

An Experimental Investigation of Surfactant-Laden non-Newtonian Jet Breakup

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Abstract

The combined effect of polymers and soluble surfactants on the dynamics of jet breakup, and especially on satellite drop formation, was experimentally investigated. Xanthan gum and Carbopol 934 NF were dissolved in water with Sodium Dodecyl Sulfate as the surfactant. Controlled disturbances were imposed on the laminar jet interface using a piezoelectric vibrating nozzle, and breakup dynamics were recorded using a high-speed camera. Drop and ligament diameters were measured from the digital images. Our focus was on how bulk and interfacial properties of the prepared liquids influenced ligament and drop evolution. It was found that if the proper concentration of surfactant is selected, and if the flow time scales are large enough, Marangoni interfacial stresses develop and lead to an increase in satellite drop size. It was also confirmed that the introduction of surfactant contributes to a delay in jet breakup.

Introduction

Breakup of liquid jets has been a subject of fundamental importance in the optimization and control of industrial spray processes or agricultural processes. These processes often involve complex liquid formulations containing polymers and/or surface active agents (surfactants). Numerous scientists have studied Newtonian capillary jet breakup and an extensive review of the subject was recently written [1]. However, the behavior of non-Newtonian and/or surfactant covered jets are still developing fields. To date non-Newtonian jets were studied experimentally by means of imaging technique such as stroboscopy or high-speed imaging [2, 3], or theoretically by mean of linear stability studies [4], one-dimensional analyses [5, 6], or direct numerical simulations [6, 7]. Key findings are that viscoelastic jets have a tendency to be less stable than Newtonian jets under the same operating conditions, and that instability waves grow faster on weakly viscoelastic jets resulting in shorter breakup lengths. Numerical solutions show the limitations arising from linear analyses: non-Newtonian jet breakup is a highly nonlinear phenomenon that cannot be accurately described by linearized equations.

Recently the presence of insoluble surfactant was found to damp the growth rate of interfacial waves because of Marangoni stresses that arise from surfactant concentration gradients [8, 9]. These interfacial stresses lead to reduction of the satellite drop size produced by a Newtonian jet [10], but to an increase in satellite size when added to a shear-thinning jet [11], or when using a large concentration of soluble surfactant [12]. The focus of this study is on how the combination of non-Newtonian rheological and surfactant affects filament/drop evolution.

Materials and Methods

The fluids to be sprayed are first routed through a gear pump (Micropump) and then into a piezoelectric driven nozzle (Model LHG-01) with a 100 μm radius exit orifice (a). Jet breakup is recorded using a high-speed video camera (Phantom V7.1, Vision Research). Proper illumination was achieved by shining a 500 W halogen lamp whose beam was passed through a water container (for IR absorption) before being coupled to an optical diffuser. Room temperature was measured to be $22.5 \pm 0.5^\circ\text{C}$. Shear-thinning liquids were prepared by adding Xanthan gum (XG; CP Kelco) powder or Carbopol[®] 934 NF (Lubrizol) powder to de-ionized (DI) water. NaCl was then added to the water-XG solution and NaOH was used to neutralize Carbopol[®]-based solutions. The effect of surfactant addition on the breakup process was investigated using SDS (Sodium Dodecyl Sulfate, SigmaUltra) in concentrations of 0.1, 0.2 and 0.3%. Rheological properties were measured on an ARG2 rotational rheometer (TA instruments) with a 60 mm diameter-2° cone. Elongational and interfacial shear viscosities were

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also estimated. A wave (square or sine) with wavenumber $ka = 2\pi a/\lambda$ and voltage amplitude $V = \pm 200V$ was supplied to the piezo electric nozzle, λ is the wavelength [m]. The type of wave employed was dependent on the polymer. Reynolds numbers (Re_0) were calculated based on zero-shear viscosity.

Results and Discussion

Surfactant addition is found to delay breakup for all concentrations, because its addition decreases the average surface tension and therefore reduces the growth rate of the interfacial capillary wave. Adding surfactant in excess, however, yields no additional increase in breakup time. This is explained by the fact that the interface is saturated with micelles and the surface concentration of surfactant no longer increases, leading to a constant breakup length. In addition, it is found that the largest XG satellites are obtained for a concentration of 0.1% SDS [Fig. 1.a], a finding that is easily explained if ones consider Marangoni stresses. In the case of low concentration, there is not enough surfactant to create a sufficiently steep interfacial concentration gradient. In the case of an intermediate concentration, there are enough surfactant micelles to create an interfacial gradient strong enough to produce a Marangoni stress that will in turn increase satellite drop size. Finally, surfactant in large concentration prevents formation of an interfacial gradient. Also the satellite drop size difference between 0.1 and 0% SDS is more significant at large wavenumber (100% increase at $ka \sim 0.7$)—at short wavelength (large ka), the gradient becomes large enough to influence satellite size. In the case of Carbopol®, no significant effect of SDS on the satellite drop is observed [Fig 1.b]. This is related to the adsorption time of SDS compared to the breakup time of Carbopol® jets—there isn't enough time for all the surfactant to be adsorbed at the interface. This observation can also be explained by the enhancement of the satellite in the presence of surfactant being more pronounced for strong shear-thinning liquids (XG) [11].

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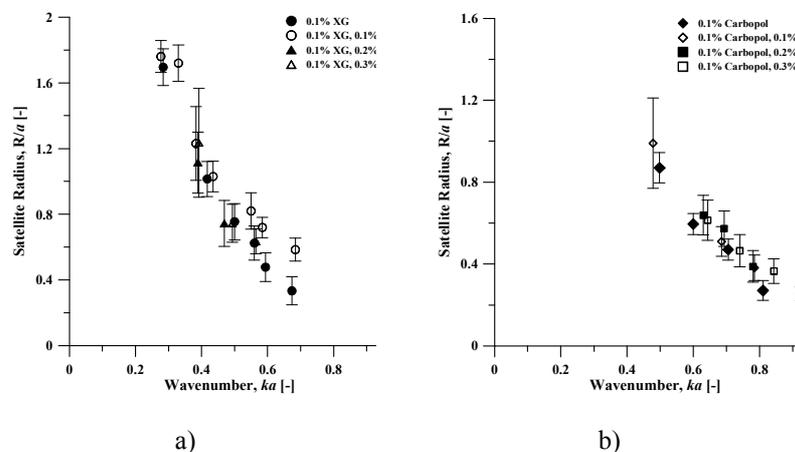


Figure 1: Dimensionless satellite radius R/a versus dimensionless wavenumber ka for a) XG-based solutions and b) Carbopol®-based solutions ($Re_0 \sim 4$)