J. Non-Newtonian Fluid Mech. 166 (2011) 297–306

Contents lists available at ScienceDirect

Journal of Non-Newtonian Fluid Mechanics

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

Experimental study of atomization patterns produced by the oblique collision of two viscoelastic liquid jets

Sungjune Jung, Stephen D. Hoath, Graham D. Martin, Ian M. Hutchings*

Institute for Manufacturing, Department of Engineering, University of Cambridge, 17 Charles Babbage Road, Cambridge CB3 0FS, UK

ARTICLE INFO

Article history:
Received 12 August 2010
Received in revised form
15 November 2010
Accepted 10 December 2010
Available online 22 December 2010

Keywords:
Viscoelasticity
Jet
Collision
Atomization
Extensional flow

ABSTRACT

Experimental observations and analysis are presented for the formation and atomization of the fluid sheet created by obliquely colliding jets of viscoelastic fluids. Solutions of mono-disperse polystyrene (PS) in diethylphthalate and of poly-disperse polyethylene oxide (PEO) in glycerol/water mixtures were used to investigate the effects of fluid elasticity on the break-up patterns generated by the impact of two jets ejected from nozzles with an internal diameter of 0.85 mm. Various regimes of behaviour were identified which depend on the jet speed. The structures observed for these elastic fluids differ somewhat from those previously reported for Newtonian viscous fluids, and also show different behaviours depending on the degree of viscoelasticity. This study focuses on the periodic atomization, the so-called fishbone pattern, which occurs when the impinging jets form a liquid sheet which breaks up into a regular succession of ligaments and droplets. High-speed flash photography reveals that low concentrations of polymers significantly affect the evolution of the sheet and its fragmentation, the shapes of the ligaments, and the final drop sizes. The maximum fishbone angle is defined and shown to be a useful tool to describe the variation of the atomization pattern with polymer concentration. For the PS solutions the variation of maximum fishbone angle with reduced polymer concentration (c/c^*) follows a single master curve, but although the same is true for PEO with high molecular weights, the curves remain separate for low molecular weights. Observation of the fishbone patterns formed by the oblique impact of jets may provide a useful tool to observe and characterize inter-chain interaction in high speed extensional flow of polymer solutions.

1. Introduction

The oblique collision of two free laminar liquid jets creates flow patterns which depend on jet velocity and liquid properties. The progression of the resulting flow from a single oscillating stream at low flow rate to a violently flapping liquid sheet at high flow rate can be observed with the aid of high-speed photography. Within a certain range of Reynolds (Re) and Weber (We) numbers, the impinging jets form a liquid sheet which then breaks up into a regular succession of ligaments and droplets: the so-called “fishbone” pattern. Heidmann et al. first reported this periodic atomization pattern while studying sprays formed by two impinging jets of glycerol–water mixture to examine the effect of discontinuities and variations in the flow of atomized propellants in rocket engines [1]. They speculated that such disintegration phenomena could originate either from unstable equilibrium in the spray or from irregularities in the jets prior to impingement.

While considerable attention has been paid by subsequent researchers to sheet thickness, the distribution of liquid velocity, and the shapes of the liquid sheets formed by colliding jets, further aspects of the periodic atomization pattern remained unexplored until Bush and Hasha reported the results of a combined experimental and theoretical investigation of the family of free-surface flows generated by symmetrical collision of two identical laminar jets [2]. For glycerol–water mixtures they investigated the particular regime in which periodic ligaments and droplets are formed as well as a succession of mutually orthogonal links of thin oval films bounded by a relatively thick fluid rim (the “fluid chain”). They concluded that the fishbone pattern was the result of a Rayleigh-Plateau instability of the sheet’s bounding rim being amplified by the centripetal force associated with the flow along the curved rim. Bremond and Villermaux studied the formation and fragmentation of an ethanol sheet and demonstrated the formation of fishbone patterns in this system as well [3]. They found that destabilization of the rim could be triggered either by external perturbation with a small wire, or by disturbing the incident jets by vibration. They concluded that the fishbone instability was of a capillary type and that the onset and amplification of the instability was very sensitive to the thickness perturbations injected in the sheet by the collision conditions. We note that the relevant timescale for capillary instability is the Rayleigh time, which is of order 1–10 ms for the fluid jets in these experiments.

---

* Corresponding author. Tel.: +44 (0) 1223 765217.
E-mail address: imh2@cam.ac.uk (I.M. Hutchings).

0377-0257/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnnfm.2010.12.006

More recently, we reported a detailed experimental investigation of the formation, destabilization, and atomization of the liquid sheets produced by the oblique collision of two Newtonian liquid jets at low Re and We [4]. As shown in Fig. 11 of that paper [4], no fishbone pattern was observed in the system when the Ohnesorge number (Oh) exceeded 0.1 (as the instability was resisted by fluid viscosity) or fell below 0.025 (as it was resisted by fluid inertia). Unexpectedly, we found [4] a remarkably symmetrical fishbone pattern composed of a regular succession of ligaments and droplets which was formed at lower values of Re and We than had been previously reported. Furthermore, the pattern did not occur for completely symmetrical jet collisions. Some asymmetry in the jet collision proved to be essential in order to generate the symmetrical fishbone pattern. We examined various ways to introduce this asymmetry: by the use of different lengths of free jet, by displacing the jets laterally, or by disturbing the surface of one jet. It was concluded that the velocity profile within the jets at the point of impact played a key role in the initiation of the instability on the rim of the fluid sheet which then develops into the fishbone pattern.

Most previous work on colliding jets has been carried out with Newtonian fluids [1–10]. Few studies have used non-Newtonian fluids, although it is known that the formation and subsequent break-up of the fluid stream from a nozzle is affected by elasticity and other non-Newtonian fluid properties [11,12]. Miller et al. reported experimental observations of fluid sheets formed by impinging laminar jets of worm-like micelle solutions in which they found a new web-like flow structure [13]. However, they did not show the entire evolution of the flow structure as the velocity was increased and paid no attention to periodic atomization.

In the present work, non-Newtonian polymer solutions were used to investigate the effects of viscoelasticity on the fluid patterns generated from two obliquely colliding jets, and specifically on periodic atomisation. We should remark that the polymer Zimm times (the longest relaxation for isolated molecules in static fluids) involved in the present work are far shorter than the Rayleigh timescale for the fluid jets, by factors of more than 10–100, and yet large effects are observed.

2. Experimental methods and fluids

2.1. Experimental arrangement

The apparatus is described more fully elsewhere [4]. Fluid from a reservoir was pumped through flexible tubing via a flow-meter to two identical stainless steel hypodermic needles (with square ends) with an internal diameter of 0.85 mm and length of 25.4 mm. The arrangement of the jets and the fluid sheet formed by their collision is shown schematically in Fig. 1. The two jets, with the same diameter D_j, were laminar and had identical flow rates within an accuracy of 1%. In order to generate a symmetrical fishbone pattern, asymmetric jet velocity profiles were produced by the use of differing jet lengths L_{j1} and L_{j2}, defined as the distances from the ends of the nozzles to the point of impact. In all the experiments $L_{j1} = 3.5$ mm and $L_{j2} = 6.5$ mm. The angle 2α between the axes of the jets was fixed at 78°. The rotor-based flow-meter gave an electrical pulse output and was calibrated for each fluid by measuring the frequency of the pulses and the volume ejected from the needles over a fixed time. The jet speeds could be varied from $\sim$1 to 6 m s^{-1} by changing the speed of the pump.

Single-flash photography with back-illumination was used to capture individual images of the jet interaction region and to extract quantitative information such as the sizes of the resulting droplets, their spacing and the angle between the droplet streams. The light source was a xenon lamp with $\sim$1 μs flash duration which was sufficiently short to avoid motion blur, and the image was captured with a 10 megapixel DSLR camera (Nikon D40×). The axis of the optical system was normal to the plane of the fluid sheet. The light source and camera were controlled and the data from the flow meter was acquired with a PC data acquisition board (NI-6016, National Instruments) programmed with Labview.

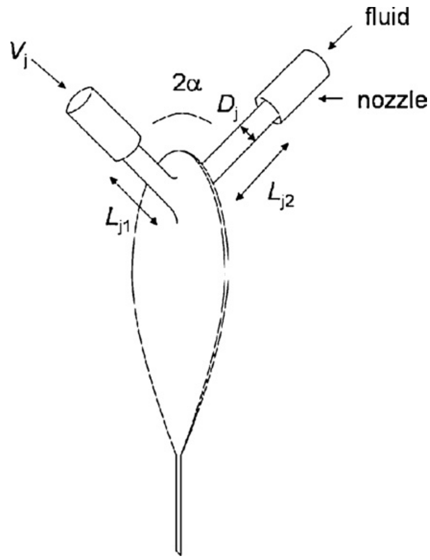

Fig. 1. Oblique collision of two liquid jets with diameter D_j, velocity V_j, free jet lengths L_{j1} and L_{j2} and included angle 2α.

2.2. Viscoelastic fluids

Two different fluid systems were used to investigate the influence of polymer concentration and molecular weight: polystyrene (PS) in diethylphthalate (DEP), and polyethylene oxide (PEO) in a glycerol/water (GW) mixture. Monodisperse PS, having a polydispersity index or PDI < 1.1, of three different molecular weights, 1.10×10^5, 2.10×10^5, and 4.88×10^5 g mol^{-1} (Dow Chemicals) was dissolved in DEP (99.5% purity, Sigma–Aldrich) to give various concentrations from 0.01 wt% to 1 wt%. The DEP is a relatively good solvent for PS at room temperature. These three groups of solutions are designated PS 110 K, PS 210 K and PS 488 K, respectively. The low-shear rate viscosities were measured with a Viscolite 700 vibrational viscometer (Hydramotion Ltd., UK), and were all between 10 and 13 mPa s at 22 °C. The equilibrium surface tension ($\sim$37 mN m^{-1}) and dynamic surface tension at 15 ms surface age ($\sim$58 mN m^{-1}) as measured with a bubble tensiometer (SITA proline 15) were almost the same for all polymer concentrations at this temperature.

Polydisperse PEO (Sigma–Aldrich) was dissolved in mixtures of glycerol (Sigma–Aldrich) and water (60%:40% by weight) to give concentrations from 0.00001 wt% to 1 wt%. PEO was used with seven different average molecular weights (all in g mol^{-1}): 1.0×10^5 (solution designated PEO 100 K); 2.0×10^5 (PEO 200 K); 3.0×10^5 (PEO 300 K); 6.0×10^5 (PEO 600 K); 1.0×10^6 (PEO 1 M); 2.0×10^6 (PEO 2 M); and 5.0×10^6 (PEO 5 M). The viscosities of these solutions lay between 10 and 13 mPa s and the equilibrium surface tension was almost constant ($\sim$56 mN m^{-1}) for all PEO concentrations. The measured dynamic surface tensions did vary with polymer concentrations and molecular weights, but were rather similar (at $\sim 68 \pm 2$ mN m^{-1}) for the PEO molecular weights and concentrations in the 15–30 ms surface age range which is relevant here. We note that Tirtaatmadja et al. [14] suggested using a surface tension reduction agent (2-butanol) to provide a constant equilibrium surface tension for PEO solutions over 10^2–10^4 ms timescales, but use of such an additive was not considered to be necessary for the shorter timescales accessed by the present experiments.