High-speed jetting following shock-wave reflection at planar and curved liquid-gas interfaces

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ABSTRACT
The reflection of a shock wave at a free liquid-gas interface leads to its impulsive acceleration. In general this momentum transfer is not homogeneously distributed over the interface. Possible reasons might be the finite size of the wave front or the curvature of the interface. Under these circumstances a fast liquid jetting phenomena in the direction of shock-wave propagation is found. Here, we study this phenomenon with high-speed photography for a planar interface impacted with a focused shock-wave and for curved liquid-gas interfaces. For the planar interface we observe (i) a fast jet at up to 80 m/s caused by the momentum transfer, and (ii) a slower one which we attribute to the shrinkage of the cavitation cloud generated below the interface. In contrast, curved interfaces lead to approximately two-times faster jets with very narrow jet tips.

INTRODUCTION
The understanding of jet formation due to the reflection of a shockwave at a free liquid-gas interface is important in various situations. For example in damage caused by shockwave induced asymmetric bubble collapse as found in diagnostic ultrasound and lithotripsy [1] or in the possible application of microinjection through sonoporation [2].

Here, the mechanism of jet formation is studied by high-speed photography combined with shadowgraphy for different geometries of the water-air interface [3]. The most fundamental is the ready available planar interface, while curvature is introduced by creating a concave meniscus inside a small diameter glass tube (1.67 mm). For small Bond numbers - that is surface tension dominates gravitational forces - the meniscus resembles a spherical cap. In both cases the focussed lithotripter generated shockwave is almost completely reflected from the interface due to the large mismatch in the acoustic impedance thereby imparting momentum to the interface resulting in jet formation.

SETUP
The high-speed camera used for the planar interface is the Shimadzu HPV-1 (1Mfps) both in a large (fig. 1a) and a small (fig. 1b) field-of-view configuration. The large view of the entire lithotripter basin (13x13x12 cm³) enables visualization of the shockwave reflection by shadowgraphy. To obtain a magnified view of the jet formation at the planar interface a long distance microscope is used (K2, infinity USA). In both setups the surface is lowered onto the focus of the lithotripter shockwave (Piezoson 100, Richard Wolf GmbH.)

For the curved interface the glass tube is aligned to the vertical axis of the path of the shock wave with the concave meniscus positioned on the shockwave focus (fig. 1c). The shockwave and the jet formation are captured with stroboscopic illumination using a frequency doubled Nd:YAG laser pulse of 7 ns duration (SoloPIV, New Wave Research, wavelength 532 nm) fed into a fluorescent cell filled with an ethanol-dye mixture (0.417 mg/ml, LDS 698, Exciton Inc., Dayton, U.S.) and then coupled into a glass fibre to the shockwave generator located on a second table. The fluorescent light allows for speckle free illumination. The light from the other fibre end is mildly diffused with a tissue paper. The images are taken with a CCD single frame camera (Imager 3S, LaVision, Goettingen, Germany) equipped with the long distance microscope (K2, Infinity, U.S.) and a CF3 objective.
RESULTS

Planar interface
Shockwave reflection and the consecutive jet formation take place in different time regimes. The focussing and reflection is a large scale phenomenon and occurs within 40 µs thereby creating a cloud of cavitation bubbles in a millimetre sized region (fig. 2). Some 50 µs after the impact a primary fast and slender jet is observed reaching velocities up to 80 m/s depending on the energy of the incoming shockwave. The collapse of the ensemble of cavitation bubbles some 200 µs after impact coincides with the emerging of a secondary slower and wider jet accompanied by a crown of droplets (fig. 3).
The small field of view reveals the jet formation in more detail (fig. 4). A peak pressure threshold of 60 MPa was found to exist for both types of jets, below which surface tension prevents their formation.

**Curved interface**

The reflection of the shockwave from the concave meniscus are shown to cause a primary jet with velocities up to twice as high for the planar interface depending on its initial curvature and the energy of the shockwave. The curvature is thought to cause the focussing of momentum thereby increasing jet velocity \[4\]. In this confined geometry the cloud of cavitation bubbles also observed below the planar interface takes on a conical shape, however the collapse of which does not cause a secondary jet presumably due to this confinement.

**CONCLUSIONS**

High speed imaging combined with shadowgraphy methods offer a revealing view of the microsecond timescale dynamics of shockwave induced jetting. The initial geometry of the interface is shown to be an important factor causing faster jets through focussing. A secondary slow jet is observed to be caused by the collapse of the cavitation bubble cloud created by the same reflection of the focussed lithotripter shockwave.

**References:**


