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Effect of surface tension on a liquid-jet produced by the collapse of a laser-induced bubble against a rigid boundary

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ABSTRACT

The effect of surface tension on the behavior of a liquid-jet is investigated experimentally by means of a fiber-coupled optical beam deflection (OBD) technique. It is found that a target under water is impacted in turn by a laser-plasma ablation force and by a high-speed liquid-jet impulse induced by bubble collapse in the vicinity of a rigid boundary. The liquid-jet impact is found to be the main damage mechanism in cavitation erosion. Furthermore, the liquid-jet increases monotonously with surface tension, so cavitation erosion rises sharply with increasing surface tension. Surface tension also reduces bubble collapse duration. From the experimental results and the modified Rayleigh theory, the maximum bubble radius is obtained and it is found to reduce with increasing surface tension.

1. Introduction

Over the last 100 years a large amount of work has been published on possible mechanisms explaining how cavitation damage occurs. Both experimental and theoretical work confirms that, when a bubble collapses near a solid boundary, provided it is sufficiently close, the boundary destroys the symmetry of the collapse process [1,2]. The result is that a liquid-jet is formed which threads the bubble and impacts on the boundary [3–5]. Studies of the mechanism of cavitation damage were then focused on liquid-jet impact.

The surface tension of a liquid is one of the basic factors determining the rate and nature of the collapse of cavitation bubbles, and hence the operation of various cavitation processes such as the erosion of solid surfaces, induced chemical reactions, etc. With regard to surface tension effect on erosion, Nowotny [6] showed that cavitation erosion reduced with decreased surface tension by conducting his tests on pure aluminum in five different liquids, which possess different surface tensions. Plesset [7] reported similar results in organic liquids. Iwai et al. [8,9] investigated the influence of surface tension on cavitation damage by relating surface tension to the observed cavitation pattern and bubble behavior. Some of the researchers focus their attention on mass loss due to different surface tensions. As the liquid-jet is the major factor in erosion, we conducted our investigation into the influence of surface tension on the liquid-jet.

Several optical methods have been used for detecting and measuring cavitation bubbles and the mechanical effects induced by jet impact, such as Fabry–Perot interferometer [10], Michelson interferometer [11], Schlieren photography [5], high-speed photography [12]. In this paper, we utilize a detection technique based on fiber-coupled optical beam deflection (OBD) [13]. Compared with other detection techniques, this detection method has many advantages, such as low cost, simple structure, and high-frequency response. It can present the temporal development of transient forces acting on the target. By this optical detector, we investigate mechanical effects of the bubble boundary interaction and the influence of surface tension on liquid-jet impact force. In addition, based on the bubble collapse time and the modified Rayleigh theory, the maximum bubble radii in liquids with different surface tensions can also be calculated.

2. Experiment

2.1. Test apparatus and procedure

The experimental arrangement based on OBD is outlined in Fig. 1, which was first reported in the literature in detail [13]. A Q-switched Nd:YAG laser with wavelength 1.064 μm and pulse duration 10 ns is focused on a sample after an attenuator group and beam splitter. The sample used in this experiment is a clear polished 0.20-mm-thick copper plate, attached to the inner wall of a cuvette. The cuvette is filled with liquids possessing different surface tensions. The maximum incident laser energy is up to

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500 mJ and the focal radius is 50 μm, measured using the "burn-paper" technique.

In the detection region, a He–Ne laser is directly incident on the epicenter of the copper plate's rear face where a part of the glass cuvette is removed. The reflected beam is then focused into a single-mode optical fiber mounted on a five-dimensional fiber-regulating stand with 0.1 μm spatial resolution. The reflected beam is monitored by a photomultiplier, fed into a two-channel digital oscilloscope and stored in a computer. A part of the scattered laser is fed into a PIN photoelectric diode to generate the trigger signal. Elements numbered 8–13 in Fig. 1 form the OBD test system. The OBD uses an optical fiber as the sensitive receiver element to detect a transient force, so that the sensitivity of this detector is increased.

When a transient normal force impacts the specimen, a surface deformation at the epicenter will be induced with a tiny conical protrusion. Considering that the probe light is incident on the conical protrude with its center overlapping the conical center, the reflected beam spot will change from a round shape into an annulus distribution: a part of light shifts out of the fiber core. As a result, the transient light flux arriving at the photomultiplier is modulated. By integral of the light flux of variation in the fiber core, the experimental probe beam deflection signal is proved proportional to the transient loading force. Furthermore, the formula scaling rule may be adopted to calibrate this force sensor [14]. Combining the detection principles of this detector with a widely used laser ablation model, the value of loading forces, including the laser ablation force and liquid-jet impact force, can be estimated.

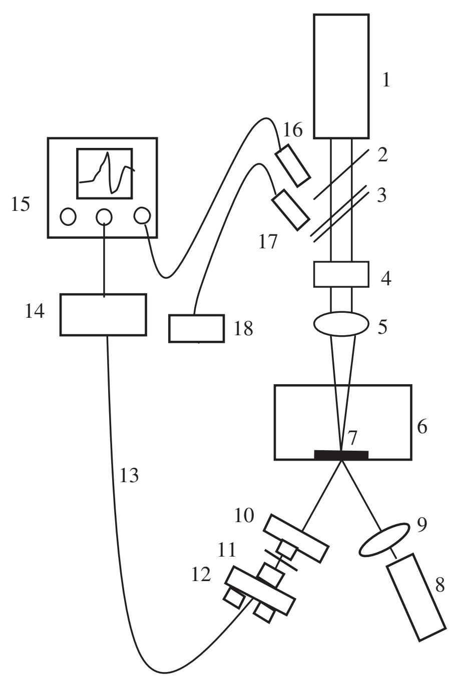

Fig. 1. Diagram of experimental setup: (1) Q-switched Nd:YAG laser (1.06 μm wavelength, pulse duration 10 ns); (2) beam splitter; (3) attenuator group; (4) concave lens ($f = 50$ mm); (5) convex lens($f = 150$ mm); (6) glass cuvette ($100 \times 100 \times 150$ mm^3); (7) copper target; (8) He–Ne laser (power 5 mW, 0.63 μm wavelength); (9) convex lens ($f = 50$ mm); (10) microscope objective (20×, $f = 4$ mm); (11) interference filter (0.63 μm wavelength); (12) 5-axis fiber chuck positioner (0.1 μm spatial resolution); (13) single-mode optical fiber (4 mm in radius); (14) photomultiplier (Hamamatsu H5773 with 2 ns rise time); (15) digital oscilloscope (Tektronix THS730A); (16) PIN photodiode (with 0.1 ns rising edge); (17) energy-probe and (18) pyroelectric energy meter.

2.2. Test liquids

The liquids used in our experiment possess different surface tensions, while the density and viscosity remained almost unchanged. The physical properties of these fluids used in our experiment are listed in Table 1 [15].

3. Results and discussion

It is well known that, when an intense pulsed laser pulse is fired into a liquid, a bubble is then formed and expands, eventually reaching a maximum radius and then collapsing violently [16]. If a bubble collapses in the vicinity of a rigid boundary, due to the radial flow retarded by the rigid boundary, the pressure at the lower bubble wall is smaller than that at the upper wall. Therefore, the fluid volume above the bubble is accelerated and focused during the collapse, leading to the formation of a liquid-jet directed towards the boundary. The liquid-jet hits the far bubble wall in the final stage of the collapse and penetrates the bubble, having the potential to cause boundary damage. The impact force against the boundary can be represented by a time-varying force acting normal to the surface as shown in Fig. 2. As the duration of this liquid-jet impact is very short [17,18], it can be considered as a point force. The incident laser energy is 34 mJ and the distance L from the laser focus to the boundary is 0.12 mm. Two peaks a and b are separated by a time interval of 248 μs. Peak a denotes the laser-induced plasma ablation impact and peak b represents liquid-jet impact forces induced by cavitation bubble collapse near the rigid boundary [13]. There is a polarity change corresponding to the first impact-peak "a", can be seen on Fig. 2. By means of this calibrated force

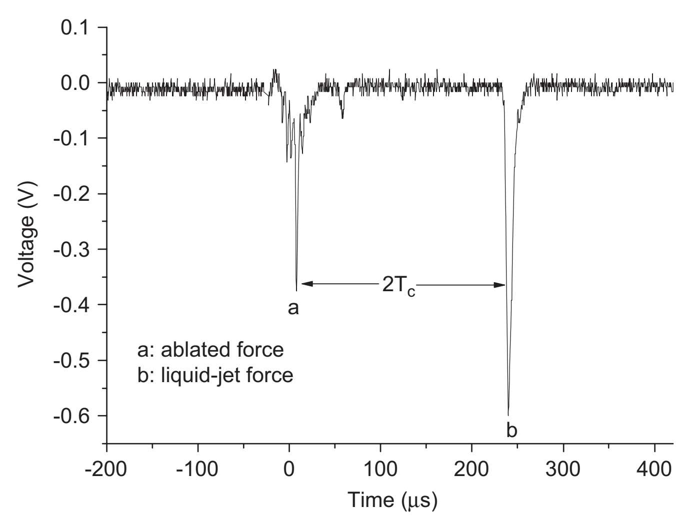

Fig. 2. Typical signal detected by the optical beam deflection method.

Table 1
Physical properties of experimental liquids at 25 °C

Fluid	Ethanol	Acetic acid	Glycerin (1% by wt)	Distilled water	Deionized water
Surface tension (10^{-3} N/m)	24.05	29.58	71.64	71.96	72.88