Bubble Collapse and Liquid Jet Formation in Non-Newtonian Liquids

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The production of shock waves and liquid jets by cavitation bubbles is a major cause of wear in many fluid mechanical devices that generate high-speed flows, and hence negative pressures in liquids (Trevena, 1987). A study of the effects of polymer additives on lubricant flow in journal bearings indicate that their role in reducing wear may be associated with the mitigating effects of viscoelasticity on cavitation (Berker et al., 1995), but the precise nature of such effects remains unclear. Fluid elasticity might be expected to play a mitigating role in cavitation damage, given its ability to reduce the nonsphericity of cavities in shear fields (Young, 1989): this reduces the tendency for jet formation, as it is the asymmetry of collapse (as a result of a pressure gradient across the cavity) that results in jet formation. Where the pressure gradient arises from the presence of a solid boundary, the resultant jet is directed onto the surface. Jet formation also arises due to cavity collapse under the action of transient pressure pulses, such as shock waves, and this mechanism may lead to the development of liquids jets of enhanced potency, in terms of their ability to damage surfaces. The experiments reported here exploit a new technique that was developed to facilitate studies of the influence of fluid elasticity on this mechanism.

Experimental Studies

Air is introduced into a column of liquid in a vertical cylindrical tube, forming a bubble whose size is chosen such that, after rising through the liquid, it rests beneath the free surface. The tube is forced upward by springs and arrested suddenly and the liquid momentarily continues its upward motion, thereby inducing a pulse of tension that generates cavitation bubbles at the base of the liquid column (Williams et al., 1997). A shock wave, emanating from the collapse of these bubbles, propagates upward through the liquid, to drive the collapse of the air bubble beneath the free surface. This produces a liquid jet. A typical sequence of (sequential) high-speed video images obtained in experiments on a Newtonian solvent (maltose syrup and water mixture) of 0.3-Pa·s shear viscosity is shown in Figure 1 (N.B. the free surface appears as the broad, dark horizontal band, and the objects above the latter are liquid splashes on the tube wall).

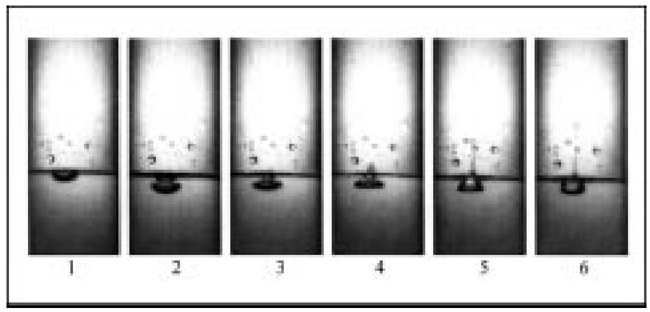

Figure 1. Liquid jet formed by bubble collapse in 0.3-Pa·s Newtonian solvent.

In Figure 1 frames 1 and 2 show the gas bubble expanding (the liquid being under tension). Frame 3 corresponds to the arrival of the shock wave at the lower surface of the bubble, causing it to collapse rapidly. A liquid jet forms, extending rapidly in air in frames 4 to 6.

The driving mechanism involves springs that are attached to a collar about the polycarbonate tube (length 100 cm, internal diameter 2 cm) (see Figure 2). A pair of Kodak EM high-speed video cameras were mounted at and above the free surface, to record the development of the liquid jets at 2,000 frames per second.

Figure 3 gives a further illustration of the phenomenon using images obtained from an ultra-high-speed Imacon image-convertor camera (Hadland, U.K.) in experiments on a multigrade lubricant (Shell ''Helix'' 10W/40). The interframe delay is 1 ms, frame duration (exposure) is 100 μs. In frame 1 the ''sacrificial'' air bubble is close to its maximum size: frame 2 captures the instant of bubble collapse as the shock wave arrives, and the ensuing development of the liquid jet is shown in frames 3−6.

Polymer solutions were made up from a Newtonian solvent consisting of maltose syrup and water, and a high-molecular-weight polyacrylamide (PAA) (Magnafloc E10) at concentrations, c, between 25 ppm and 200 ppm. The shear viscosity, μ, of the solvent (0.3 Pa·s) was measured using a CSL

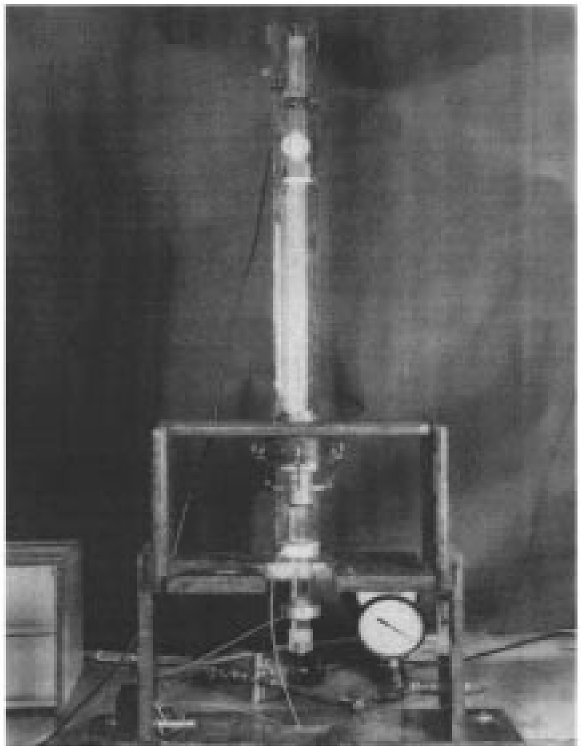

Figure 2. Apparatus with the tube mounted in a wooden vertical frame and supported by springs attached to a collar.

rheometer (TA Instruments, U.K.) fitted with a cone-and-plate measuring geometry. For these solutions, the variation of μ above that of the solvent was negligible. All measurements were conducted at 21°C ($\pm$1°C).

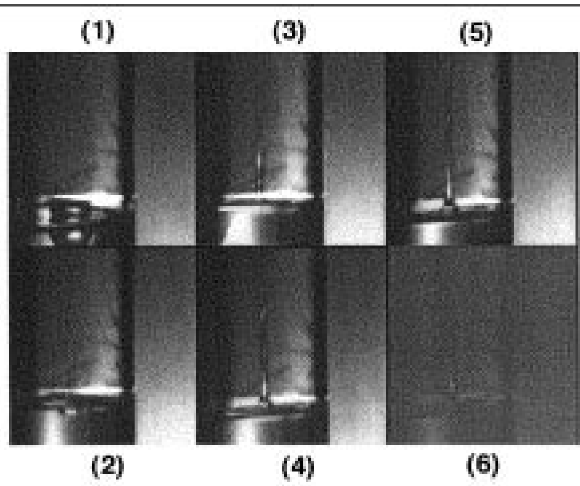

Figure 3. Sequence of images obtained in experiments on a multigrade lubricant using an ultra-high-speed Imacon 468 CCD image convertor camera.

For the sake of comparison between experiments involving viscoelastic solutions and Newtonian solvents, results reported here are taken from experiments involving gas bubbles of approximately the same initial diameter (about 1 cm.), and shock waves incident upon them of approximately the same amplitude (130 bar) and rise time (3 μs).

Results and Discussion

The high-speed video images were used to study the effect of polymer concentration on the length and velocities of the liquid jets formed by bubble collapse in the Newtonian solvents and the viscoelastic solutions. Typical sequences of bubble growth, collapse under the shock wave, and jet development are shown in Figures 4a and 4b for experiments conducted on the 0.3-Pa·s solvent with 25 ppm and 100 ppm of PAA, respectively. In these figures the basic sequence of events is as follows. Immediately prior to the attainment of maximum bubble size and the arrival of the shock wave, a small initial jet is formed: this is seen to penetrate the bubble from the direction of the free surface, a phenomenon that has also been noted in spark-induced cavitation experiments (Chahine, 1977). In the following frames the formation of the ''main'' liquid jet accompanying the bubble's collapse (under the shock wave) is seen.

The mechanism of jet production is progressively affected by the increasing concentration of PAA, resulting in a marked reduction in the length achieved by the jets. The results are summarized in Figure 5, which shows the average jet length achieved in ten separate experiments on the polymer solution and the Newtonian solvent. The height of the symbols indicates the estimated uncertainty in determining the average jet length.

The influence of only 25 ppm of PAA was found to have a marked effect on the length of the jets (see Figure 5): for the solvent the length was about 75 mm, falling to 20 mm for 25 ppm of PAA. Further addition of PAA, up to 100 ppm, caused the jet length to be further reduced, to approximately 10 mm. An increase in PAA concentration up to 200 ppm was found to produce no further significant reduction in jet length.

Cheny and Walters (1996) have reported that the addition of small amounts of polymer to a Newtonian solvent leads to an order-of-magnitude reduction in the length of the so-called ''Worthington jet'' formed when a sphere is dropped into a reservoir of liquid: the effect was ascribed to an increased resistance to ''elongational'' flow, conferred by the polymer; and it is reasonable to assume that the results reported herein may be explained in the same terms. This is supported by the following considerations.

Figure 6 shows the differences in liquid-jet velocity for the 0.3-Pa·s Newtonian solvent and the corresponding solution containing 75 ppm of PAA at different times following the bubble's collapse. The velocities were measured with reference to the tip of the jet. After 2 milliseconds the jet velocity for the PAA solution has decreased by approximately 1 ms^{-1} relative to its Newtonian counterpart. If this higher deceleration is ascribed to the development of enhanced elongational stresses in the viscoelastic filament, then an estimate of the stress magnitude can be made, as follows.

The video images show a maximum bubble diameter prior to the arrival of the shockwave of ca. 1 cm, and the diameter

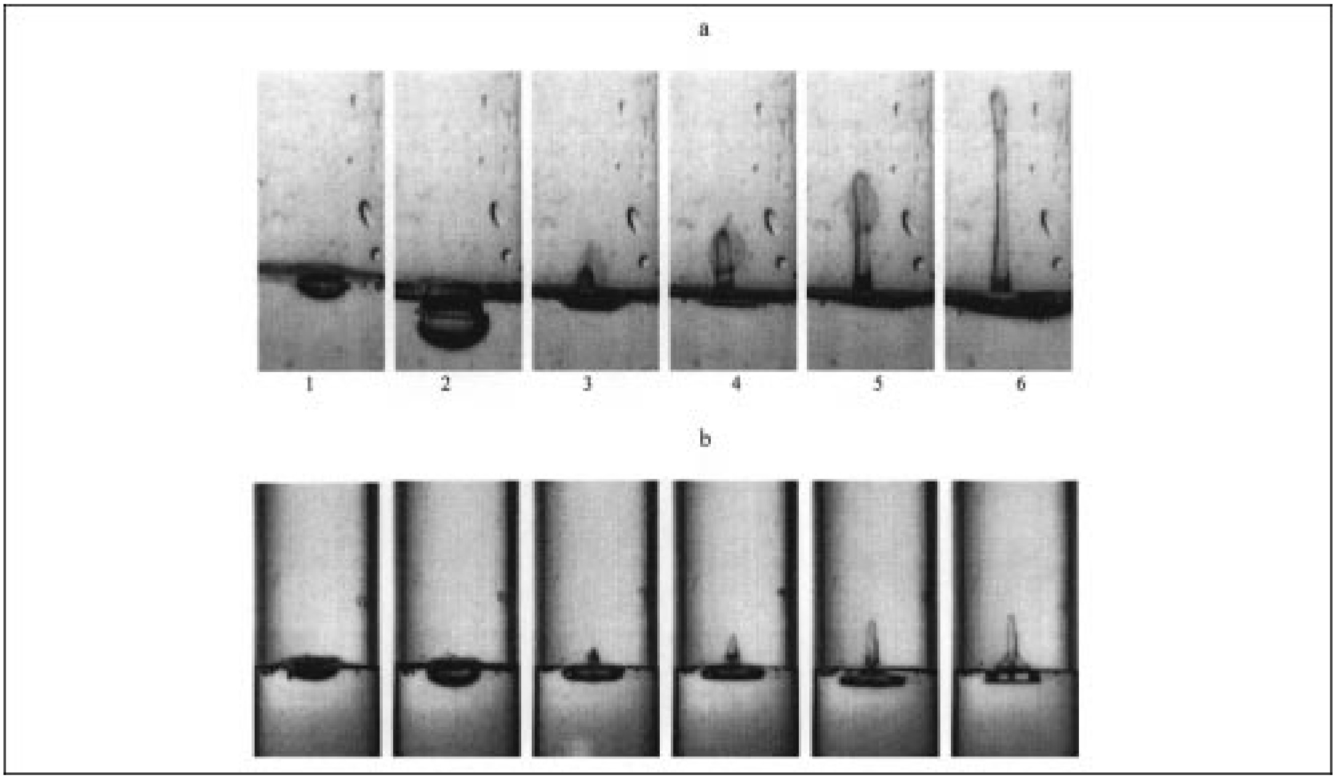

Figure 4. Liquid jet formed by bubble collapse in 0.3-Pa·s Newtonian solvent with: (a) 25 ppm of PAA; (b) 100 ppm of PAA.

of the stretching jet to be approximately 0.5 mm. The liquid density is taken to be 1,000 kg·m^{-3}. Then, for a spherical bubble that is annihilated in 2 ms by the impinging shock wave (as seen in the video images) to form a stretching liquid jet, a simple calculation based on considerations of momentum transfer between the annihilated mass of the bubble and the stretching jet leads to an enhancement to elongational stress, σ_E, of approximately 0.3 MPa being developed in the

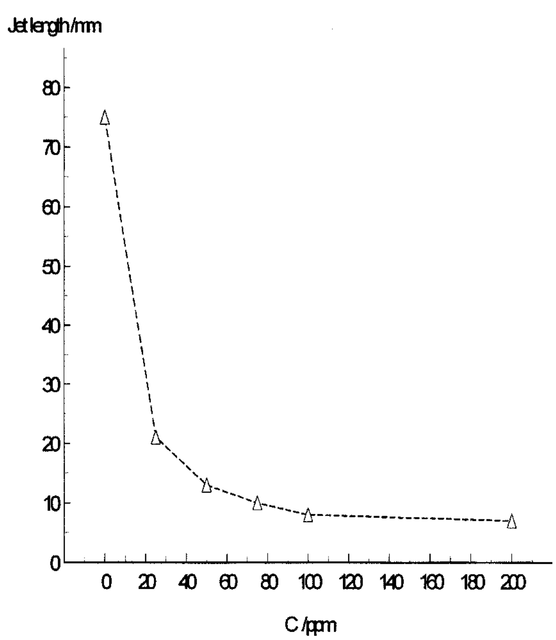

Figure 5. Influence of polymer concentration on jet length for liquid jets formed by bubble collapse in 0.3-Pa·s solutions.

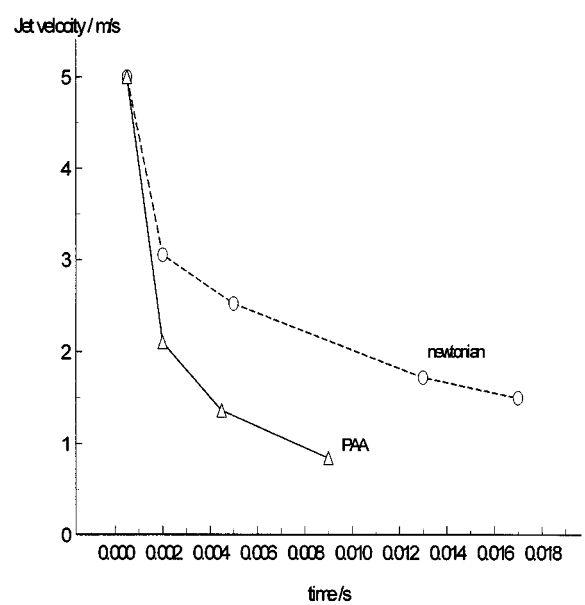

Figure 6. Liquid jet velocity for the 0.3-Pa·s Newtonian solvent and the corresponding solution containing 75 ppm of PAA at different times following the formation of the jet.

jet over this experimental time scale. Knowing the jet velocity, the corresponding rate of uniaxial elongational deformation, $\dot{\epsilon}$, over this time scale may also be estimated, giving a rate of approximately 2,000 s^{-1}. A transient elongational viscosity η_E $(=\sigma_E/\dot{\epsilon})$ may subsequently be defined and compared to μ, the shear viscosity of the Newtonian solvent (0.3 Pa·s). This gives a Trouton ratio, $T_r(=\eta_E/\mu)$ of about 550, indicating a significantly enhanced resistance to elongational flow in the case of the solution, the corresponding value of T_r for a Newtonian liquid being 3.

Concluding Remarks

The technique used in this work offers a simple means for studying liquid-jet production by bubble collapse under cavitation-generated shock waves, and the influence of polymer additives on their development. It is reasonable to conclude that the results can be explained in terms of an increased resistance to elongational flow, which is conferred upon the liquid by the polymer. Insofar as liquid-jet development (in terms of both their length and velocity) is found to be reduced, the results reported here identify a ''mitigating effect'' of viscoelasticity on a mechanism implicated as a major contributing factor in cavitation damage. Further experiments are planned to realize higher jet velocities, in work involving lower viscosity liquids, and vapor-filled cavities in place of the gas-filled bubbles used at present. The results will be communicated in a future paper.

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Manuscript received Sept. 8, 1998, and revision received July 9, 1999.