syringes in order to inject a light-absorbing liquid into the channels.

As shown in Fig. 1(b), the optical setup to create a laser-induced cavitation bubble includes a pulsed laser, several optical components, and an inverted microscope. The bubbles were generated by the Nd:YAG laser (Orion, New Wave Research, Fremont, CA) with a single laser pulse at the wavelength of 532 nm and a duration of approximately 6 ns. The laser was focused through a microscope objective (20×, NA = 0.50) into the micro/nanochannel to vaporize the liquid. The images were captured by a high-speed camera ((SA-1.1, Photron). The bubble dynamics was recorded at 300000-500000 frame per second (fps). The exposure time for each frame is 370 ns. By gradually shifting the triggering time of the camera, the dynamical evolutions of the bubble are studied in detail.

Figure 2 shows the temporal evolution of an initially stationary gas bubble (B1) perturbed by a laser-induced bubble (B2) in a 3.7-µm channel. A pressure wave is created by vaporizing a small amount of liquid with a laser pulse. The strong pressure gradient causes the gas bubble deformation. The flow focusing leads to the formation of a liquid axial jet. At the same time, part of the gas bubble is split from the main body, and forms small bubbles in front of the jet. In this experiment, the interaction between the two bubbles happens in a short time. As shown in Fig. 3, the jet has already reached the maximum length at $t = 3 \mu s$. The growth time of the microjet is much shorter than that in a capillary tube (i.e. 30 µs) [15]. Surface tension controlled the jet retracting process. The remaining region inside the reexpansion B1 is gray. It suggests that there is a thin liquid film between B1 and the main body. Figure 4 shows the initial microjet velocity as a function of the laser energy with different distances between the laser focus and gas bubble surface.
film left on the glass surface inside B1 when the rebounding gas pushes out most of the liquid. The cavitation bubble ends its expansion in 1.5 µs, and then collapses into a small remaining gas bubble within 20 µs. However, we didn’t observe vigorous compression and reexpansion of B2 during the expansion period of B1. That means the pressure wave is damped very fast in the microchannel.

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. 2, the ruptured part shrunk into a cylindrical thread within 2 µs. The Rayleigh-Plateau instability causes the breakup of a long fluid cylinder into small bubbles [16].

Figure 3 shows the evolution of the jet velocity in the microchannel. The jet tip travels from the gas bubble surface into the center with an initial velocity of 35 m/s. After reaching its maximum length, the liquid slowly retracts from the gas bubble. The retracting jet velocity is much slower. While the jet penetrating process is dominant by inertia, the retracting process is controlled by the surface tension and viscosity. Fig. 4 shows the initial jet velocity as a function of the laser energy with different distances between the laser focus and the bubble surface. It is demonstrated that the jet velocity is increased by decreasing the distance between the two bubbles, as well as increasing the laser energy. As noted before, the experimental results suggest that the velocity is proportional to the pressure of the shock wave. In Fig. 4, the jet velocity reaches 65 m/s. Calculated from Eqn. (1), with $\rho = 1 \times 10^3$ kg/m$^3$, $c = 1497$ m/s, the pressure strength can be estimated as 11 MPa to 49 MPa when the initial jet velocity is changed from 15 to 65 m/s.

Figure 5 shows that the jetting in the nanochannel (h = 550 nm) is much milder due to the viscous effects. The jet accelerating process is very short. As shown in the frame $t = 0$, a thin layer of liquid film penetrates into the gas bubble within 370 ns. Thereafter, liquid columns formed from the breakup of the triangular liquid jet. The dynamics after the first frame is slow. The gas/liquid interface moves outwards due to the collapse of the nanobubble, while surface tension further minimizes the surface area. The liquid column gradually contracts into a droplet (18 femtoliter). The thickness of the thin liquid layer is estimated as $160 \pm 30$ nm from conservation of mass. It offers possibilities on precision fluid handling, nanodroplet generation.

The nanojet velocity is also sensitive to the laser energy and the distance. Fig. 6 shows the nanojet velocity as a function of the distances between the laser focus and bubble surface when the laser energy is 6 µJ. The power of the jetting attenuates fast with increasing distance. The jet velocity decreases from 32 m/s to 3 m/s while the distance is only reduced 6 µm. The laser power has a much greater effect when the distance is shorter as shown in Fig. 7. When the laser energy changes from 7.5 µJ to 11.5 µJ, the jet velocity increases by 140% for $D = 9$ µm, while only by...
40% for $D = 13 \, \mu m$. No obvious effect can be observed when the distance is increased to $20 \, \mu m$.

**CONCLUSIONS**

In conclusion, the laser-induced bubble causing nano/microjets in thin films is studied. The dependency of the jet velocity on the laser energy and inter-bubble distance is demonstrated. Surface forces play important roles in the confined regions. While part of the gas bubble is split by the shear stress with the microjet, the nanojets can only penetrate into the gas bubble as thin as 1/3 of the channel height. This study provides insights in the fundamental research on liquid jets within confined environments and potential applications in biomedical fields.

**REFERENCES**


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