A STUDY OF LIQUID DYNAMIC RUPTURE IN MICROFLUIDICS

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ABSTRACT

This paper demonstrates the dynamic stressing of viscous liquids in microfluidic channels. An infrared laser pulse is focused within the testing liquid in a microfluidic channel and a spherical shock wave near the interface is created. The shock is reflected by the free surface due to acoustic impedance mismatch. The displacement of the free surface in hundred nanoseconds is captured by a developed double-exposure optical system. The tensile strength can be estimated by using a series of results from different distances between the bubble and the free surface. This study has a great potential in the optical breakdown of biomaterials.

KEYWORDS

Dynamic rupture, viscous liquid, double-exposure

INTRODUCTION

The tensile strength of liquids has been investigated for hundreds of years since the pioneer work of Berthelot [1-5]. It is affected by many physical properties of liquids and one of them is shear viscosity. Several studies have been conducted to investigate the relation between the tensile strength *TS* and the shear viscosity μ [6-9]. All results can be expressed as $TS \sim \mu^n$, but the value of the exponent *n* is 0.2 in Ref [6] and 0.1 in Ref [7-8]. However, the use of a large volume of liquids introduces heterogeneous nucleation, which causes a remarkable decrease of the tensile strength. Recently, a dynamic stressing method by using a microfluidic platform has been developed and the rupture of water has been observed with very strong tensile waves [10]. The decreased volume of the liquid and the nanosecond dynamic process significantly increases the probability of the homogenous nucleation. In this paper, a double-exposure technique is developed to investigate the dynamic rupture of viscous liquids in microfluidic channels. The tensile strengths of four glycerol-water solutions with different viscosities are measured.

WORKING PRINCIPLE

A technique to estimate the tensile strength of liquids is illustrated in Fig 1. An IR laser pulse is focused into the testing liquid in a microfluidic channel and a shock wave is formed due to the optical breakdown. The shock wave is reflected by the free surface since the acoustic impedance mismatch between the testing liquid and air. Double exposure picture photograph is used to capture the deformation of the free surface. In one-dimensional analysis, the shock wave velocity propagates as $P/\rho U$. Hence, the water detaches the free surface at an initial velocity of $2P/\rho U$. The contribution of the reflected negative shock wave is $TS/\rho U$. Therefore, the initial velocity V_0 of the deformed free surface is expressed as [9]

$$V_0 = (2/\rho U)(P - TS/2) \tag{1}$$

where *P* is the maximum pressure of the laser pulse, *TS* is the negative pressure induced by the reflected shock wave, ρ is the density of the water, and *U* is the velocity of shock wave. Using the double exposure technique, the deformed free surface can be observed two times (the solid and dash lines) and the value of V_0 for different distances under the same laser pulse energy can be calculated. By extrapolating to zero velocity, $TS = 2P$, the tensile strength of the testing liquid can be estimated.

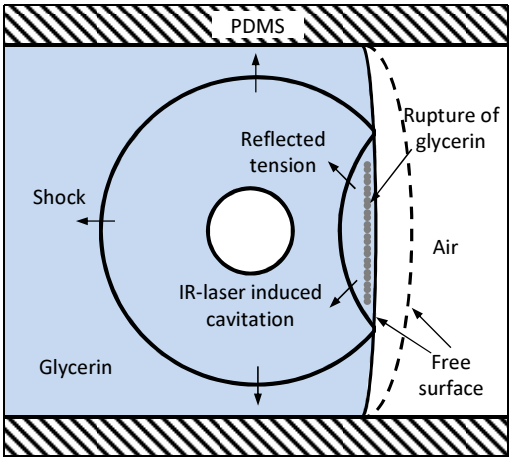

Figure 1: Illustration of liquid in microchannel

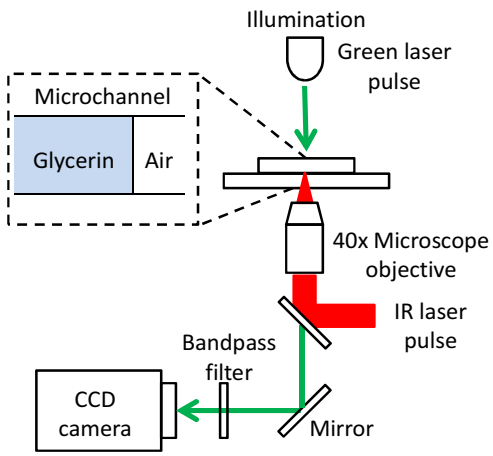

Figure 2: Schematic of experimental setup

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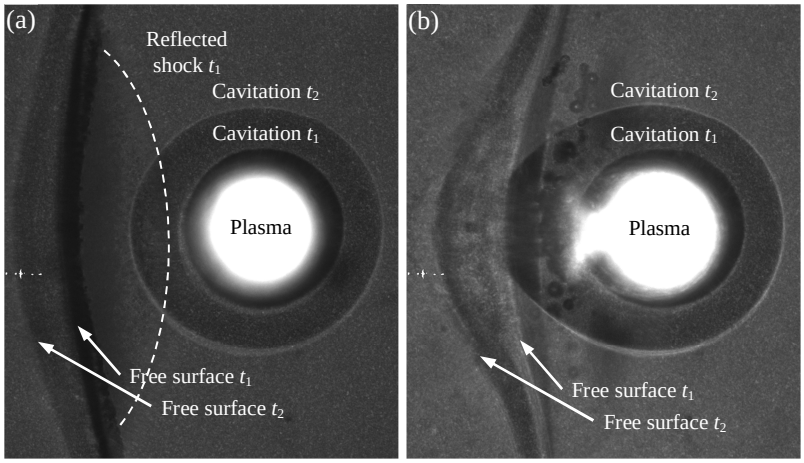

Figure 3: Double-exposure images of dynamic stressing of water under a distance of (a) 113.4 µm and (b) 71.5 µm.

The double-exposure experimental setup is shown in Fig. 2. The testing liquid is partially filled in a polydimethylsiloxane microchannel with a height of 85 µm and a width of 400 µm. An Nd:YAG laser creates single laser pulses at 1064 nm (infrared/IR, 7 ns duration) of 1.40 ± 0.05 mJ energy and 532 nm (green, 6 ns duration). The IR pulse is focused within the testing liquids (40×, NA = 0.8). The green pulse as the illumination light is split into two beams by a 50:50 beam splitter and the time delay between the two beams can be controlled by adjusting the length difference of the two optical fibers. DI water and glycerol are measured and the dynamic viscosities are 1.005 and 1250 mPa·s, respectively.

RESULTS AND DISCUSSIONS

Figure 3 shows two images of the dynamic stressing of water. As shown in the images, the bright spot is the emission of the plasma and two spherical bubble walls at t_1 and t_2 are captured simultaneously in a single image. t_1 and t_2 are controlled by the length of optical fiber (30 m and 50 m in this paper) and the time interval is 156 nanoseconds in this case. The shock front is reflected by the free surface due to the acoustic impedance mismatch between water and air. The dash arc shows the reflected shock at t_1. The free surface is deformed by the shock loading. The distance between the bubble and the free surface is 113.4 µm and 71.5 µm, respectively, for Fig. 3(a) and (b). With larger distance, the deformed distance in the same time interval is smaller.

To determine the pressure distribution with the shock, the bubble dynamics in liquid droplet is firstly examined. A water /glycerol droplet on a glass slide is used as the testing medium. The time evolutions of the bubble radius in DI water and glycerol droplets are plotted in Fig. 4 (a). The error bars show the standard deviation of six distinct experimental results. The radii increase with time for both fluids. But the radii of bubble in glycerin droplets are always smaller than that in DI water droplets at the same time. This is due to the fact that the viscosity damps the bubble growth. The evolution of the shock front and the bubble wall in water is plotted in Fig. 4(b). The shock dynamics is simulated by solving the multicomponent Euler equations (2D with azimuthal symmetry) and the thermodynamic state is governed by Tait equation of state along an isentrope. The initial bubble radius is 12 µm and the initial bubble pressure is 6 GPa. The simulation and experimental results agree very well with each other as shown in Fig. 4(b).

The pressure distribution for different time points after optical breakdown is plotted in Fig. 5(a) as a function of the distance x between the bubble and the shock front. The peak pressure decays at a rate of $x^{-1.25}$ in the simulated

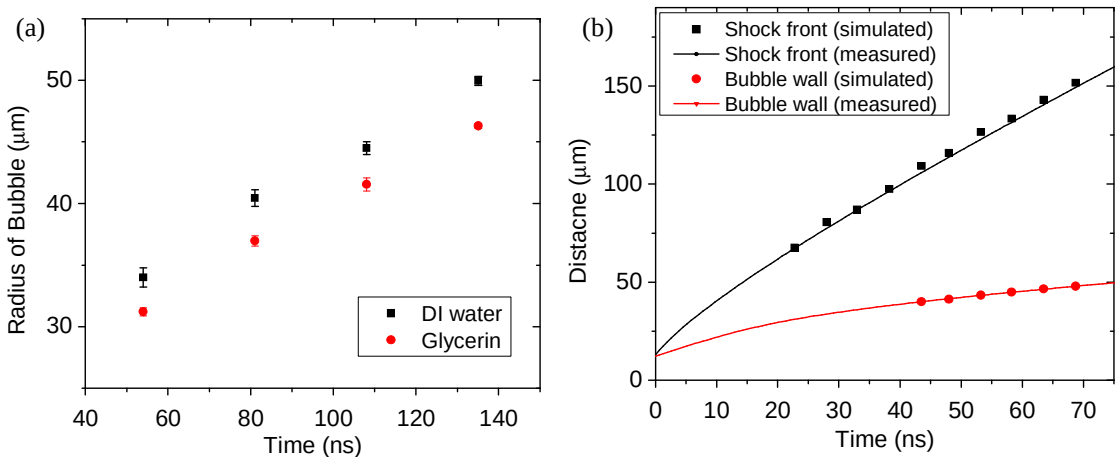

Figure 4: (a) Bubble radius in DI water and glycerol droplets as a function of time. (b) Simulation and experimental results of shock front and bubble wall in water.

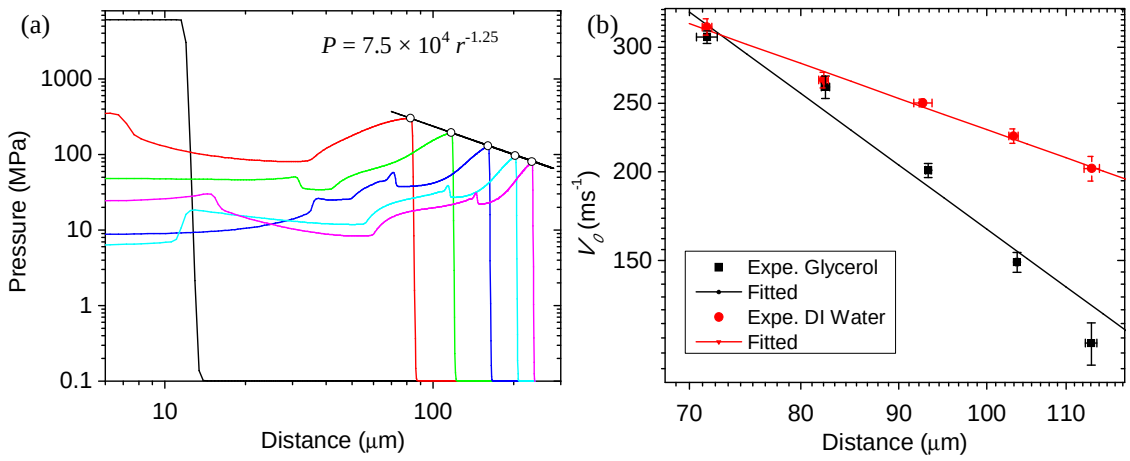

Figure 5 (a) The simulated pressure distribution 0, 12, 24, 36, 48, 60 and 72 ns after the optical breakdown. (b) Measured free-surface deformation velocity as a function of the distance between the bubble and free surface.

range (from 80 μm to 300 μm). The pressure P at any distance r can be estimated by using the simplified equation

$$P = 7.5 \times 10^4 r^{-1.25} \quad (2)$$

where r is the distance in micrometer.

The results of the free surface deformation velocity as a function of the distance between the bubble center and the free surface are plotted on a "log-log" scale in Fig. 5(b). The error bars show the standard deviation of six distinct experimental results. Extrapolations to the measurement accuracy, 6.37 and 6.37 m/s (for $V_0 \sim 0$), give the values of 4137.3 μm and 511.3 μm for DI water and glycerol, respectively. This predicts the tensile strength of DI water and glycerol are 34.8 MPa and 61.7 MPa, respectively. This means that the tensile strength increases with the increase of the viscosity.

CONCLUSIONS

In conclusion, the dynamic rupture of viscous liquids is investigated by using a microfluidic platform. A double-exposure optical system is developed to capture the deformation of the free surface. The pressure distribution is obtained by numerical simulation. The tensile strength can be estimated based on the displacement of the free surface and the pressure distribution. Two liquids, DI water and glycerol, are tested. The tensile strength of glycerol is larger than that of DI water. These clearly suggest that the viscosity has a huge effect on the bubble nucleation. This study has a great potential in the optical breakdown of biomaterials.

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