Experimental Thermal and Fluid Science 60 (2015) 54–65

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Computer-controlled Two-Roll Mill flow cell for the experimental study of particle and drop dynamics

Israel Y. Rosas [a,*], Marco A.H. Reyes [b], A.A. Minzoni [c], E. Geffroy [a]

[a] Instituto de Investigaciones en Materiales, Universidad Nacional Autónoma de México, Apdo. Postal 70-360, Circuito Exterior, Cd. Universitaria, Coyoacán, 04510 México, DF, Mexico
[b] Departamento de Termofluidos, Facultad de Ingeniería, Universidad Nacional Autónoma de México, Circuito Exterior, Cd. Universitaria, Coyoacán, 04510 México, DF, Mexico
[c] FENOMEC, Instituto de Investigaciones en Matemáticas Aplicadas y Sistemas, Universidad Nacional Autónoma de México, Apdo. Postal 20-726, Circuito Exterior, Cd. Universitaria, Coyoacán, 04510 México, DF, Mexico

ARTICLE INFO

Article history:
Received 3 May 2013
Received in revised form 11 August 2014
Accepted 12 August 2014
Available online 23 August 2014

Keywords:
Two-Roll Mill
Flow-type parameter
Nonlinear control
Drop deformation

ABSTRACT

In this paper, we present for the deformation of a drop under flow, using an experimental device based on the Two-Roll Mill geometry. To study the drop deformation for extended periods of time, the use of this device requires implementation of a non-linear control scheme that has not previously been used. The device and control scheme generate well characterized flow fields, which present a richness of behavior of the drop dynamics that smoothly varies from that observed in simple shear flows, where the vorticity dominates, to those observed in purely Hyperbolic flows. The Two-Roll Mill flow cell allows detailed studies such as the critical capillary number versus the critical viscosities ratio for elongational flows with significant vorticity. As well, the experimental device is able to track the time evolution of the drop shape permitting to study its complex time evolutions. Experiments were performed for sub-millimeter size drops with the determination of the surface tension with high accuracy.

1. Introduction

The deformation and break-up of a single drop within a stress field are phenomena of great relevance in countless important industrial operations. Also, the drop dynamics can be extrapolated to a qualitative understanding of more concentrated systems, such as those in the food and pharmaceutical emulsions, paint manufacturing and polymer processes among others, see for example references in [1–12]. Many researchers have contributed to this knowledge, beginning with the pioneering work of Taylor [13] which includes both theoretical analysis and experimental observations, focused on the deformation of single drops suspended in a second liquid. In general, Taylor's work showed that when a drop with radius r_0 and viscosity μ_0 is immersed in a second immiscible fluid with viscosity μ_1, and is subjected to a shear-rate $\dot{\gamma}$ in a flow field, the deformation will depend basically on: (1) the viscosity ratio between the drop and the continuous phase, $\lambda = \mu_0/\mu_1$; (2) the capillary number defined as $Ca = r_0\mu_1\dot{\gamma}/\sigma$, which relates the magnitude of the viscous stresses acting to deform the drop and the magnitude of the stresses due to the interfacial tension σ on the interface, that opposes to the drop deformation; and (3) the flow field applied, where the deformation rates and its vorticity are the two most important parameters.

Most theoretical and experimental studies on drop deformation—under flows not driven by pressure differentials—have addressed the fluid dynamics effects using two types of flow fields: simple shear flows (where the magnitudes of the vorticity and the strain rate are equal) and pure extensional flows (with no vorticity). The two most frequently used experimental devices used to generate these flows were: the Parallel Band apparatus **PB** (for simple shear) and the Four-Roll Mills apparatus **FRM** (for planar elongation). Major experimental contributions to our understanding of the dynamics of a drop in simple shear flow are due to Rumscheidt and Mason [14], Torza et al. [15], Grace [16] and more recently by Guido and Villone [17], Guido et al. [18,19], Guido and Greco [20], Birkhofer et al. [21] and Megias-Alguacil et al. [1]. These include measurements of the critical capillary number for break-up of drop in simple shear flows, [16], and computer controlled versions of the shear band apparatus [17,21].

An exception to the use of simple shear flows are studies using four-cylinder flow devices, which allow a richer set of flow fields and are capable of inducing large deformation of a drop, hence its usefulness to study its nonlinear dynamics. In 1934, Taylor [13] used these, with a manual control, subjecting a drop to an elongational flow for an extended period. Much later, Leaĺs groups at Caltech and UCSB—see for example: Bentley and Leal [22,23],

* Corresponding author. Tel.: +52 55 5622 4630.
E-mail address: isroye@yahoo.com.mx (I.Y. Rosas).

http://dx.doi.org/10.1016/j.expthermflusci.2014.08.006
0894-1777/

Nomenclature

B	shortest axes of the ellipsoidal drop cross-section (m)
Ca	capillary number, $Ca = r_0\mu_1\dot{\gamma}/\sigma$
Ca_{crit}	critical capillary number
D	deformation parameter used for the interfacial tension calculus $D = \Lambda_1 - \Lambda_2$
D_0	initial deformation in the retraction process, measured with Taylor deformation D_T
D_T	Taylor deformation parameter (L – B)/(L + B)
de	distance that separates the axes of the rotating cylinders (m)
$\boldsymbol{E}$	rate of deformation tensor $\boldsymbol{E} = (\nabla u + \nabla u^T)/2$
$II_{2\boldsymbol{E}}$	second invariant of $\boldsymbol{E}$
L	longest axes of the ellipsoidal drop cross-section (m)
R	radius of the cylinders (m)
r_0	drop initial radius (m)
$\boldsymbol{S}$	second rank tensor used by Maffetone [47] to describe the drop shape
$\bar{\boldsymbol{w}}$	vorticity tensor, Astarita [26]
$\nabla\boldsymbol{u}$	velocity gradient tensor

Greek symbols

α	flow type parameter $\alpha = \frac{\Vert\boldsymbol{E}\Vert - \Vert\bar{\boldsymbol{w}}\Vert}{\Vert\boldsymbol{E}\Vert + \Vert\bar{\boldsymbol{w}}\Vert}$
$\dot{\gamma}$	shear rate $\dot{\gamma} = \sqrt[2]{\Vert II_{2E}\Vert}$ (1/s)
θ	orientation angle of the longest axes L respect to the x-axis (degrees°)
Λ	eigenvalues of the tensor $\boldsymbol{S}$
λ	viscosity ratio $\lambda = \mu_0/\mu_1$
μ	dynamic viscosity (Pa s)
σ	interfacial tension (N/m)
ϕ	half the angle between the incoming and outgoing axes (degrees °)
ω	angular velocity of the cylinders (rad/s)

Stone et al. [24], Milliken et al. [25]—used a precise computer-based control for the FRM to study the deformation of a drop under flow conditions, other than pure extensional, for extended periods of time, while applying complex flow histories. These flow fields cover a wide range of planar elongational—Hyperbolic—flows that, on one end, asymptotically approach a simple shear flow condition, and at the other, a purely 2D-extensional flow.

This family of 2-dimensional flows can be characterized by the *flow-type parameter* α that prescribes the velocity gradient tensor $\nabla\boldsymbol{u}$ of the flow field at the region centered within the 4 cylinders, and specifies the ratio of the magnitude of the rate of deformation tensor to that of the vorticity

$$\frac{\text{magnitude of deformation rate}}{\text{magnitude of vorticity}} = \frac{1+\alpha}{1-\alpha}. \tag{1}$$

Thus, α is given by

$$\alpha = \frac{\Vert\boldsymbol{E}\Vert - \Vert\bar{\boldsymbol{w}}\Vert}{\Vert\boldsymbol{E}\Vert + \Vert\bar{\boldsymbol{w}}\Vert}, \tag{2}$$

where $\boldsymbol{E} = (\nabla\boldsymbol{u} + \nabla\boldsymbol{u}^T)/2$ is the rate of deformation tensor. The vorticity tensor $\bar{\boldsymbol{w}}$ [26], measures the rate of rotation of a material point with respect to the rate of deformation's principal axes at that point. The case of $\alpha = -1$ corresponds to a pure rotational flow, $\alpha = 0$ to simple shear flow, and $\alpha = 1$ describes a pure extensional flow. Flows with α values between $-1 < \alpha \leqslant 0$ are classified as *weak*, because they have significant amounts of vorticity and are not expected to produce large deformations on an embedded object. On the contrary, flow fields with α values between $0 < \alpha \leqslant 1$ induce significant deformations because two neighboring elements of fluids separate in time exponentially, so the flow induces significant changes on the microstructure of the fluid; these are classified as *strong flows* [27,28].

The central region of the FRM flow has a stagnation point; thus, it is possible to study a deformed drop under well characterized extensional flows and for long periods of time. However, maintaining the position of the drop is quite difficult as the velocity field about the stagnation point is an unstable saddle point; i.e., carrying out these experiments manually is possible only for a short time. During the 1980s, Bentley and Leal [22,23] perform a series of experimental studies for strong flows with α values different from zero or one, using a computer-controlled version of Taylor's setup, coupled with modern camera technology. The setup objective was to cancel the permanent drift of the drop away from the stagnation point due to its saddle-point condition. Real-time video monitoring of the drop position allows implementation of a feedback loop, where the stagnation point location is adjusted for minimum drift while the flow-field deformation parameters remain steady. The control scheme adjusts individually the rotational speed of all cylinders—4 degrees of freedom—and displaces the instantaneous position of the stagnation point within a small region of the flow. The stagnation point is proportionally relocated towards the drop centroid position in the flow to cancel the drift of the drop. By maintaining the drop within this region, its residence time can be very long given that the drift field is negligible.

However, for small α values (say, less than 0.3), one pair of cylinders is rotating significantly slower than the other. For these cases, the performance of the linear control-scheme deteriorates. Studies by Bentley and Leal [22], and Yang et al. [29], using the FRM device, show that the most effective range of α values are within $0.4 \leqslant \alpha \leqslant 1$. So, even while four-roll mills and parallel band devices cover a wide interval of the flow-type parameter values appropriate for drop dynamics, there is still a gap in flow type studies in which a strong competition of vorticity and deformation dynamics may affect the time evolution of highly deformed drops. Besides, on one hand, the qualitative behavior for deformation of drops in flows with $0.6 \leqslant \alpha$ is very similar to that for $\alpha = 0.2$, see Fig. 28 in Ref. [23]; on the other, the drop behavior for flow types with values of $\alpha = 0$ differs greatly from those with values of α higher than 0.2.

In order to fill this gap of knowledge and cover a range of flow parameters not previously studied, the co-rotating Two-Roll Mill can be used. This device is particularly effective for flows covering the remaining gap in α values; i.e., between $0.03 \leqslant \alpha \leqslant 0.3$ [30–32]. But this proposition comes with a caveat: the lack of a linear control algorithm to maintain the drop at the stagnation point in a two-dimensional flow field. In essence, a control scheme based on the intrinsic hydrodynamics of the Two-Roll Mill is needed, while allowing for robust closed trajectories of the drop about the stagnation point.

With this flow geometry, the modification of the rotational speed of the cylinders displaces the stagnation point position along a direction transversal to the drift of the drop centroid. Hence, there is no possible scheme similar to that used by Bentley and Leal [22] to bring the centroid closer to the stagnation point. However, there is a control method of a different kind that can be used. It is based on Poincaré–Bendixson's Theorem for possible trajectories about a saddle-point region [33]. Hence, the scheme equally requires a computer control, base on feedback provided by the video imaging of the real-time drop position.