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Drop formation from a capillary tube: Comparison of different bulk fluid on Newtonian drops and formation of Newtonian and non-Newtonian drops in air using image processing

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ABSTRACT

The formation of water drops as a Newtonian fluid and formation of a shear-thinning non-Newtonian fluid, Carboxyl Methyl Cellulose (CMC) from a capillary into different bulk fluids are experimentally investigated. A high speed camera is used to visualize the images of the drops and an image-processing code employed to determine the drop properties from each image. It was found that the properties of the water drops when they are drooped into the liquids bulk fluids such as toluene and n-hexane are almost the same while they differed substantially when they were drooped into the air bulk fluid. It is shown that during the formation of water drop in all three kinds of bulk fluids, the drop forms from the inner diameter of the needle and it moves toward the outer diameter. In addition, the properties of a low-concentration CMC in the air was almost identical to the properties of water drops, however the high-concentration CMC shows significant variations as compared to the both low-concentration CMC and water drops.

1. Introduction

Mechanisms of drop formation have been subject of extensive studies for more than 100 years. A review by Eggers [1] cites more than 250 references, with the earliest dating back to 1600s. Although the wonderful nature of drop formation might have contributed to the earliest works, there is no doubt that its widespread application has great potential for the continuation of studies thus far. This process plays a significant role in industrial applications such as spray dying, spray cooling, combustion processes, ink-jet printing, cooling of energy storage systems, etc [2–5]. In addition, the processes in which a drop moves through a continuous phase such as liquid-liquid extraction for mass transfer and direct-contact heat exchangers for heat transfer are widely used in industries [6,7]. Optimization of these processes as well as the hope for designing new ones have made this field open to researchers. Understanding the mechanisms of drop formation is a key factor in achieving this purpose. Depending on the flow rate of the fluid, drops are formed either pendantly (the so-called dripping mode), by jetting, or by atomization [8]. This piece of research deals with pendant drops.

Earlier studies in this field aimed at predicting the drop volume at low flow rates in terms of fluid properties, flow rate and nozzle geometry by using the force balance analysis. The results of a study by Hayworth and Treybal [9] revealed that by increasing in fluid velocity through the nozzle, the drop radius uniformly increases at low flow rates. Similarly, they found out that an increase in the nozzle diameter and surface tension leads to increase in drop diameter. Furthermore, they presented a simplified equation from force balance, which predicts the drop volume. Later two-stage models were adopted to predict the drop volume during its formation from the tip of a capillary. The first stage is the drop growth, which is static, and the second is drop detachment, which is considered dynamic. The prediction made by these methods showed up to 20 percent deviation from the experimental results [10,11].

In addition to earlier experimental-theoretical works, some researchers aimed at finding dynamic theories for drop formation. Pimbley and Lee [12] provided one-dimensional axisymmetric equations for inviscid flows. Schulkes [13] introduced some modifications to Lee's work to make it more accurate. However, major breakthrough took place after Eggers, Dupont [14] and Papageorgiou [15] presented their models. They derived a one-dimensional equation for velocity and radius of the drop from Navier-Stokes equations, showing singularities at the pinch-off. Studies by Ambravaneswaran et al. [16] revealed that the

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Nomenclature

Bo	Bond number
d	diameter, m
$d_{capillary}$	wetted diameter, m
eff	effective
F_B	buoyancy force, N
F_D	drag force, N
F_K	inertial force, N
F_σ	interfacial tension force, N
g	gravitational acceleration, m s^{-2}
Q	flow rate of the dispersed phase, m^3 s^{-1}
r	drop radius, m
u_{drop}	velocity of the growing drop, m s^{-1}
u_d	dispersed phase velocity, m s^{-1}
ρ_d	density of the dispersed phase, kg m^{-3}
$\Delta\rho$	density difference, kg m^{-3}
η_c	continuous phase viscosities, m^2 s^{-1}
η_d	dispersed phase viscosity, m^2 s^{-1}
θ	contact angle, deg
σ	surface tension, N m^{-1}

one-dimensional models are useful for flows in which surface tension dominates. Zhongcheng Pan et al. [17] studied droplet formation in granular suspensions by systematically varying the volume fractions and particle diameters. Yang et al. [18] worked on the oscillations of free-falling drops to measure the transient shear viscosity and the dynamic surface tension of shear-thinning fluids. Also, the dynamic behavior of liquid-droplet spreading via capillary action in a vertically aligned carbon nanotube array has been investigated experimentally and theoretically by Huang et al. [19].

By increasing in computational potential, more studies focused on numerical simulation of the drop formation process. Schulkes [7] investigated the dynamics of drop formation in an inviscid and irrotational flow using a two-dimensional axisymmetric model. He was able to predict the mechanisms of post-bifurcation (pinch-off) phenomena such as fluid thread vortex and formation of satellite drops. Richards et al. [20] investigated drop formation in pendant drop and jetting modes by numerically simulating a time-dependent axisymmetric equations using combination of volume-of-fluid (VOF) and continuous-surface-mode (CSM) methods. Other similar studies are conducted by Wilkes et al. [21], Zhang and Stone [22], Chen et al. [23] and Fawehimni et al. [24].

Despite the rich history of studies on drop formation, experimental research has a relatively more recent history as it is highly dependent of new technologies such as high-speed cameras. The images provided by Hauser et al. [25] may be the first valuable work demonstrating the complexities of drop formation phenomenon. About half a decade later, the studies of Peregrine et al. [26] were a milestone in experimental research. Using the image processing, they were able to investigate the various phenomena regarding droplet formation such as necking, bifurcation of the initial drop, vortex of the fluid due to capillary pressure and satellite drops. In this regard, Shi et al. [27] conducted experiments, which revealed that by an increase in viscosity, liquid thread length would increase. The results also reflected that one thread can break down to several other threads. Later, Zhang and Basaran [28] examined experimentally the dynamics of drop formation in ambient air in low flow rate by an 80 fps camera. Wang et al. [29] used high speed cameras to investigate the formation of a drop in low flow rates. They measured various parameters such as contact angle, drop height, length of the neck, and wetted diameter. They divided the drop formation mechanism into four stages according to the contact angle evolution. They also demonstrated the balance of forces on the drop during the growth stage. Computational analyses and the experiments using high-speed cameras made it possible to investigate the drop formation in non-Newtonian fluids for which theoretical models are difficult to obtain due to their complex flow behavior [30]. Amarouchene et al. [31] examined experimentally the effects of addition of a type of polymer to water droplets. Later, VOF numerical method was adopted by Davidson et al. [32] to predict the behavior of a shear-thinning drop from a capillary tube. The studies of Furbank and Morris [33,34] focused on the formation of drops of particulate suspension composed of spherical, neutrally buoyant, non-colloidal particles in a viscous fluid. Aminzadeh et al. [35] conducted a study comparing the features of Newtonian and non-Newtonian drops in two bulk fluids, namely air and water. They focused on droplet size oscillations and found that the frequency of a drop size during falling or rising varies with drop properties. They also found out that the effects of addition of non-Newtonian properties is much more salient in air than the water. Aytouna et al. [36] investigated the pinch-off dynamics of drops of yield stress and shear-thinning fluids.

To implement the processes in which non-Newtonian fluids are involved, it is necessary to have an in-depth understanding of the behavior of Newtonian and non-Newtonian fluids. This study is intended to draw a comparison between Newtonian and non-Newtonian fluids through finding the behavioral pattern in drops of Newtonian and non-Newtonian fluids. This study consists of three sections. In the 1st section, three separate experiments have been conducted in which water droplets are dispersed into three different fluids—n-hexane, toluene, and, air. The aim of this section is to make a comparison between various bulk fluids using the same dispersed fluid. In 2nd section, it is attempted to obtain the length of the wetted diameter at different moments of drop formation using the parameters obtained at the first section for the water drop in toluene bulk fluid through the balancing of surface tension and buoyancy forces. In the third section, water, 0.5% Carboxyl Methyl Cellulose (CMC) solution and 1% CMC (based on mass) solution in water are dispersed in air. The purpose of 3rd section is to make a comparison between drop formation behavior in Newtonian and non-Newtonian fluids. Using image processing, two parameters of contact angle and drop length are computed and their time evolutions are plotted and compared.

2. Experimental setup and procedure

An AG high speed camera which is capable of capturing 1000 images per second with a resolution of 800 × 600 is employed in this experiment. Each pixel of the camera covers an area of approximately 0.0135 mm^2. A 1000 W projector is used for illumination. Fig. 1 schematically shows the apparatus used for the experiments for which air, toluene and n-hexane are the bulk fluid; these experiments include dispersion of water in air, toluene and n-hexane. In addition, dispersion of water, 0.5% CMC solution and 1% CMC solution in air are investigated. As it is evident from the figure, the drops were released from a needle attached to a buret. The DIN 12,700 buret equipped with a valve is used to control the flow rate of the falling drops. Furthermore, it creates a stationary setup during the capturing, which is essential in image processing. A hypodermic needle, Ichikawa Co No. 14, with inner and outer diameters of 1.8 and 2 mm, is tightly fitted to the end of the buret.