Advances in Colloid and Interface Science 161 (2010) 15–21

Contents lists available at ScienceDirect

Advances in Colloid and Interface Science

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

Fluctuations in Rayleigh breakup induced by particulates

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ARTICLE INFO

Available online 6 October 2009

JEL classification:
82.70.-y
47.15.-x
47.57.-s
47.61.-k

Keywords:
Jet
Rayleigh instability
Particles in shear
Fluctuations

ABSTRACT

A jet of liquid is intrinsically unstable to radial perturbations and will spontaneously break to form a series of droplets. This well known instability, the Rayleigh–Plateau instability, is controlled and used commercially in continuous inkjet printing. In this application it is important that fluctuations in drop velocity are minimised. However, the addition of particulates to the liquid is observed to strongly increase these fluctuations. The particulates are usually in the form of pigment particles of size $O(100\text{ nm})$ and at a concentration where they may hydrodynamically interact, particularly in the strong shear field within the nozzle ($O(10^7\text{ s}^{-1})$). The boundary layer thickness within the nozzle is $O(1\ \mu\text{m})$ and therefore the particulate size is a significant fraction. We therefore expect that the particles are capable of perturbing the boundary layer and hence the jet. Measurement of jet breakup fluctuation leads to a description of particulates interacting within and with the shear field associated with the boundary layer at the nozzle wall.

Contents

1. Introduction

In recent years jets and the Rayleigh–Plateau instability [1–3] have been widely studied both theoretically and experimentally [4,5], at least in part because of their importance within the context of inkjet printing [6]. For drop-on-demand printing, there is usually a thread of liquid that follows drop ejection and which subsequently disintegrates to form unwanted satellites. For continuous inkjet [7], the continuous formation of droplets from a jet in a controlled fashion is fundamental to the robust operation of the process.

Jet breakup has been studied at varying levels of complexity and sophistication [4,5]. For our purposes the growth of a perturbation to the jet is sufficiently represented by a linear approximation of the complete equation set such that the breakoff length, which is the distance from the nozzle at which the jet disintegrates to form a stream of droplets, may be calculated quite easily [8]. The breakoff length is determined by liquid properties, the dimension and velocity of the jet and a parameter that describes the size of the initial perturbation. In the absence of active stimulation, a jet will disintegrate into droplets randomly but with a well defined mean periodicity and size distribution.

Many continuous inkjet systems perturb the jet via a pressure pulsation generated behind the nozzle. These systems are generally limited to operation at a particular frequency since the pressure pulsation is generated by acoustic resonance within a cavity. The frequency chosen is close to the Rayleigh frequency for the system so that the greatest effect can be achieved. Such systems are also limited in the material viscosity range that can be routinely accommodated. An alternative mechanism has recently been described [9–11] wherein a thermal perturbation to the surface of the jet drives a Marangoni flow that initiates breakup. Such devices can be manufactured via MEMS fabrication routes and are therefore precise and robust.

For inkjet inks it is often preferable to use a colorant based on a pigment. Such pigments are typically insoluble organic particles of

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doi:10.1016/j.cis.2009.09.006

diameter order 100 nm that are used at moderate volume fractions that can neither be considered dilute nor concentrated. This type of dispersion occurs widely but is intrinsically difficult to model since both particles and hydrodynamics need to be considered in a coupled fashion.

Within the nozzle of a continuous inkjet device there exists a strong shear field which may be approximated as the jet velocity divided by the boundary layer thickness. For typical inkjet nozzles, the nozzle length is much shorter than the diameter and therefore the boundary layer remains a small fraction of the nozzle diameter. It is well understood, even from elementary linear models, that flow perturbations will lead to fluctuations in the breakup of the jet and therefore to droplet velocity fluctuations. Indeed a statistical analysis leads to a predicted drop size distribution for a simple jet that can be fitted by a gamma distribution [5]. Should particulates within the shear flow in the boundary layer affect the overall flow field, then they too will be expected to lead to fluctuations in jet breakup.

The macroscopic properties of suspensions of particles are determined by the spatial organization of the particles, that is their microstructure. In the absence of flow a wide range of microstructures are realized dependent on the balance between particle–particle interactions and Brownian motion. During flow, the microstructure will rearrange to accommodate the hydrodynamic forces and thereby modify the flow field. Understanding the coupling between flow and microstructure during flow has been the subject of many studies (for a review see Vermant and Solomon [12]). Various numerical methods have been developed to model such colloidal systems: Stokesian dynamics [13], fluid particle dynamics [14], lattice Boltzman [15], and several others, together with modern variants. In the majority of cases these methods have been used to model the resulting rheological behaviour of significantly more concentrated systems than the pigmented ink system described above. Of these studies, Catherall et al [16] in particular have calculated the stress on a single particle in a high-shear flow comparable with the nozzle flow field, and observe significant fluctuations. The work presented here suggests a subtle flow perturbation induced by particulates that leads to macroscopic velocity fluctuations in jet breakup.

2. Experimental

The experiments performed in the present study employed a micro-electromechanical system (MEMS) fabricated nozzle including a resistive heater. This device was mounted in a standard pin-grid array prototype chip holder the back of which was drilled to allow the entrance of liquid. A programmable pulse generation device (NIOS) was used to provide approximately a 200 kHz signal (the Rayleigh frequency for the jet was typically chosen) comprising a voltage pulse of up to 5 V and duration of 1 μs. Liquid was forced from the nozzle with a static pressure of up to 65 psi (approx. 448kPa) which generated a jet with velocity up to approximately 25 m/s. The nozzle diameter used was 17.6 μm. The resulting jet had a Weber number, We $(=\rho U^2 D/\sigma)$ of $O(100)$. The fluid handling arrangement is shown in Fig. 1a.

Jet breakup was observed using a long working distance optical microscope; a Navitar 6000× zoom lens with Mitotoyu 10× APO Plan objective (Fig. 1b). The images were captured with either a Watec LCL-902c Black and white video camera attached to a LabView 1405 framegrabber card, or a Prosilica EC1380C firewire digital camera. In both cases the images were analysed with a LabView code written for the purpose. Lighting was provided by an HSPS high speed spark strobe system, which generated 30 ps light flashes. These flashes were synchronised with drop generation via the NIOS pulse generator and an HP 8111A pulse generator used to decimate the base signal and an SRS DG535 delay generator to delay the pulse and enable observation of the drop as a function of phase (Fig. 1c). The position of the nozzle relative to the camera was adjusted using a micrometer motor drive with indexer (Oriel model 18011). Thus the distance from nozzle to jet breakup or to camera observation point could be accurately measured (+/−5 μm).

The liquid jetted comprised various concentrations of glycerol in water. To these solutions polystyrene particles were added. The polystyrene particles were made in our labs and are charge stabilised. They therefore require no added surface active component to disperse them. Each sample had a relatively narrow size distribution as determined by particle size analysis. These particles were mixed, at a variety of concentrations, with a range of aqueous glycerol solutions so as to investigate background viscosity, particle size and volume fraction independently.

Although jet breakup was initiated by a well defined thermal pulse, i.e. a known power for a known time, it was observed that the coupling of this power to an initial perturbation varied depending on the solution being used together and the jet velocity. Therefore an initial calibration experiment was performed to enable perturbations of the same effective size to be used for the various liquids and jet parameters. The breakoff length, i.e. the distance from the nozzle at which the jet first ruptures, at the Rayleigh frequency, was measured as a function of pulse power. The measured breakoff length is accurately approximated via the linear version of the jet equations [8] over the accessible range of powers,

$$L = CDWe^{1/2}(1 + 3Oh) \tag{1}$$

where L is the breakoff length, D the jet diameter, We the jet Weber number and Oh the jet Ohnsorge number $(=\mu/\sqrt{(\rho\sigma D)})$ and C a constant related to the size of the initial perturbation, i.e. the pulse power. It should be noted that at the Rayleigh frequency, the surface profile closely matches a growing exponential until non-linear breakoff processes intervene, i.e. where the radial perturbation is greater than approximately 1/3 of the initial radius. This well controlled behaviour arises since the perturbation to the jet is via a spatially constrained thermal Marangoni driving force [9] rather than an acoustic resonance as in conventional continuous inkjet. Hence, the non-monotonic breakoff length as a function of modulation power observed by others [17] is not observed here. Irrespective of the precise nature of the initial perturbation, the Rayleigh instability ensures that the various wavector modes grow at well defined rates. Thus we choose to consider the initial perturbation as if it were a perturbation to the radius of the jet then $C=\ln(R/\xi)$, where R is the radius of the jet and ξ is the perturbation. Thus we can relate the measured breakoff length to an *effective* perturbation size ξ. In practice measurements of both breakoff length as a function of power and breakoff length as a function of driving frequency were made and fitted using independently measured parameters of viscosity, density, surface tension and jet radius. The effective perturbation obtained in this way is a linear function of pulse power used to perturb the jet over the accessible range of powers. For the data presented below, measurements at constant effective imposed perturbation are compared.

Of interest here is the fluctuation of drop velocity. This was measured by measuring the position of many individual drops and obtaining the standard deviation of the resulting Gaussian distribution (Fig. 2). Since the lighting system was synchronised to the pulse generating the drop, the fractional velocity fluctuation is equal to the fractional positional variation,

$$\frac{\delta u}{u} = \frac{\sigma}{d} \tag{2}$$

where u is the droplet velocity, d is the distance from the formation of the drop to the measurement location and σ is the measured standard deviation of droplet position. Note that in practice three adjacent drops were simultaneously measured. Therefore, knowing the drop formation frequency as set, the velocity of the drops was also obtained. Further by plotting distance between the first two drops (A–B) against the distance