Atomization of thin films and fluid sheets of viscoelastic fluids

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In this talk we report on the experimental observations of the flow kinematics and stability of thin fluid sheets produced by a series of commercially available flat-fan and hollow-cone spray nozzles for a series of viscoelastic wormlike micelle solutions. The structure, kinematics and stability of thin films has been well studied both experimentally and analytically throughout the literature for Newtonian fluids. However, despite the importance of these fluids and flows to a host of commercial and industrial applications such as agrochemical spraying, spray coating, and inkjet printing, little work has been done to study the break-up of thin films of viscoelastic fluids.

The viscoelastic wormlike micelle solutions used in these experiments were produced by mixing a surfactant, CTAB, and salt, NaSal, in water at a series of different concentrations to vary the viscoelasticity of the fluids. As the flow rate through the nozzles was increased, the viscoelastic fluid sheets were found to grow larger; eventually become unstable, and atomizing into drops. For the flat-fan spray-nozzles, Newtonian water sheets were found to first destabilize along the fluid rim. The addition of viscoelasticity was found to stabilize the rim while simultaneously destabilizing the fluid sheet. The internal rims produced by multiple rupture eventually collide within the fluid sheet to produce a complicated highly interconnected structure which is similar to the ‘fluid webs’ observed for impinging jets as seen in Figure 1. Increasing the viscoelasticity of the test fluid was found to stabilize the thin films produced by both the flat-fan and hollow-cone spray nozzles. However, even though viscoelasticity was found to forestall the breakup of these fluid sheets to larger flow rates once the flow rate was increased beyond the critical flow rate for sheet rupture, increasing the fluid elasticity was found to enhance the atomization of the viscoelastic fluid sheets by increasing the number and growth rate of holes in the sheet while simultaneously reducing the initiation time for sheet rupture. Although drop size distribution measurements were not possible in these experiments, based on the increasing size of the interconnecting fluid filaments within the ruptured sheet

Figure 1: High speed photographs of the fluid sheets formed by impinging jets of 25mM CTAB/NaSal at 6.2m/s.

one would expect an increase in the final atomized drop size with increasing elasticity.

The transitions from jetting to complete atomization of the hollow cone are shown in Figure 2 for the 10mM CTAB/NaSal wormlike micelle solution for a series of increasing flow rates. Many of the flow transitions observed in Figure 2 are observed for both water and the viscoelastic wormlike micelle solutions, however, the previously unobserved flow phenomena seen in Figure 2c and d are clearly a direct result of the fluid elasticity. At low flow rates, a rotating fluid jet is produced from the hollow-cone nozzle; see Figure 2a. As the flow rate and subsequently the rotation rate of the jet are increased, the jet transitions from a circular cross-section to a much flatter cross-section taking on a twisted ribbon-like appearance; see Figure 2b. As the rotation rate is increased further, the edges of the ribbon are destabilized, fingers grow and are ejected outward by the fluid inertia; see Figure 2c. The length of the fingers grow with increasing flow rate and because of the large extensional viscosity of the wormlike micelle solutions, they remain remarkably coherent forming intricate structures resembling ‘fluid trees’; see Figure 2d. Close inspection of the ‘fluid trees’ near the nozzle exit in Figure 2d shows the early formation of the hollow-cone. With further increase in the flow rate the fluid trees gradually transition into a partial cone; see Figure 2e. This partial cone eventually closes in upon itself forming a stable, closed hollow cone; see Figure 2f. The stable closed cone is observed only for water and the lowest concentration wormlike micelle solution. Additionally, the stable closed cone was observed over a very small range of flow rates, eventually becoming unstable and atomizing with increasing flow rate; see Figure 2g. Even with this rich structural evolution, our experiments clearly demonstrate that the hollow-cone nozzles are much more efficient at atomizing viscoelastic fluids.

Given time we will also present our recent work into the impact dynamics of drops on thin films of a viscoelastic wormlike micelle solutions. The composition and thickness of the thin film is modified to investigate the effect of fluid rheology on the evolution of crown growth, the formation of satellite droplets and the formation of the Worthington jet. The addition of elasticity to the thin film fluid is found to suppress the crown growth and the formation of satellite drops with the largest effects observed at small film thicknesses. A new form of the splashing threshold is postulated which accounts for the effects of viscoelasticity and collapses the satellite droplet data onto a single master curve dependent only on dimensionless film thickness. Additionally, a plateau is observed in the growth of the maximum height of the Worthington jet height with increasing impact velocity. It is postulated that the complex behavior of the Worthington jet growth is the result of a dissipative mechanism stemming from the scission of wormlike micelles.

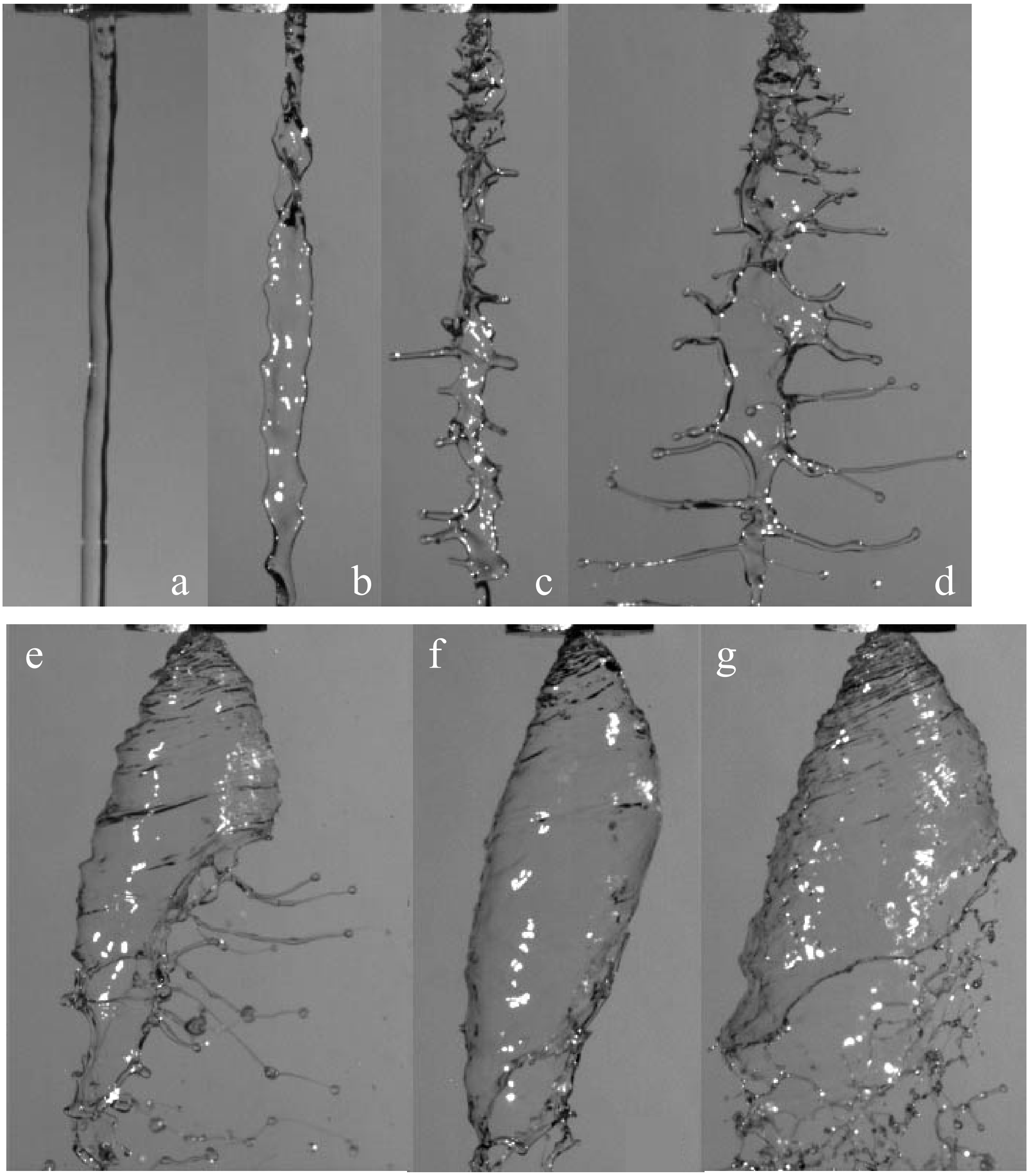

Figure 2: The effects of flow rate increase on fluid sheet break-up are shown for 10mM CTAB/NaSal for volume flow rates of a) 1.9×10^{-6} m^3/s, b) 2.4×10^{-6} m^3/s, c) 2.7×10^{-6} m^3/s, d) 2.8×10^{-6} m^3/s, e) 2.9×10^{-6} m^3/s, f) 3.1×10^{-6} m^3/s, and g) 3.6×10^{-6} m^3/s from a hollow-cone nozzle.