SUPERSONIC CONTROLLED MICROJET

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Summary By focusing a laser pulse in a liquid-filled glass-microcapillary open at one end, a small mass of liquid is instantaneously vapourised. This leads to a shock wave which travels towards the concave free surface where it generates a high-speed microjet. The initial shape of the meniscus plays a dominant role in the process. The velocity of the jet can reach supersonic speeds while maintaining a very sharp geometry. The entire evolution of the jet is observed by high-speed recordings of up to 10^6 fps. A parametric study of the jet velocity as a function of the contact angle of the liquid-glass interface, the energy absorbed by the liquid, the diameter of the capillary tube, and the distance between the laser focus and the free surface is performed, and the results are rationalised. The method could be used for needle-free injection of vaccines or drugs.

INTRODUCTION

Thin, axisymmetric liquid jets have been studied from various perspectives due to their widespread application and the fundamental interest in them (see e.g. the review article by [1]). One of the important applications of such thin liquid jets is needle-free drug injection in which a liquid solution containing the drug is jetted into human or animal tissue through the skin [2]. For this last purpose, it is necessary to push the limits of jet generation toward higher velocities (more than 200 m/s), lower diameters (down to 30 μm), and improved controllability [2, 3]. In the present study, we describe the generation of even faster and thinner jets and the way in which their velocity can be controlled by the suitable choice of experimental parameters.

EXPERIMENTAL SETUP AND CONTROL PARAMETERS

Figure 1(a) shows a sketch of the whole experimental setup. One end of the capillary tube is connected to a syringe pump (Model PHD 2000, Harvard Apparatus, USA) containing a water-based red dye. The other end is open to the air. A 532 nm, 6 ns laser pulse (100 mJ Nd:YAG laser, Solo PIV, New Wave, USA) is focused through a 10× microscope objective on a point inside of the capillary. The laser energy is monitored by means of an energy meter (Gentec-eo XLE4 or Gentec-eo QE12SP-S-MT-D0, Canada) placed behind the capillary. The jet formation was recorded using high-speed cameras with a frame rate of up to 10^6 fps (HPV-1, Shimadzu Corporation, Japan and SA1.1 and Photron, USA). A long-distance microscope (Model K2, Infinity, USA) with a maximum magnification of 12× was connected to the camera in order to capture the jet formation from the side and vary the field of view by adjusting the magnification.

The experimental parameters are indicated in figure 1(b) together with a side view of the capillary. The distance between the meniscus and the laser focus position is H, E is the absorbed laser energy, θ is the contact angle of the liquid with the glass capillary with diameter D; l_v is the distance offset of the laser focus with respect to the capillary axis in the vertical plane, and l_h is the focus offset of the laser in the horizontal plane. Three different borosilicate glass capillary tubes (Capillary Tube Supplies Limited, UK) were used in the experiments, with inner diameters D of 50, 200 and 500 μm and outer diameters of 80, 220 and 520 μm, respectively. The inner surface of the tip of the capillary tube was dipped in a hydrophobic solution (1H, 1H, 2H, 2H-Perfluorooctyltrichlorosilane), to vary the contact angle θ between 20° and 90°.

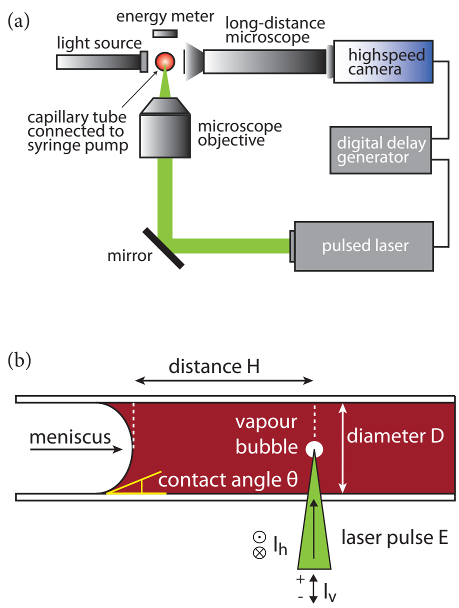

Figure 1. (a) A sketch of the experimental setup. The capillary tube is aligned perpendicular to the paper. (b) All experimental parameters with a side view of the capillary in which the microjet formation takes place.

RESULTS

An example of such a supersonic jet is shown in figure 2. The capillary is on the right, the jet tip is on the left, and the jet travels from right to left with a speed of 490 m/s. The tip of this jet has grown into an almost spherical mass which will

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eventually detach as a droplet. At the other end, the jet is thicker and slower.

Figure 3 shows the dependence of the jet velocity upon absorbed energy E for 50 μm tube diameter. The data are well fitted by a linear function with a positive intercept at $V_j = 0$. This intercept embodies the existence of a certain threshold E_{heat} below which no jet is formed. It is interesting to note that the linear relation between V_j and $E - E_{heat}$ is preserved even when the jet speed becomes supersonic.

The dependence of the jet velocity upon the other controlling parameters has been investigated in a series of experiments the results of which have been summarised in the empirical relationship provided in equation (1).

$$V_j \simeq C_0 \frac{(E - E_{heat})(1 + \beta \cos\theta)}{HD}. \quad (1)$$

where $C_0 = 0.0027\,(\text{Pa}\cdot\text{s})^{-1}$ and $\beta = 12.6$.

The velocity is very strongly dependent on the curvature of the interface, which is a function of the tube-liquid contact angle. This result suggests that the mechanism underlying the phenomenon is the focusing of the shock wave produced by the nanosecond-scale phase change induced by the absorption of the laser energy similarly to the phenomenon exploited in shaped charges. Thus, the jet velocity is critically dependent on the amount of liquid vaporized and on its distance from the free surface, both of which can be varied by varying the position of the laser focus. The jet velocity is inversely proportional to the distance H. It is well known that the pressure amplitude of a locally generated shock wave in a free fluid decreases inversely with the distance. In our conditions, the fluid is confined within the tube but the size of the initially vaporized liquid is at least one order of magnitude smaller than the tube diameter so that this geometrical attenuation may play a role. Another possibility is that there is viscous attenuation of the shock strength due to the no-slip condition at the tube wall. It has been found that the effect of the offset of the laser focus with respect to the tube axis has a strong and very non-trivial effect.

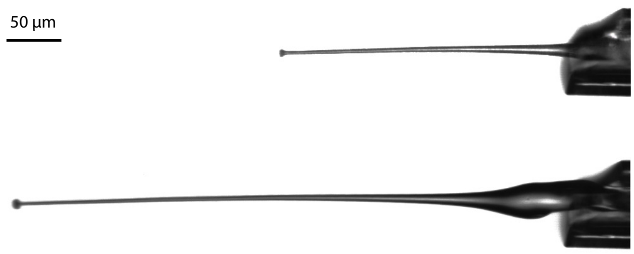

Figure 2. Images of a supersonic microjet generated in a 50 μm capillary tube. The capillary is visible on the right side, the jet tip is shown on the left. The jet travels from right to left with a speed of 490 m/s. Time between images is 500 ns.

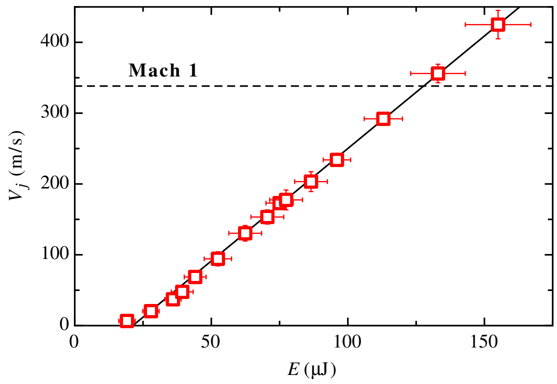

Figure 3. Jet velocities V_j of supersonic microjets as a function of the energy absorbed by the liquid in the capillary tubes with 50 μm inner diameter. Every data point consists of at least five measurements. The line is a linear fit to the data. Even for the supersonic speeds we see that the linear dependence holds.

CONCLUSIONS

The dynamics of the high-speed microjet generated by laser-induced rapid vaporization of water in a micro-tube has been studied. The empirical relationship for the jet velocity shows the effect of the distance between the laser focus and the liquid meniscus at the mouth of the micro-tube, the absorbed laser energy, the liquid-tube contact angle and the tube diameter.It has been shown that the jets so generated are able to reach suprersonic speeds with good controllability [4]. The insights gained through this research and the ability to generate focused, controllable, and high velocity microjets opens new doors for the realization of reliable needle-free drug delivery systems.

References

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