Journal of Non-Newtonian Fluid Mechanics 213 (2014) 57–67

Contents lists available at ScienceDirect

Journal of Non-Newtonian Fluid Mechanics

journal homepage: http://www.elsevier.com/locate/jnnfm

Dispensing of rheologically complex fluids at the dripping regime

Hyejin Han, Chongyoup Kim *

Department of Chemical and Biological Engineering, Korea University, Anam-dong, Sungbuk-ku, Seoul 136-713, Republic of Korea

ARTICLE INFO

Article history:
Received 13 September 2013
Received in revised form 25 August 2014
Accepted 28 August 2014
Available online 8 October 2014

Keywords:
Drop size
Filament breakup
Dripping mechanism
Transient elongational viscosity
Strain hardening

ABSTRACT

Dispensing characteristics of rheologically complex fluids are investigated experimentally at the dripping regime. Two mixtures of ethylene glycol and glycerin (50:50 and 31:69) were used as base Newtonian fluids. As the polymer solution, 1000 ppm of polyacrylamide of 5–6M g/mol was added to the 50:50 base Newtonian fluid. 2.5, 5 or 7.5 vol% of polystyrene particles of 2 μm in diameter were added to the liquids to prepare particle suspensions. The liquids were dispensed to the air by using a nozzle with the inner and outer diameters of 0.61 and 0.91 mm, respectively. It was found that the drop size is primarily determined by the balance of drop weight and surface tension force holding the drop, and hence drop size does not depend on volume flow rate. The drop diameter is approximately 10% smaller for elastic liquids due to the severe extension of the filament before the detachment from the nozzle. The result also shows that the dripping characteristics of the fluids without the polymer are mainly determined by the balance of the gravity force, surface tension force holding the liquid volume and pressure force. The addition of less than approximately 10% of 2 μm spherical particles hardly changes the dispensing characteristics of Newtonian fluids except at the final stage of detachment. For polymeric liquids, the transient extensional property drastically changes the dripping dynamics. The force balance shows that the strain hardening of the polyacrylamide solution under the extensional flow causes severe retardation of the filament breakup. The filament breakup of the polymeric suspension is further decelerated by the increase in zero shear viscosity as a result of the particle addition.

1. Introduction

Dispensing is one of the techniques of supplying a volume of liquid to the air or another liquid and is widely used in food, pharmaceutical and electronics-manufacturing industries [1–3]. In these industries, dispensed fluids can be suspensions of micrometer-sized particles. In the manufacturing of phosphor-based white LEDs (light emitting diodes), for example, a dilute suspension of phosphor particles of a few micrometers is dispensed and coated over the blue-light emitting semiconductor [4]. In pharmaceutics, dispensing is used in packaging for ensuring uniformity of mass and content of capsules. When the contents of pharmaceutical capsules are particles, their sizes should be of primary importance in rate and extent of dissolution, and for the ingredients with low dissolution rate, micrometer scale particles can be effective [5,6]. In food engineering, starch particles have micrometer scales [7]. Even though the suspension used in the industry is usually non-Newtonian due to the particles and additives such as surfactants and binders, the physics of the dispensing process of those suspensions is not fully understood yet and hence many of the dispensing processes are operated on trial-and-error basis.

The flow of dispensed fluid is characterized into two different regimes. At a low dispensing rate, drops are detached from the nozzle one by one, and this is called dripping regime. In contrast, a continuous jet is formed from the nozzle at a high flow rate, and this is called jetting regime. The dripping regime is the interest of this paper. During the dripping process, fluid flows out of a nozzle while forming a liquid bulb. When the liquid bulb reaches a critical volume, the gravity force acting on the hanging bulb begins to exceed the surface tension force holding the bulb under the nozzle, and the bulb falls down after rapid thinning of the liquid column or neck between the liquid bulb and the nozzle. As the neck thins rapidly, a uniaxial deformation becomes dominant in the dripping process and the rheological properties of the liquid strongly affect the thinning characteristics since extension rate becomes large. Despite the complex nature of drop formation, dripping is widely used in industrial processes as stated above. When complex fluids with a moderate level of viscoelasticity are dispensed, the physics of the dripping process becomes more complicated due to the combined effects of material properties and the inertia since there is no dominant variable to govern the dripping

* Corresponding author. Tel.: +82 2 3290 3302.
E-mail address: cykim@grtrkr.korea.ac.kr (C. Kim).

http://dx.doi.org/10.1016/j.jnnfm.2014.08.019
0377-0257/

dynamics. As efforts to understand the dripping dynamics, diverse researches on drop formation of Newtonian fluids, viscoelastic fluids, and Newtonian fluids containing spherical particles have been carried out. In this work, we will try to extend this knowledge to dripping dynamics of the suspension of micrometer scale particles in the viscoelastic liquid with a moderate level of viscoelasticity.

The studies on the formation of drop in the ambient air from a nozzle have been carried out by many researchers beginning the works in the 1800's on the jet instability of Newtonian fluid [8–10]. A number of similarity solutions of capillary force driven decay and breakup of a Newtonian liquid filament have been studied [11–15] and reviewed in Eggers [15]. Extending the knowledge of the capillary breakup of the Newtonian jet, the dripping process of Newtonian fluid has been also studied [16–18]. In these studies, the linear decrease of filament diameter is observed for Newtonian fluids as predicted in the theoretical studies [11–15]. Especially, Clanet and Lasheras [19] investigated the critical Weber number for the dripping/jetting transition of Newtonian fluids considering the effects of gravity, inertia, and surface tension in the axial direction by mathematical modeling.

Beginning from the observation of severe retardation of a viscoelastic jet breakup in the 1960's [20], the breakup of the viscoelastic filament has been investigated experimentally and numerically [21–27]. These studies are reviewed in Renardy [27]. In addition to the jet breakup analysis, the thinning dynamics of viscoelastic filaments have been studied [28–30] and reviewed [30]. In these works [28–30], various stages of the thinning process due to the transient extensional properties and the finite extensibility of the polymer chain are considered. Especially the exponential decay of viscoelastic fluid is observed during the thinning stage for sufficiently extended polymer chains. Here we should note that the filament thinning characteristics alone cannot explain the whole dispensing process and the dispensing can be characterized only partially by the filament stretching characteristics even in the case of highly viscoelastic materials. The knowledge of the viscoelastic filament thinning has been extended to the dripping dynamics of viscoelastic fluids [1,31]. Cooper-White et al. [31] investigated the dynamics of drop formation of constant low-viscosity, elastic fluids, and rationalized the dripping characteristics based on Chang et al.'s [29] discussion on the effects of the filament recoil, iterated stretch and so on. Tirtaatmadja et al. [32] extended the study on drop formation dynamics of viscoelastic fluids by systematically probing the effects of polymer molecular weight and concentration when the inertial and elastic stresses are dominant. Keiller [33] performed a theoretical analysis on the stretching of the filament during dispensing of the Boger fluid assuming the Oldroyd B model and compared with the experimental data by Jones et al. [34]. Recently, Clasen et al. [1] investigated the operational conditions of dispensing process for diverse fluids by using six non-dimensional numbers, and discussed the different stages of the dripping process of Boger fluids.

To investigate the roles of rheological properties on the dripping dynamics of viscoelastic fluid, it is important to understand the transient extensional properties of the viscoelastic fluid. In extensional flows, the transient properties develop as the coiled configuration of the polymer molecules transforms to the stretched conformation due to the elongation of the fluid filament. When the polymer chains are stretched, the extensional viscosity of the fluid increases reflecting the elasticity of the polymer chains. Noting that a large extensional deformation occurs during the dripping process, dripping dynamics of viscoelastic fluids have been studied to estimate the transient extensional properties [34–36]. To estimate the transient extensional properties of the viscoelastic fluids, Jones et al. [34] used pendant drop dynamics, and Szabo [35] and Szabo et al. [36] used the filament stretching process by a constant weight. The changes in accelerations and directions of the movements of the fluid elements were correlated with the extensional stresses.

The effect of dispersed particles on dispensing also has been of interest to many researchers [37–41] because fluids containing solid particles are often subjected in many dispensing industries. Furbank and Morris [37,38] studied various dispensing phenomena related to particles of a few hundreds micrometers dispersed in a viscous liquid, and observed the rapid drop detachment due to the particle rearrangement in the fluid thread. The rapid breakup of particle suspensions has been confirmed by many researchers [39–41].

Despite the previous studies and the importance of particle suspensions in viscoelastic liquids in industrial applications such as LED manufacturing, a comprehensive understanding of influences of the added polymers and/or particles, especially of moderate viscoelastic properties and of micron-sized particles dispersed in the viscoelastic fluids, on dispensing process has been lacking. Also, the studies on dispensing of viscoelastic fluids have been focused mainly on filament stretching characteristics as in Keiller [33] and Jones et al. [34]. In the present study we will seek a deeper understanding of the whole dispensing processes of viscoelastic fluids and suspensions in viscoelastic fluid as well. To do so, spherical particles of a few micrometers are dispersed in Newtonian and viscoelastic fluids and the effects of the added particles on dripping dynamics are studied. This article begins with characterizations of different kinds of model fluids subjected in this study, i.e. Newtonian and polymeric base fluids and particle suspensions in those base fluids. We then describe the experimental apparatus and procedure. In the following section, results of dispensing of the fluids and the dripping characteristics are discussed. Next, the drop size analysis and the thinning profile analysis conducted by image processing are addressed. Lastly, the axial force balance analysis and the roles of the various factors on dripping processes are discussed in detail.

2. Experimental

2.1. Materials and equipment

Two different mixtures (NF1 and NF2: The sample names are listed in Table 1) of ethylene glycol (Junsei Chem. Co.) and glycerin (Junsei Chem. Co.) by volume were prepared and used as base Newtonian solvents. A viscoelastic liquid (PF) was prepared by dissolving polyacrylamide (PAAm, Sigma-Aldrich Co., molecular weight of 5–6M Dalton) in one of the base Newtonian solvents (NF1) at a concentration of 1000 ppm. Spherical particles of polystyrene (PS particles) were synthesized by the dispersion polymerization method [42] and dispersed directly in the Newtonian or the viscoelastic base fluids. Particle volume fraction (ϕ) was 0.025, 0.05 and 0.075. The size of PS particles was in the range of 2.03–2.05 μm, hence they were practically mono-disperse. Table 1 shows the sample identification, composition and some physical properties used in this study.

Fluids were dispensed to the ambient air at room temperature (23–26 °C) through a circular stainless steel nozzle (Nordson EFD, West-lake, OH). The inner and outer diameters were 0.61 mm and 0.91 mm, respectively. The nozzle was connected to a syringe pump (PhD 2200, Harvard Apparatus) by using a plastic tube. The motion of fluid exiting the nozzle was observed and recorded by using a high speed CMOS sensor (Mikrotron, EoSENSE MC1362 and Phantom V7.3) accompanied with a Nikon lens (50 mm). Various extension tubes were used to optimize the qualities of the images. The pixel resolution was between 12 and 20 μm/pixel. Frame rate was varied between 600 and 800 frames per second depending on liquids. To observe the elongation of the thin fila-