

Experimental Studies of Laser-Induced Hydrodynamics and Bubbles by PIV and PDA

by

X.S. Wang⁽¹⁾, Z.L. Xue⁽²⁾ and H.-H. Qiu⁽³⁾

Department of Mechanical Engineering
The HONG KONG University of Science & Technology

Clear Water Bay, Kowloon,

Hong Kong SAR, China

⁽¹⁾E-Mail: xswang@ust.hk

⁽²⁾E-Mail: lanzy@ust.hk

⁽³⁾E-Mail: meqiu@ust.hk

ABSTRACT

Research on laser-liquid interaction and its induced fluid flows, as well as microbubbles, is important in many applications, such as laser ophthalmic microsurgery, manufacturing and repairing of micro-electronic-mechanical devices, laser deposition of thin liquid film to a specific location in micro system, etc. This work was focused on the interaction mechanisms of a laser pulse with distilled/degassed water as well as the characteristics of the microbubbles. Microbubbles and optohydrodynamic flows induced by a Nd:YAG pulse laser (New Wave Research) were studied. A recently improved PIV and PDA system were used to analyze the bubble dynamics and fluid flow quantitatively. Two CCD cameras were used to capture the images of microbubbles and visualize the laser induced Optohydrodynamic flows. The experimental results show that a bright fluid beam (density flow) with duration less than $127\mu\text{s}$ is produced by a focused laser pulse while an explosive cavitation just around the focus point is also occurred. Immediately following the fluid beam and the explosive cavitation, two new fluid regions which may be formed with the superheated dense fluid were found. One of them is just under the fluid beam due to the optical pressure while the other one is around the explosion area due to the force caused by the explosive cavitation. As shown in Figure 1, Single and multi microbubbles were generated immediately after the cavitation explosion when the nucleation conditions were satisfied. In addition, the characteristics, such as bubble velocities and diameters, were measured by a recently improved phase-Doppler anemometry (PDA). These results will help to have a better understanding of the mechanisms of laser-induced optohydrodynamic flows and bubbles related phenomena, which is crucial to numerical modeling.

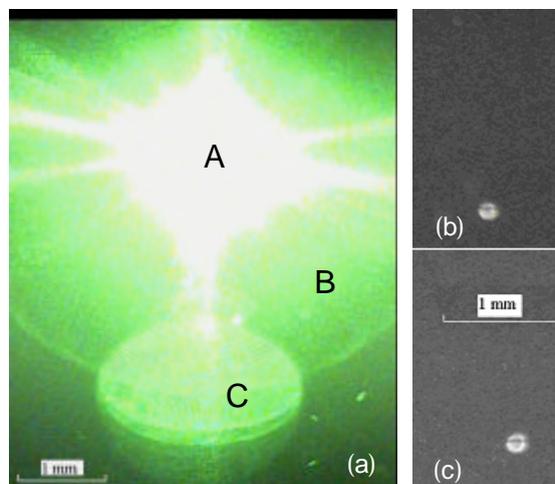


Figure 1 Micro bubble generation-induced by a 30 mJ laser pulse; (a) first frame after the pulse shot ($t=0\text{ms}$),

(b) $t=40\text{ms}$, (c) $t=120\text{ms}$

1. INTRODUCTION

Research on laser-induced microbubbles and optohydrodynamic flows is important in many applications, such as laser ophthalmic microsurgery, manufacturing and repairing of micro-electronic-mechanical devices, laser deposition of thin liquid film to a specific location in micro system, and diffusion of a pollutant liquid, etc. (Longtin and Tien 1997; Shozude et al. 1999; Baghdassarian and Chu, et al., 2001; Casner and Delville, 2003; Tomohiro, et al., 2004). Furthermore, some recently developed micro actuators utilizing pulse heater as the driving force. To optimize those devices, a better understanding of ultra fast pulse heating is crucial. Akhatov et al. (2001) studied collapse and rebound of a laser-induced cavitation bubble preliminary. However, there are several major challenges to the understanding of transport phenomena involving ultra fast pulse heating and transient nucleation, namely, the small time and space scales; the coupling of interfacial heat transfer, fluid dynamics, phase change, thermal capillary effect and mass transfer; and the fluctuation nucleation at/near the interface with homogeneous and heterogeneous boiling. For instance, when the heating surface is reduced to micro size and the heating rate is reaching to 10^{12} K/s or higher, it is important to know how large superheat will be generated locally and whether the boiling regime will remain unchanged. It is also important to understand what the mechanisms of ebullition at the micro-scale size and near the interface are. The effective cooling of chips for GHz pulse devices becomes the dominate parameter in the chip design. It is well known that when a high intensity laser beam is illuminating a mini/micro channel, both the liquid and the substrate will be heated. However, the heating mechanisms are quite different. The former is directly heating through the relaxation of absorbed photons, ionized and dissociated molecules, while the later is through heat conduction and nucleate boiling from the substrate. Due to the complexities of non-linear absorption effect, the mixing of homogeneous and heterogeneous nucleation boiling, and thermal capillary effect in a micro channel, the relationship between the evaporation rate, laser intensity, liquid film thickness and properties, and substrate temperature is not well understood. For example, for laser cleaning it is important to vaporize a moisture droplet in a micro system without burning the channel substrate. Furthermore, when a droplet in a micro channel is heated by a laser pulse, the heating induced evaporation and internal flow may change the force balance and cause thermal capillary effects. This will have a great effect on the further evaporation and the motion, as well as break up, of the droplet. Therefore, it is important that the interaction between the thermal energy, fluid flow and the nucleation boiling in the liquid and near the heating substrate can be clarified.

Many techniques have been used or developed to investigate the hydrodynamics and micro bubbles behaviors. For instance, Ohl et al. (1998) recorded the acoustic transients at bubble generation and at bubble collapse with a PVDF (Polyvinylidene fluoride) hydrophone as well as an intensified CCD system (PicoStar, LaVision) with a gated multichannel plate and a photocathode were used to suppress the intense continuum light emission of the dielectric breakdown process. Akhatov et al. (2001) also recorded the acoustic transients at laser breakdown and bubble collapse with a PVDF hydrophone while the shock wave was measured with a fiber optic probe hydrophone and the bubble dynamics was filmed with a high speed camera (227 000 frames per second). Baghdassarian et al. (2001) analyzed the luminescence spectrum of the laser-induced bubbles with a photomultiplier monitored the bubble radius versus time by a shadowgraph technique. However, due to the complexities of non-linear absorption effect, the mixing of homogeneous and heterogeneous nucleation boiling, the relationship between the evaporation rate, bubble size, liquid flow velocity, laser intensity, and repetition frequency has not been well understood, especially, the mechanisms of the generation of micro bubbles with a pulsed laser are still not clear.

Therefore, ultra fast heating, microbubble generation, and micro bubbly flows in water have been investigated experimentally in this study utilizing recently improved PIV and PDA system, respectively. This study is mainly focused on the interaction mechanisms of the laser pulse with distilled water as well as the characteristics of the microbubbles. The microbubbles and optohydrodynamic flows were induced by a New Wave 200 mJ Nd:YAG pulse laser, where two CCD cameras were used to capture the images of the induced microbubbles and visualize the laser induced Optohydrodynamic flows. These images provide some new information on generation of microbubbles and optohydrodynamic flows. For instance, a bright fluid beam with duration less than $127 \mu\text{s}$ is caused by a focused laser pulse while a cavitation explosion just around the focus point is also occurred, although the later one has a little longer duration than the former one. Followed the fluid beam and the cavitation explosion, two new fluid regions are formed with the superheated dense fluid, one is just near the end of the fluid beam and with ellipse like shape due to the optical pressure while the other one is around the cavitation explosion area due to the force caused by the cavitation explosion. The single or multi microbubbles are generated just after the cavitation explosion when the nucleation conditions are satisfied for the expanded superheated fluid, and the bubble behavior show that the moving direction of the bubble is also influenced by the explosive cavitation.

2. EXPERIMENTAL SETUP

As shown in Figure 2, a LaVision PIV system was used to investigate the laser-induced optohydrodynamic flows and microbubbles, where a Qswitched Nd:YAG laser (Tempest and Gemini PIV 200) was used to deliver pulse at wavelength of 532nm with 5 ns duration. The maximum pulse energy is about 100 mJ at 532 nm as well as 200 mJ at 1064 nm. The repetition rate of the laser can be adjusted to the experimental needs between 1 to 15 Hz. In order to increase the focused pulse energy, a beam expander was used to expand the 5 mm laser light to about 20 mm, and then the expanded laser is focused into a cuvette (about 6 mm under the water surface) that is filled with distilled water with a 50 mm focus lens.

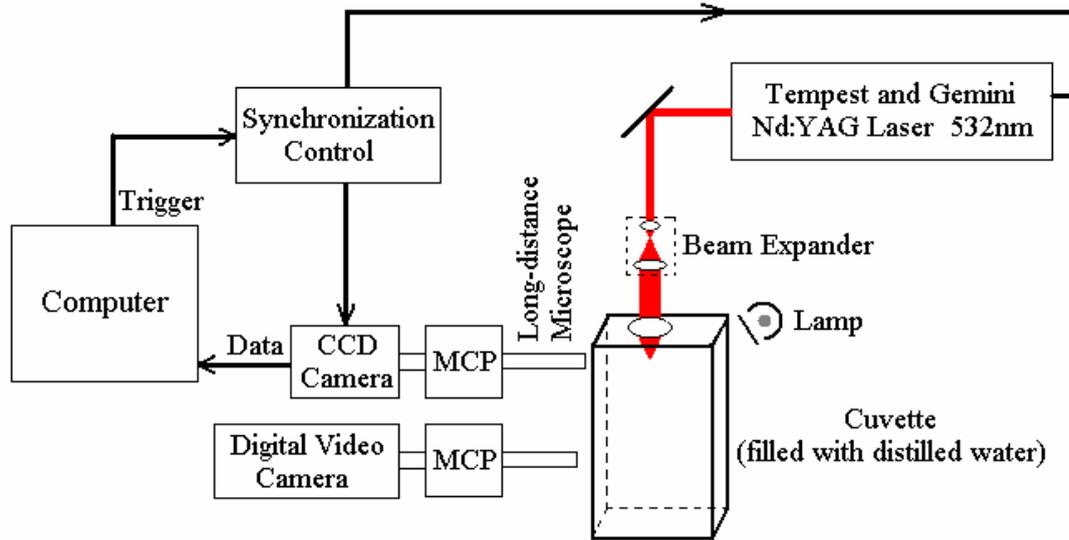


Figure 2 Schematic diagram of the experimental setup

A MEGAPLUS camera (ES 1.0) with a 45x long-distance micro lens was used to visualize the laser-induced optohydrodynamic flows. This camera has a maximum repetition rate of 30 Hz, 1008(H) × 1008(V) light sensitive elements (pixels) and possible exposure time of 127 μ s. Both the camera and the laser can be properly triggered via DaVis PIV Software. In addition, a JVC TK-C1381EG video camera coupled with a 35x micro lens together with a SONY DCR-TRV20E digital video camera (1,070,000 pixels) was used to image the microbubbles. A UNOMAT LX901GZ lamp was used to illuminate optohydrodynamic flows and microbubbles. The bubble size and velocity were measured by PDA system, as well as the velocity field of the induced flow was reconstructed with DaVis PIV system. The water temperature was kept fairly constant at the room temperature of 22°C during the experiments.

3. EXPERIMENTAL RESULTS AND DISCUSSION

It is well known that when an intense laser pulse is focused into a liquid, an optical breakdown may occur, which leads to plasma formation and produce cavitation bubbles, where the bubble is produced by the plasma expanding (Vogel et al., 1996). However, the problems, such as what is the fluid behavior after the optical breakdown and when the cavitation bubbles are generated, are still not clear. Therefore, a LaVision PIV system was adjusted to visualize the fluid flow when a pulsed laser focused into the liquid, where a bright fluid beam was clearly seen just after the pulse shot. As shown in Figure 3 (with *single frame/single pulse* mode of the PIV camera), a bright beam is formed just along the pulse light path with length about 1 to 2 mm while a area with expanding fluid is formed just around the position of the pulse focus. And it is obviously shown that the higher the pulse energy is, the longer the fluid beam as well as the larger the area of the expanding fluid will be. To our understanding, the bright fluid beam may be mainly caused by ultra fast heating of the water which within a bulk confined by the waist of a Gauss light. In order to observe their onset and duration of the fluid beam and the cavitation explosion caused expanding fluid area, the LaVision PIV system was then adjusted to work with

double frame/single pulse mode, and the results show that before the second camera starts to capture images, i.e., at least about 127 μ s after the pulse shot, the bright fluid beam is vanished but the cavitation explosion caused expanding fluid area is still alive (as shown in Figure 4). This phenomenon can be explained as the duration of the former one is mainly related to the pulse shot which has the duration shorter as 3 to 5 ns, while the later one is caused not only by the optical breakdown (e.g., the explosive cavitation) but the processes of the superheated fluid expanding and recombination, etc.

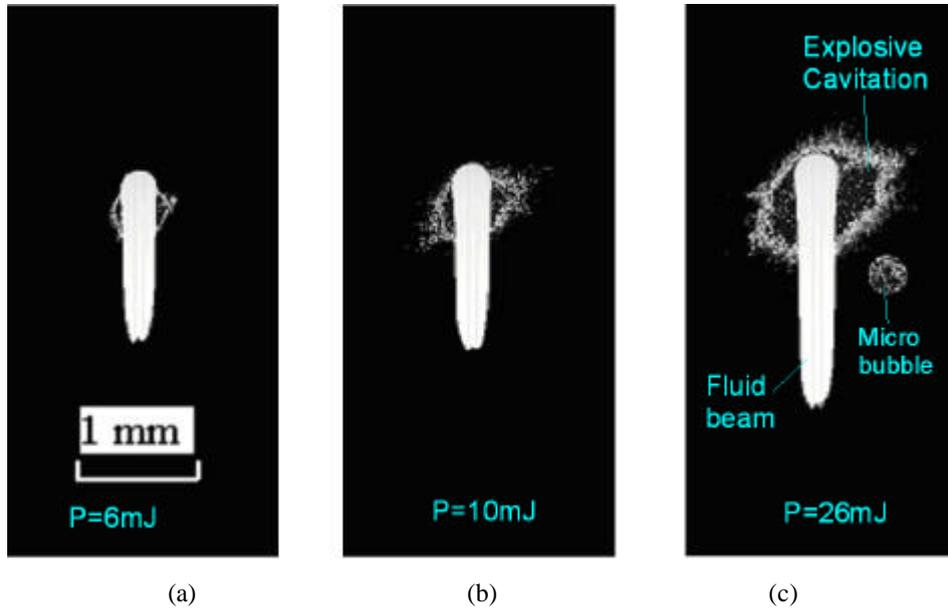
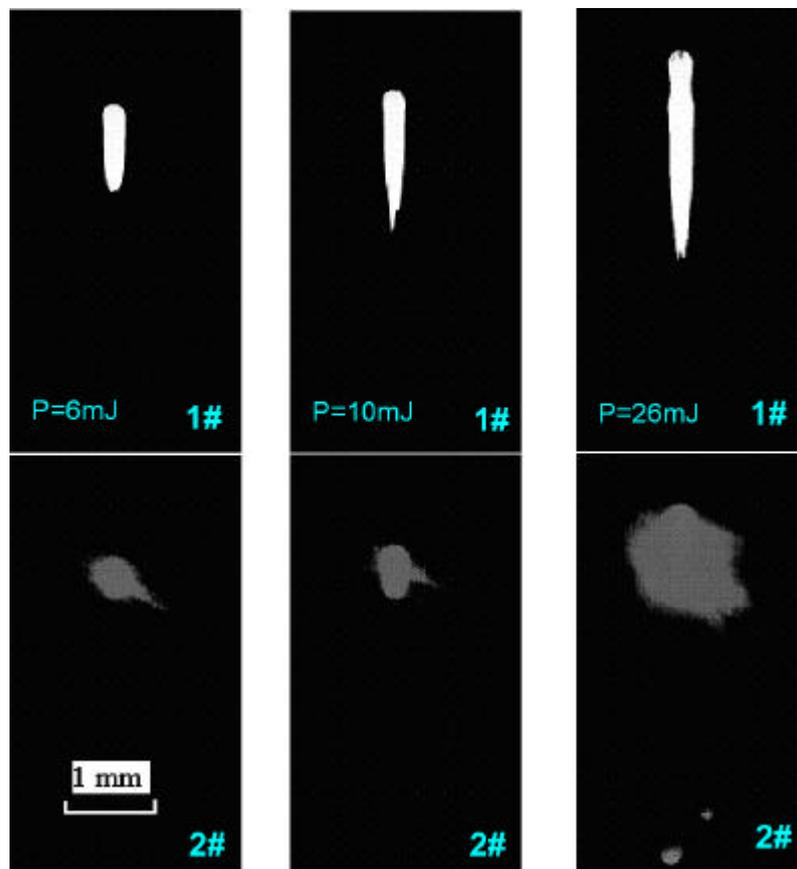


Figure 3 Patterns of laser-induced optohydrodynamic flows with different pulse energies (the exposure time is 127 μ s)



(a) (b) (c)

Figure 4 Images of optohydrodynamic flows captured with double frame/single pulse mode (the exposure time of the first frame (1#) is 127 μ s)

In addition, Figure 3 (c) and Figure 4 (c) show when the pulse energy, P, is increased to a higher value (e.g., 26 mJ in this study), single-/multi-microbubble(s) will be generated although the bright fluid beam and the cavitation explosion occurred during almost the cases. This illuminates that both of the fluid beam and the expanded fluid are not the cause of the bubble generation, and the bubble may be produced at the same time at the onset of these two flows when the saturation conditions are satisfied. In other words, all of the bright fluid beam, the expanded fluid and the microbubbles are three different newly generated flows due to the optical breakdown, where the first one has the shortest duration (less than 127 μ s) while the last one has the longest life (can exceed several seconds) to survive. Figure 5 (a) and (b) give the pattern of these three fluid flows generated with different pulse energies, which are captured with the JVC TK-C1381EG video camera coupled with a 35x micro lens with the rate of 25 frames per second.

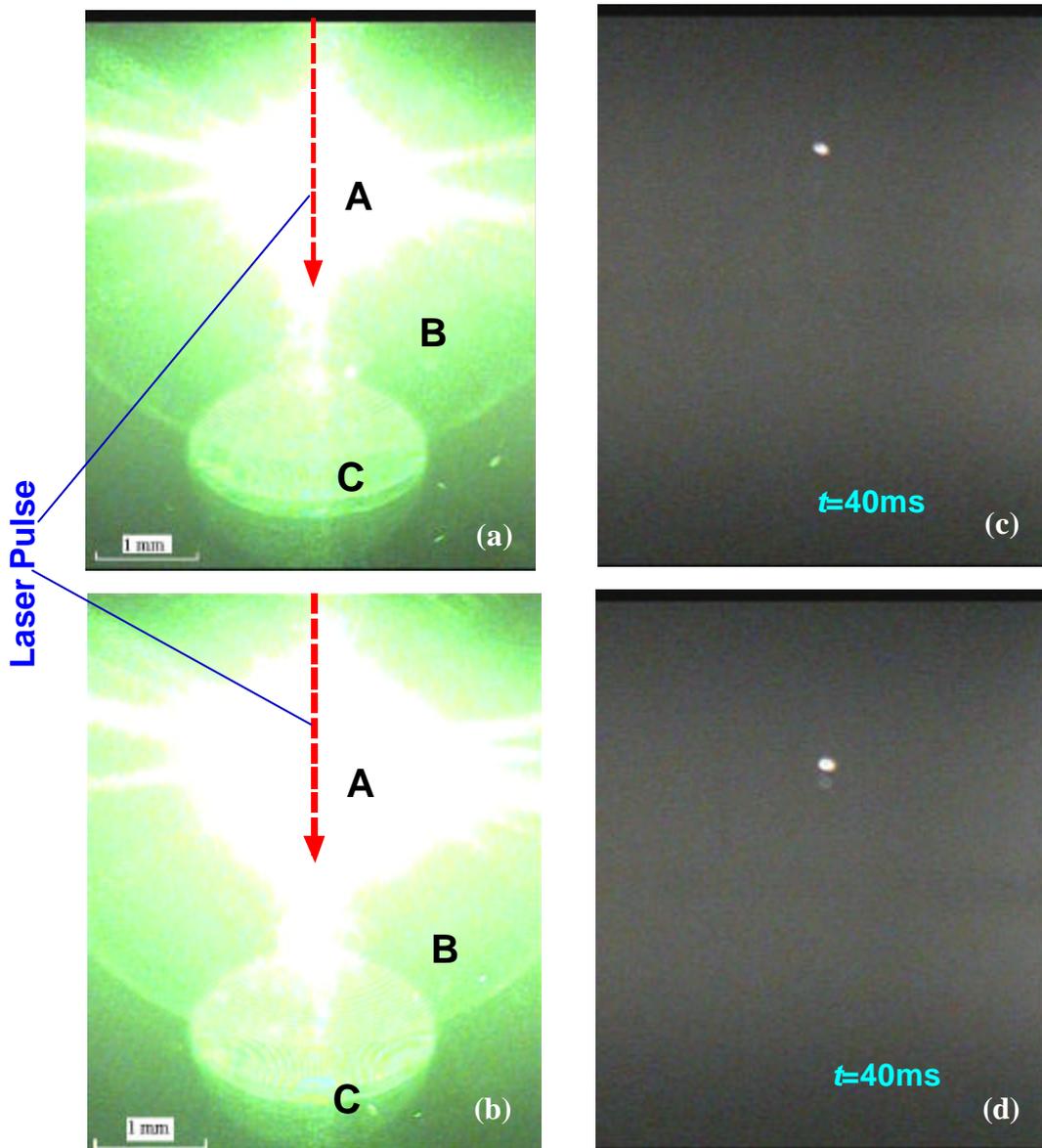
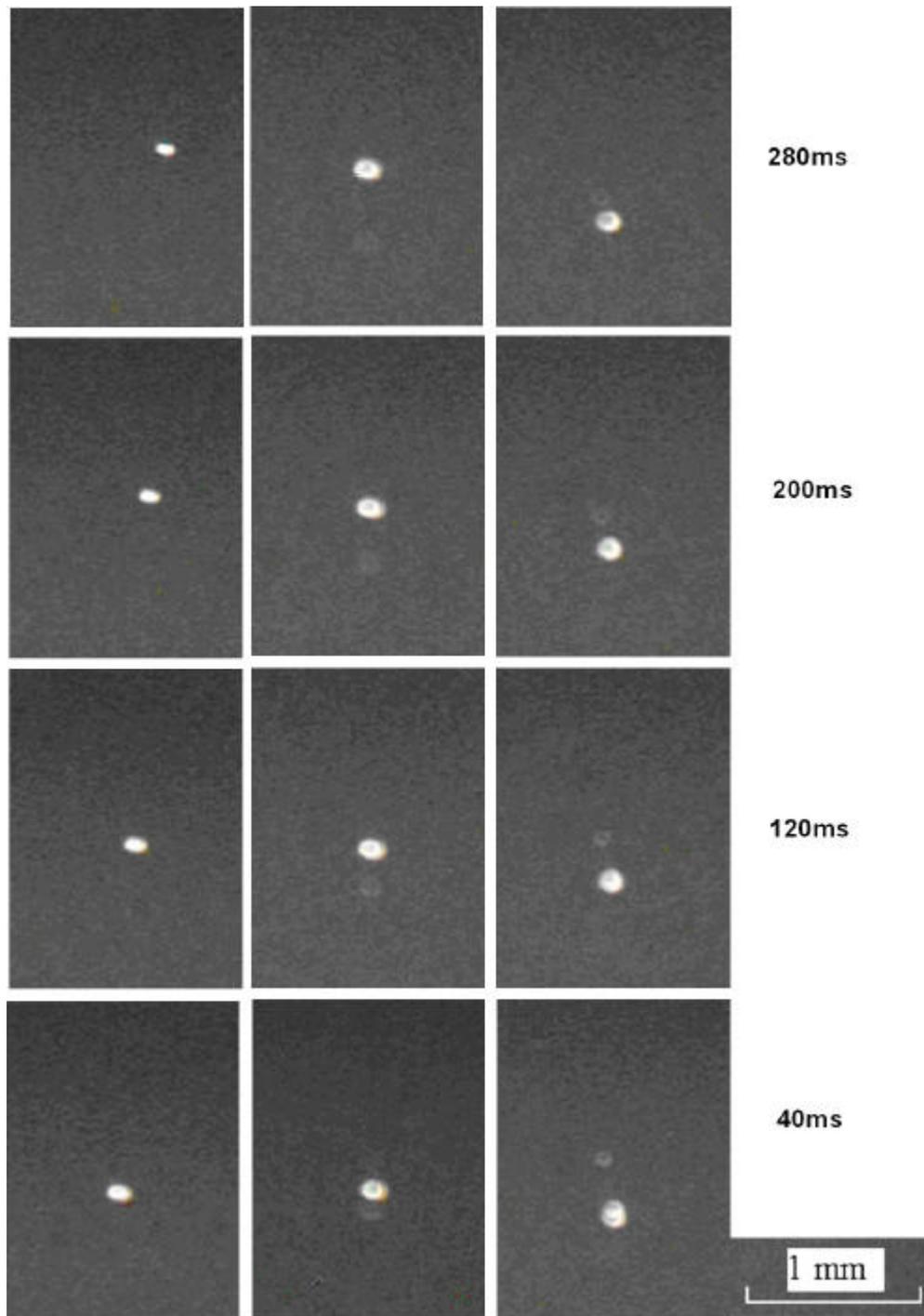


Figure 5 Patterns of laser-induced optohydrodynamic flows and micro bubbles; (a) and (b): first frame after the 30 and 45 mJ pulse shots at $t=0$ ms, respectively; (c) and (d) the frames at $t=40$ ms

As signed in these images, “A” is just represents the cavitation explosion zone due to the optical breakdown where the bright fluid beam is not clearly seen, this may be caused by its shorter duration (less than 127 μ s) and the longer imaging

time (i.e., 40 ms). “B” is a newly formed zone contains the superheated dense fluids and expanded due to the cavitation explosion. And “C” is also a newly formed elliptic like zone contains the superheated fluids and compressed due to the optical pressure. Single bubble was produced within the range of the expanding fluid flow, and moved upward or radically away from the light path. Its moving direction maybe depends not only upon the balance between optical pressure, buoyancy and gravity, but the forces caused by the cavitation explosion. As shown in Figure 5 (a) and (b), the cavitation explosion is not homogeneous in expanding, the strong force is formed at the both sides of the light path (within the viewing plane). Therefore, if the bubble is produced just at the center position of the cavitation explosion, it will move upward due to the buoyancy or downward due to the optical pressure and gravity. And while the bubble produced at the left or right side of the light path, it then will move left or right away from the path. Sometime, the bubble also can move downward at first, and then upward. All of these dynamic behaviors can be seen in Figure 6.



(a) (b) (c)

Figure 6 Dynamic behavior of the laser induced micro bubbles (a), $P=30$ mJ (b): $P=40$ mJ (c) $P=45$ mJ

Microbubbles and optohydrodynamic flows induced by multi-laser pulse exposures were measured by using the recently developed phase-Doppler anemometry as described by Qiu and Hsu (2003) as shown in Figure 7.

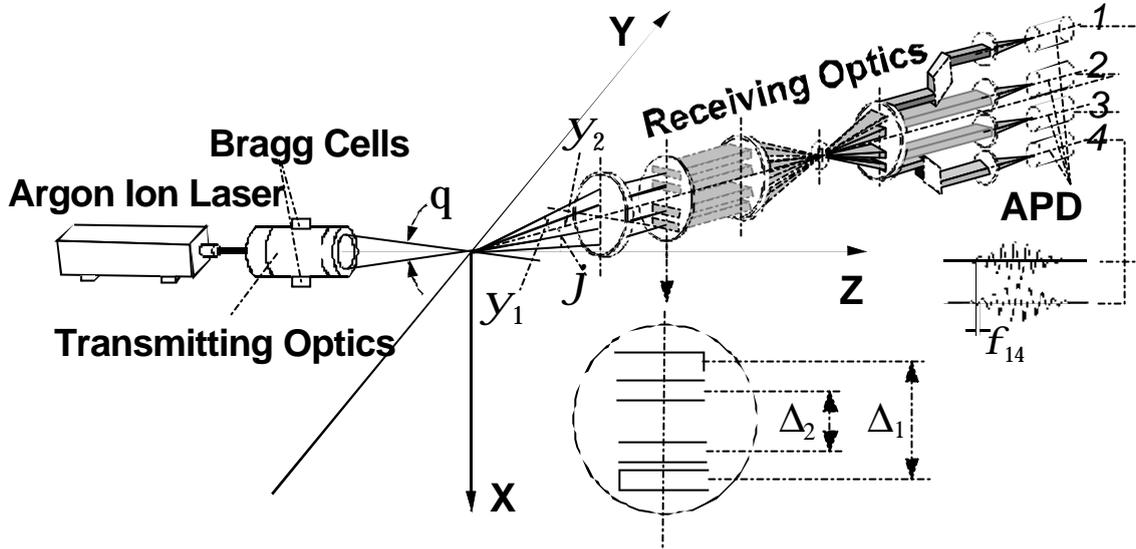


Figure 7 Optical layout of four-detector phase Doppler anemometry: APD, avalanche photodiode

According to previous analysis by Qiu and Hsu (2003), the optimized receiving angle j can be determined from:

$$j = \begin{cases} \arccos \left[\left(\frac{1}{4m^2} (1 + 4m^2 + \sqrt{1 + 8m^2}) - 1 \right) \right] & \text{for } m > 1 \\ \arccos(2m^2 - 1) & \text{for } m < 1 \end{cases} \quad (1)$$

where m is the refractive index of medium.

Furthermore, the recently improved particle image velocimetry (Tian and Qiu, 2002) was also utilized in the measurements to eliminate any unnecessary background scattering. The measurement results are shown in Figure 8 and Figure 9 for flow velocity and bubble dynamics, respectively.

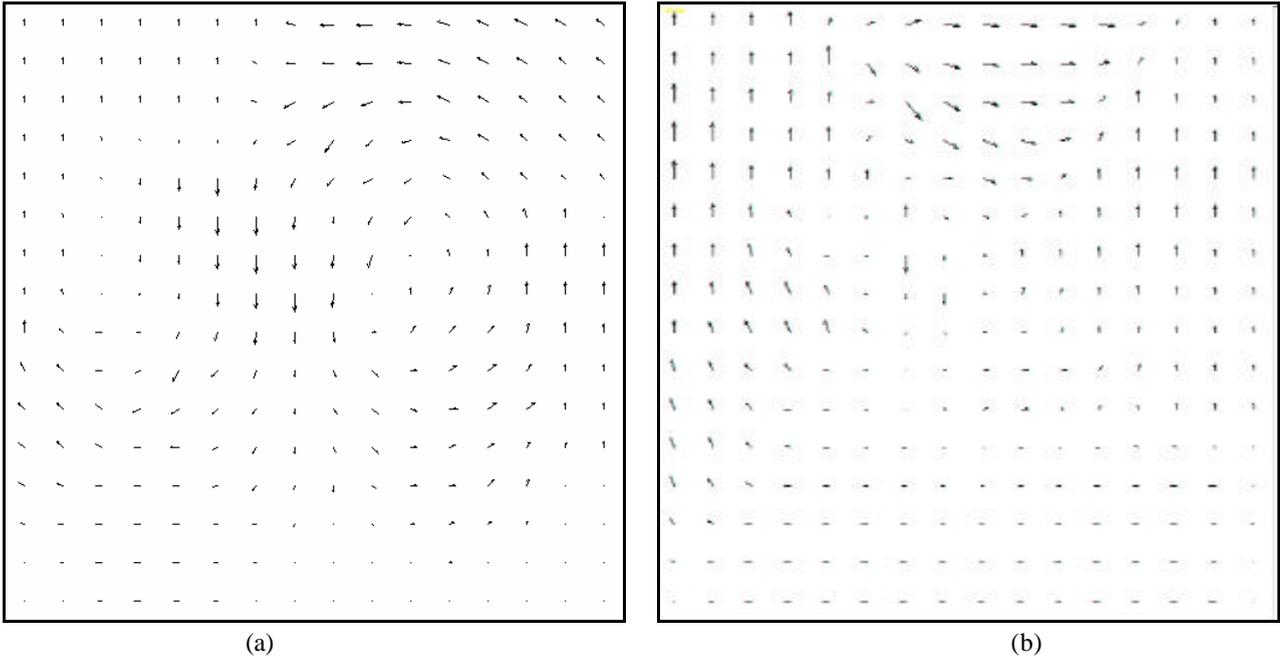


Figure 8 Velocity of laser-induced optohydrodynamic flows reconstructed with PIV; (a) laser repetition frequency, $f = 5\text{Hz}$, (b) laser repetition frequency, $f = 10\text{Hz}$,

In Figure 8, the beam is propagating downwards along the vertical centerline of the image with different repetition frequencies. The microbubbles were formed along the laser beam. The measured velocities of the flow field along the centerline are also moving downwards which is contradicting to the buoyancy force direction (upwards) of microbubbles. This phenomenon may be caused by the effect of laser induced pressure wave and explosive cavitation. Circulations were formed along the centerline of the laser beam, but they were slightly asymmetric. The flow field shows a different pattern when the repetition of laser pulse frequency is changed. It was found that the laser power and the laser repetition rate have great impact on the bubble generation and dynamics.

+ --- Z=0mm □ --- Z=4mm △ --- Z=8mm ● --- Z=12mm
 ◇ --- Z=2mm ○ --- Z=6mm ▲ --- Z=10mm ▼ --- Z=14mm

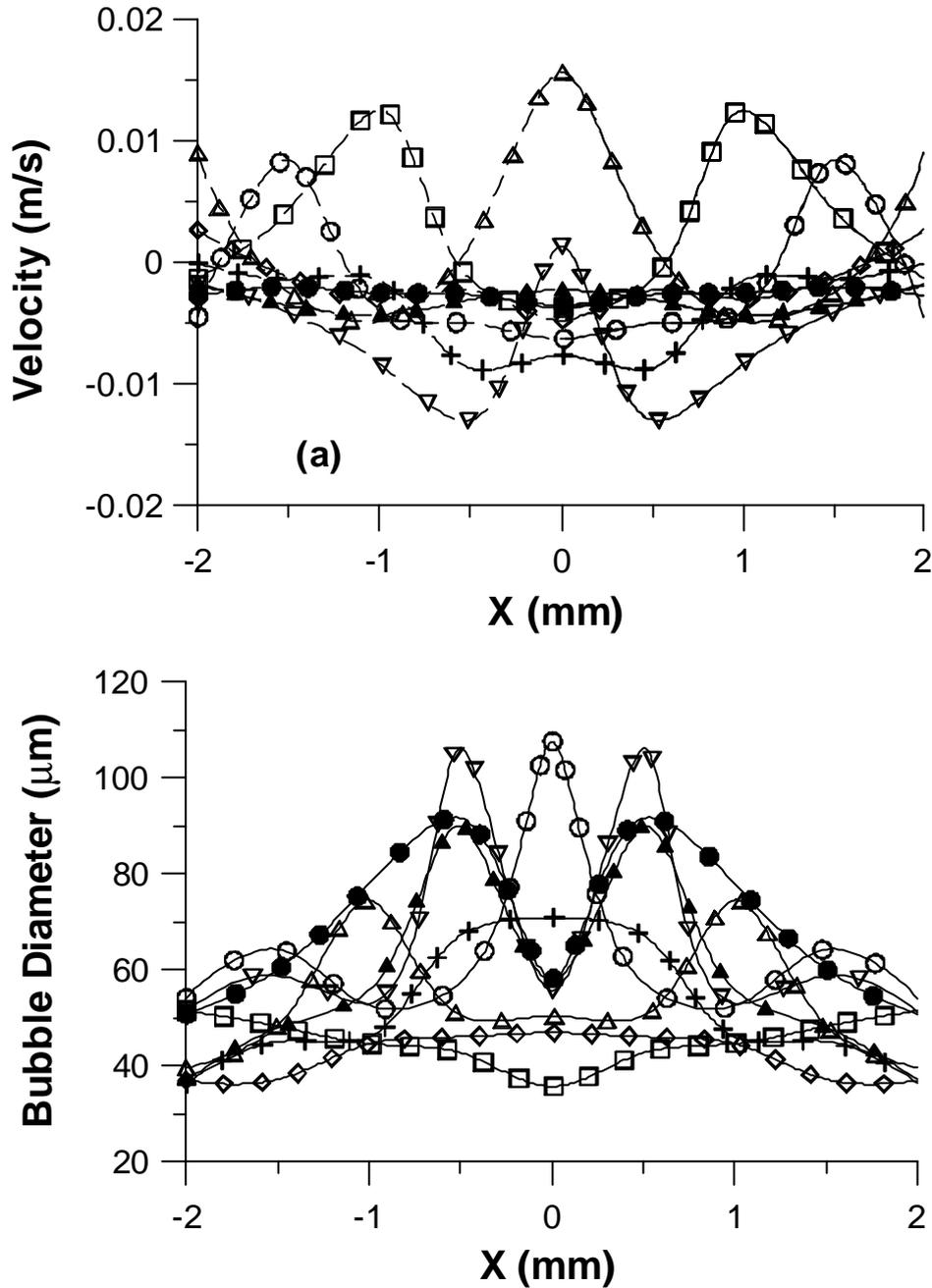


Figure 9 Bubble velocity and diameter measured by PDA

The velocity and diameter of microbubbles were measured with PDA system as described previously. Figure 9 gives the typical measured results. It was found that the microbubbles have several maximum positive velocities (moving downwards) along the centerline. The positive velocity may be caused by the pressure wave induced by the laser pulses. At other positions along the centerline all of them have a negative velocity (moving upwards) caused by buoyancy force and there are some places where the bubble velocity is about zero, although the measured flow field shown in Figure 9 demonstrates a downwards velocity along the whole centerline. Therefore, it is necessary to distinguish the velocities between the flow and microbubbles.

The measured mean bubble diameters are shown in Figure 9. They are ranged between 35 to 110 μm. It is interesting to note that the largest and smallest bubble diameters along the centerline were found at Z=6mm (at the focus position) and Z=4mm (2mm above the focus position), respectively, where Z indicates the coordinate value from the water surface. The mechanisms behind these phenomena can be explained with the consideration of the effects of the cavitation explosion

and the buoyancy force. As discussed above, the bubble generally moves downward at first due to the optical pressure and the forces caused by the cavitation explosion, and then moves upward due to the buoyancy force. During this dynamic process, the bubble size decreased extremely due to more times collapse and re-expand. In other words, the measured position, $Z=6$ mm is just at the location where the first maximum collapse radius occur, while $Z=4$ mm just met the minimum collapse radius. Based on the theory of bubble collapsing that was first proposed by Rayleigh (1917), the collapse time corresponds to the maximum radius of the collapsing bubble, t_c , can be determined via Rayleigh's formula as:

$$t_c = 0.915R_{\max} \sqrt{\frac{\rho}{P_0 - P_v}} \quad (2)$$

where $\rho=998.2$ kg/m³ is the density of water, $P_0=10^5$ Pa is the ambient pressure, and $P_v=2330$ Pa is the vapor pressure. Based on the measured results of bubble diameters, t_c was estimated with the value less than $10 \mu\text{s}$. Therefore, if a bubble with the velocity of 0.6 mm/s is considered, there will be hundreds times collapse during its moving from $Z=6$ mm to $Z=4$ mm. Such size reduction can also be seen in Figure 10 (for single bubble) and Figure 11 (for multi bubbles), where $t=0$ denotes the time at which the laser pulse is shot.

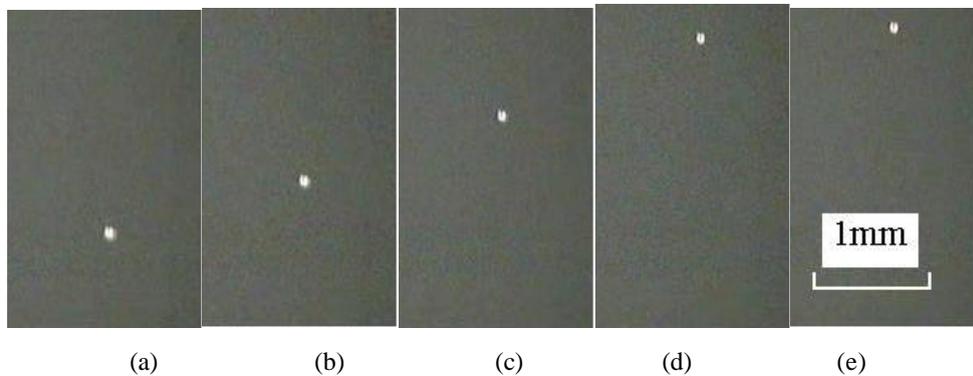


Figure 10 Dynamic process of single laser-induced bubble ($P=35\text{mJ}$); (a) $t=40\text{ms}$ (b) $t=200\text{ms}$ (c) $t=400\text{ms}$ (d) $t=600\text{ms}$ (e) $t=700\text{ms}$

4. CONCLUSIONS

Laser-induced optohydrodynamic flows and micro bubbles had been investigated utilizing a LaVision PIV system and a novel PDA system. The image patterns of the laser-induced optohydrodynamic flows and micro bubbles under different pulse energies were visualized. The experimental results show that a bright fluid beam with duration less than $127 \mu\text{s}$ is produced by a focused laser pulse while a cavitation explosion just around the focus point is also occurred, although the later one has a little longer duration than the former one. Followed the fluid beam and the cavitation explosion, two new fluid regions which may be formed with the superheated dense fluid are formed, one is just under the fluid beam due to the optical pressure while the other one is around the explosion area due to the force caused by the cavitation explosion. And the single or multi microbubbles are generated just after the cavitation explosion when the nucleation conditions are satisfied. Both of the fluid beam and the cavitation explosion caused expanding fluid are not the cause of the bubble generation, and the bubble may be produced at the same time at the onset of these two flows when the saturation conditions are satisfied. In other words, all of the bright fluid beam, the expanded fluid and the microbubbles are three different newly generated flows due to the optical breakdown, where the first one has the shortest duration (less than $127 \mu\text{s}$) while the last one has the longest life (can exceed several seconds) to survive. In addition, the characteristics, such as bubble velocities and diameters, were measured by a recently improved phase-Doppler anemometry (PDA), and it was found that the largest and smallest bubble diameters were measured just around and 2 mm above the focus position along the center line, these may mainly due to bubble dynamical behavior as well as its collapsing.

Future work will focus on measurement of the temperature distribution of the laser-induced optohydrodynamic flows and numerical investigation of the bubble generation and its dynamics.

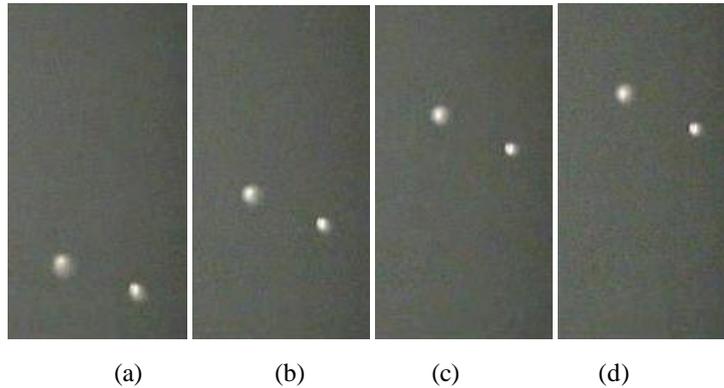


Figure 11 Dynamic process of laser-induced multi bubbles ($P=50mJ$); (a) $t=40ms$ (b) $t=150ms$ (c) $t=300ms$ (d) $t=400ms$ (The scale is same as indicated in Figure 10)

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