Deformation and Break-up of a Drop in Contraction Flow

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Abstract

Drop deformation in a cylindrical contraction geometry, characterized here by the formation of a thread of drop fluid in the contraction, is predicted using a Volume-of-Fluid numerical technique. The predicted drop shape is found to closely follow the observed deformation. A capillary instability in the developing drop thread in the contraction was predicted, in agreement with experimental observation.

Keyword: *contraction flow, drop deformation, numerical method, Volume-of-Fluid*

1. Introduction

An understanding of the deformation and breakup of a liquid drop within another liquid is important for the production of oil-water emulsions. Contraction flows can deform drops by significantly increasing the velocity gradients experienced by a drop. Although drop deformation in simple steady shear or extensional flow has been extensively studied (e.g. [1-2]) and remains a subject of considerable interest [3], contraction flow is not purely shear or extensional. Instead a drop will experience a non-steady combination of shear and extensional flow (laminar or turbulent) as it moves through the device [4-5].

Recently, Whyte et al. [6] reported preliminary experiments and numerical simulations of deformation of a drop passing through a contraction and expansion. The simulations were performed using a Volume-of-Fluid (VOF) finite difference technique due to Rudman [7]. The authors obtained qualitative agreement between predicted and observed deformation of a drop in water, which featured the entry of the drop as an extended thread into the contraction. The aim of the present paper is to extend the work of Whyte et al. [6] by relaxing some model assumptions that are incompatible with the experimental conditions.

2. Problem Definition

The experimental contraction-expansion geometry analysed consists of two vertical pipes, each 12 mm in diameter (radius R = 6 mm) and 180 mm in length, connected by a capillary of diameter 3 mm and length 45 mm. Water is pumped downwards through the device at a uniform flow rate, and an oil drop (nominally with diameter d = 6 mm) is injected at the upstream end. The subsequent motion of the drop through the contraction-expansion was recorded with a high speed camera. The oil/water density ratio $\rho_o/\rho_w = 0.93$ and viscosity ratio $\mu_o/\mu_w = 10$. For the flow considered, the Reynolds number $\mathrm{Re} = \rho_w \overline{U} R/\mu_w = 500$, Weber number $\mathrm{We} = \rho_w \overline{U}^2 R/\sigma = 1.04$, and Froude number $\mathrm{Fr} = \overline{U}/\sqrt{gR} = 0.35$ where $\overline{U}$ denotes the mean water velocity at the inlet and σ denotes the oil-water interfacial tension.

To reduce calculation time, Whyte et al. [6] used a substantially truncated computational domain in which the drop was released close to the contraction. However, in practice the drop is inserted near the inlet pipe entry and will develop a steady shape, slip velocity, and internal recirculation as it traverses the length of the inlet pipe. In this paper the simulation of the experiment is performed in a computational domain which extends $20R$ before the contraction and $20R$ after the expansion. This allows for the proper development of the drop and water flow fields upstream. It proved to be unnecessary to consider the full $30R$ pipe lengths on either side of the capillary.

3. Results and Discussion

Fig 1 shows the predicted drop outline overlaying the camera images of the drop at corresponding times measured from that at the first image when the drop presents to the contraction. The calculation is axially symmetric on a uniform grid with 64 cells over the pipe radius.

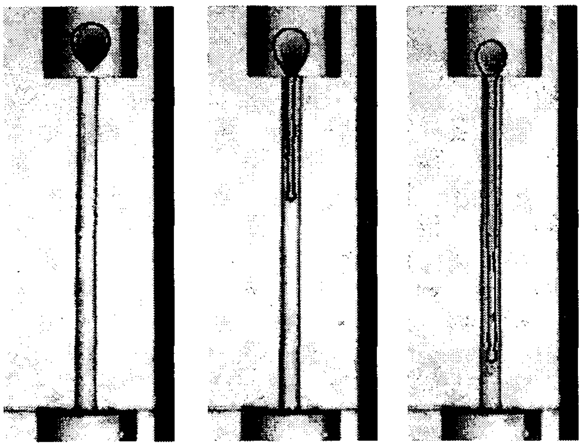

Fig. 1. Comparison of predicted and experimental drop shape in the contraction at dimensionless time intervals $\overline{U}t/R = 0.2$ measured from that of the left-most image.

The results show that the predicted drop shape and length of extension agrees well with the deformation which consist of a "balloon" shape extending into a thread in the capillary. Both predicted and observed threads exhibit capillary instability which can occur in core-annular flow [8]. In addition, the rate of change of dimensionless area of the drop in the plane of the image was found to agree closely with the measured value shown in [6]. Thus, it seems that allowing for the development of drop flow prior to the contraction (as in this work) does not significantly alter the dynamics of drop deformation in the capillary in this case. Certainly, substantial recirculation is predicted with dimensionless velocities as high as 0.45 within the drop relative to its motion. However, the Weber number ($We = 1.04$) is sufficiently low that the drop remains spherical until it reaches the contraction as is observed experimentally. When the interfacial tension is reduced so that $We = 4.03$ (results in the full paper), the drop is predicted to deform into an ellipsoidal shape in the inlet pipe which contradicts experimental observation. This probably occurs because the reduction in surface tension in the experiment is achieved by adding surfactant, the transport of which can result in "surface hardening" of the drop caused by surface tension driven flow. The current calculations do not include surfactant transport and development of such a model will be a topic of future research. (Acknowledgement: The authors wish to thank Amanda Lundqvist and Peter Schaerringer for conducting the experiment, and David Whyte for making available examples of his initial calculations.

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