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Control of the liquid jet formation through the symmetric and asymmetric collapse of a single bubble generated between two parallel solid plates

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HIGHLIGHTS

- The mechanisms of the liquid jet formation of a single bubble generated between two parallel solid plates are investigated through the strobe photography experimental method and numerical simulations.
- It is found that the jet speed and diameter could be adjusted by the relative size and generation position of the bubble between the plates.
- The laser energy can be controllably transformed into the directional mechanical force through bubble interactions with a pair of solid plates.
- The controllable liquid jet induced by the interactions of the bubble and a pair of plates can be applied to assist micro-injections of bio-materials or living cells positioned on one of the plates, or to help directional transport of target samples in micro-fluidic systems.

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ABSTRACT

The liquid jet formation can be induced by the asymmetric collapse of the cavitation bubble located nearby boundaries. The jet translational direction and speed can be influenced by the type of the boundary, e.g. solid boundary, free surface or elastic boundary, and the relative locations of the cavitation bubble and the boundary. The mechanisms of the liquid jet formation of a single bubble generated between two parallel solid plates are investigated through the strobe photography experimental method and numerical simulations. It is found that there are two conditions for the bubble to split into two smaller bubbles, which could collapse respectively toward the boundary closer to them and form the liquid jet. The first condition is that the proportion of the maximum bubble diameter to the distance of the two plates, which is denoted as ρ, surpasses the threshold of 0.78. The distance of the bubble center to one of the plates, which is closer to the bubble, is denoted as d. The proportion of d to the maximum bubble radius is denoted as γ. The second condition is that γ surpasses the minimum value, which decreases from 1.1 to 0.3 as ρ grows from 0.78 to 1.35. The size of the separated bubble, that locates closer to one of the plates, decreases as the original bubble moves from the middle toward the other plate. Furthermore, it is found that the maximum jet speed of about 100 m/s appeared when the optimum relative bubble size equals to 1.09 and for the bubble located at the middle of the plates. Therefore, the jet speed and diameter could be adjusted by the relative size and generation position of the bubble between the plates. In this way, the laser energy can be controllably transformed into the directional mechanical force through bubble interactions with a pair of solid plates.

1. Introduction

Cavitation bubbles can be generated at the depressurized areas in the liquid, when the local pressure drops below the saturated vapor pressure [1]. On the contrary, they can also be initiated from a high pressure steam center generated by the laser-induced

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optical breakdown [2] or electrical discharge induced breakdown [3] in the liquid. Dynamics of a cavitation bubble in the bulk have been investigated since 1917 [4]. Theoretical models of the cavitation bubble have been improved through considering the acoustic and viscose damping of the bubble energy [5,6], as well as a better modeling of the materials state inside a cavitation bubble [7,8]. Progresses in the experimental method [9], especially the high speed photography method [10], have highly improved the understanding of the cavitation bubble dynamics. The non-spherical collapse of a bubble can be achieved through the presence of an interface, e.g. a rigid boundary [11,12], an elastic boundary [13,14], or a free surface [15,16], near the bubble. As a result of the non-spherical collapse, a liquid jet directed toward the rigid boundary [17] or away from the free surface [18,19] could be formed and pierce through the bubble during the collapse and rebound of the bubble. The non-spherical collapse of the bubble can also be induced by shock-waves [20,21]. Furthermore, interactions between a pair of laser-induced bubbles will also lead to liquid jet formation [22,23]. Through the dimensionless method [24–26], it has been found that the jet properties can be adjusted by the relative bubble size, the dimensionless bubble distance and the phase difference of the bubbles [27,28]. The controllable liquid jet is a promising tool as a micro-pump or a micro-propeller [29] for directional transport of target samples in micro-fluidic systems [30], or as an injector for micro-injection of bio-materials or cells [31].

The interaction of the biomedical target, e.g. cells or tissue samples, with the liquid jet is usually implemented in a narrow gap between two parallel solid plates [32]. The mechanical force delivered to the target is nearly parallel to the plate surfaces. This can bring difficulties for the propulsion or injection of the target, which is attached on one of the plate inner surface as a thin layer, e.g. a layer of cells. Studies of a single bubble generated between two solid plates show that the bubble may be divided into two bubbles and bring damages to the plates [33,34], which enlightened the investigations of the formation of the liquid jet that displaces in the normal direction of the plate surface in this work. The investigations in [32] have shown that the wall effect remarkably appears when the ratio of the bubble radius to half of the distance of the plates grows more than 2/3, and the bubble could divide into two bubbles owning to the lateral pressure. In Ref. [33], a 3D numerical model was established based on the boundary integral method to simulate the symmetrical and asymmetrical bubble breakup, which was not able to be modeled through the numerical model based also on boundary element method in [32]. It has been found that a pressure peak is induced at the moment of the bubble splitting.

The strobe photography experimental method and numerical modeling with OpenFOAM are implemented. The numerical method has been proved to be able to handle the big distortion and rupture of the materials during the collapsing of the bubble, especially the whole process of the jet penetrating the bubbles. The influences of the relative bubble size to the distance of the two parallel plates, i.e. the gap height, and the relative distance of the bubble center to one of the plate, on the bubble evolution properties and the liquid jet speed are discussed. The controllable liquid jet induced by the interactions of the bubble and a pair of plates can be applied to assist micro-injections of bio-materials or living cells positioned on one of the plates, or to help directional transport of target samples in micro-fluidic systems.

2. Experimental and numerical methods

The dynamics of the bubble generated between two parallel solid plates are investigated following the dimensionless method. The scheme of the definitions of the governing dimensionless parameters is shown in Fig. 1. The upper and lower solid plates are denoted by plate 1 and plate 2, respectively. The symmetric plane is denoted by P_s. The maximum bubble radius, when the two plates are at the infinite distance to the bubble, is denoted by R_{max}. The expansion time of the bubble from the inception to the maximum radius is denoted by T_{exp}. The distance of plate 1 and plate 2 is D. The distances of the bubble center to plate 1 and plate 2 are d_1 and d_2, respectively. The relative distances of the bubble center to plate 1 and plate 2 are defined as $\gamma_1 = d_1/R_{max}$ and $\gamma_2 = d_2/R_{max}$. The relative size of the bubble is defined as $\rho = 2\times R_{max}/D$. The relative time is defined as $\tau = t/T_{exp}$. The related bubble radius is defined as $r = R/R_{max}$.

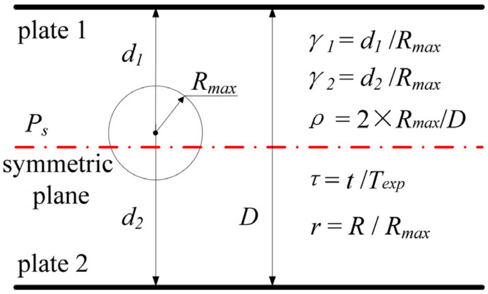

Fig. 1. Scheme of the definitions of the governing dimensionless parameters of the bubble generated between two parallel solid plates.

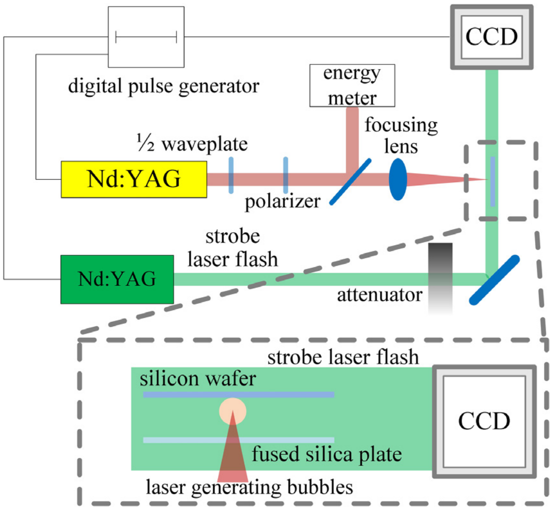

Fig. 2. Scheme of the strobe photography experimental setup. (For interpretation of the references to color in the text correlative with this figure, the reader is referred to the web version of this article.)

2.1. Experimental setup

The scheme of the strobe photography experimental setup is shown in Fig. 2. The laser-induced bubble is generated between a fused silica plate and a silicon wafer plate. The bubble center is at the laser focus. The forming of the bubble is started by the laser-induced plasma in water at the laser focus spot and the explosive evaporation of water due to the intensive heating of the plasma. The laser generating the bubble is the Nd:YAG laser set, i.e. yellow laser in Fig. 2, with the pulse width of 7 ns @ 1064 nm. The initial energy of the bubble could be adjusted by the 1/2 λ wave plate and the polarizer. Another Nd:YAG laser set, green laser in Fig. 2, offers the strobe flash with the pulse width of 7 ns @ 532 nm. The programmable digital pulse generator is used to manage the working sequence of the two laser sets and the CCD (Microvision MV-VS200FM). The temporal resolution of the pulse generator is 1