Mechanisms of Drop Formation in Continuous Ink-Jets

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Abstract

In this paper, we present our work on the subtle mechanisms of rupture of a continuous ink-jet submitted to various types of initial disturbances. Several experimental methods such as spectral analysis of signals and digital particle image velocimetry (DPIV) are used to characterize both the evolution of the forced liquid jet from nozzle exit to break-off and the formation of main and satellite drops.

The spectral measurements allow to quantify the various non-linear hydrodynamic phenomena for the free surface flow under consideration. The experiments can be used for example to explain the appearance of small droplets at low initial perturbation and/or provide an explanation for a drop formation devoid of satellites when a high initial perturbation is used. Finally, our measurements show that some of the numerical results that have been published recently are only capable of providing qualitative results since the appropriate boundary conditions are not taken into account.

Digital particle image velocimetry measurements performed on a forced scaled-up model jet demonstrate that there is a coupling phenomenon between kinematic and surface tension effects. More precisely, we show how near break-off, energy is transferred within the jet. Indeed, the results obtained allow to emphasize that a damping of velocity oscillations coincides with an enhancement of radial perturbations. These results which represent the first known measurements of local velocity within the jet improve our knowledge on jet break-up and should provide a significant breakthrough for an appropriate numerical simulation of the continuous ink-jet problem.

Introduction

Liquid drop formation is a topic of interest in many engineering applications. Indeed, technologies for producing streams of small more or less uniformly sized droplets have been developed for a number of applications such as aerosol calibration standards,[1,2] spray and combustion studies[3-6] and ink-jet printing.[7-10] Continuous ink-jet technology requires for example the formation of calibrated drops, from a jet, at a well-defined rate.

On one hand, it is always possible, imposing a complex periodical signal to obtain a stream of drops devoid of satellites. This has been successfully demonstrated for piezoelectric excitation,[11,12] for the electrohydrodynamic stimulation technique[13,14] and the thermal disturbance of the jet.[15] On the other hand, experimental evidence and industrial practice show that a purely sinusoidal signal fed to the acoustic transducer could also suppress the formation of satellites provided that the signal is of large amplitude.[16] It has been conjectured by Lopez et al[16] that this behavior could be due to a strong mixture of kinematic and surface tension effects. It is of importance to recall here that none of the theoretical work predict a break-up both and without satellites just by taking into account the value of the amplitude of perturbation. This is true both for the modeling based on the full Navier-Stokes equations[17] or on the one-dimensional formulation of the jet problem.[18] We hypothesize that this due to the fact that the appropriate initial conditions are not taken properly into account.

In this paper, we first report results obtained under different experimental conditions using a laser photometric method which has been shown to be adequate for non-intrusive measurements of the jet surface profile. Spectral analysis is used in conjunction with the above method to process the signals and recover the amplitudes of the different Fourier modes as well as the phase shifts of the harmonics with respect to the fundamental of the waveform. Secondly, to complete the picture from an experimental point of view, we have also performed digital particle image velocimetry[19] on a scaled-up model jet. This technique used for the very first time on a small forced jet essentially allows obtaining a map of the instantaneous velocity field in correlation with the pulsing of the piezoelectric transducer. In this aspect, it helps to distinguish various types of non-linear effects. These effects may be related to the nozzle geometry in which case they happen close to the exit. They may be due also to the propagation of the initial perturbation which are known to be predominant close to the pinch-off location.

Our work differs in at least the following aspects from others usually found in the literature:

1) We report results on a jet submitted to the superimposition of a sinusoidal perturbation on a steady flow. Other works concentrate on steady flow.

2) We provide results on the continuous evolution of the free surface from nozzle exit to jet break-up. Other works are essentially limited to the measurement of global parameters such as break-up lengths or drop sizes.
3) We pinpoint here the interactions between velocity oscillations and radial perturbations, which develop along the jet and lead to drop break-off. This important aspect has never been considered in previous works.

Experimental

In this section, we present two different drop-forming devices. The first one is a standard industrial continuous ink-jet head, whilst the second one is a proprietary scaled-up model of the ink-jet head. These two devices have each associated measurement techniques which are exposed more or less in detail in the following sub-sections.

Industrial Continuous Ink-Jet Head

The continuous ink-jet head is based on the piezoelectric stimulation technique.[21] This drop forming device essentially consists of a fluid chamber comprising a resonator i.e. a piezoceramic-rod assembly at one end and a nozzle at the other. The expansion and contraction of the resonator helps to impose a periodical disturbance onto the jet issuing from a nozzle. The mechanisms of initial velocity perturbations within the ink-jet head which lead to jet break-up either in presence or absence of satellites have been given elsewhere.[16,21]

A commercial frequency function/amplifier generator is used to drive the resonator with a periodically varying voltage comprised between 1 and 200 Volts peak to peak at a frequency of 62 kHz. It should be noted that the temperature-controlled fluid in the fluid chamber is supplied from a nitrogen pressure regulated reservoir. Typical pressures used are of the order of 0.4 MPa. The fluid used in all the experiments has been shown to be Newtonian over a large range shear and deformation rates using different methods[22] and as a shear viscosity of the order of 4.5 mPa.s. The diameter of the jet, which has been measured accurately, is of the order of 66 μm.

The measurements techniques associated to the continuous ink-jet head are two-fold. For instance, on the right side of figure 1, one finds a view of the stroboscopic method which helps to capture still images of jet break-up using a CCD camera (j) and a computerized phase scanning device associated to a LED (l). On the left side of figure 1 is a schematic of the laser photometric system. The principal optical components this system are a laser diode (g) and various lenses (h) that shape the laser beam into a thin sheet and magnify the shadow of the jet.

The transmitted light that gives the jet profile passes through a diaphragm and a slit before being focused by a lens and projected onto a photodiode (i). The signal collected by the photodiode is amplified, sampled and finally processed using a standard Discrete Fourier Transform (DFT) procedure. This procedure allows expanding the jet radius into Fourier modes and to extract information on both amplitudes and phase shifts between the fundamental and the harmonics of the jet radius. The evolution of the jet radius as a function of location and time can be written as[20]:

$$R(z,t) = A_0 + \sum_{n=1}^{N} A_n(z) \cos\left(n\left(2\pi ft - \frac{2\pi}{\lambda} z \right) + \phi_n(z) \right) \quad (1)$$

where R is the radius of the jet, z the location, t the time, f the frequency, λ the wavelength, the A's being the Fourier amplitudes and the ϕ's representing the phase shifts with respect to the fundamental. The number of Fourier modes considered depends on the initial perturbation which is a function of the excitation voltage. In general, the higher the voltage, the larger the number of modes to be taken into account.

Scaled-Up Model Head

Side and front views of the experimental set-up used in the present study are shown in figure 2. The apparatus for forming the jet essentially consists of a fluid chamber (6) mounted on a motorized translation table and comprising an acoustic transducer at one end. The transducer is situated close to the nozzle at a distance of about 2 cm from the exit and has been built in-house using a parallel bimorph glued on a thin steel foil. The transducer is used as the source of forcing of the jet. The stimulation signal is provided by a same frequency function/amplifier generator as for the first set-up working in a sinusoidal mode at a frequency of 250 Hz for a jet diameter of the order of 2.4 mm. The above frequency is the most unstable for the operating conditions chosen in our experiments. We have shown elsewhere[23] that in order to replicate accurately with the scaled-up model head the physical phenomena encountered in the industrial continuous ink-jet head, it was necessary to follow the well known rules of similarity.[24] The non-dimensionalization process using the Navier-Stokes equations gives the following dimensionless numbers (Reynolds, Weber, Strouhal and Froude respectively):

$$Re = \frac{\rho V D}{\mu} \qquad We = \frac{\rho V^2 D}{\sigma} \qquad Str = \frac{f D}{V} \qquad Fr = \frac{V^2}{D g} \quad (2)$$

The first three dimensionless numbers can be kept constant from one set of experiments to an another. In the model head, in contrast to industrial ink-jet experiments, the gravity effects are quite large. In order to remedy to that situation, the jetting head is placed horizontally in order to dissociate gravity and kinematic effects.

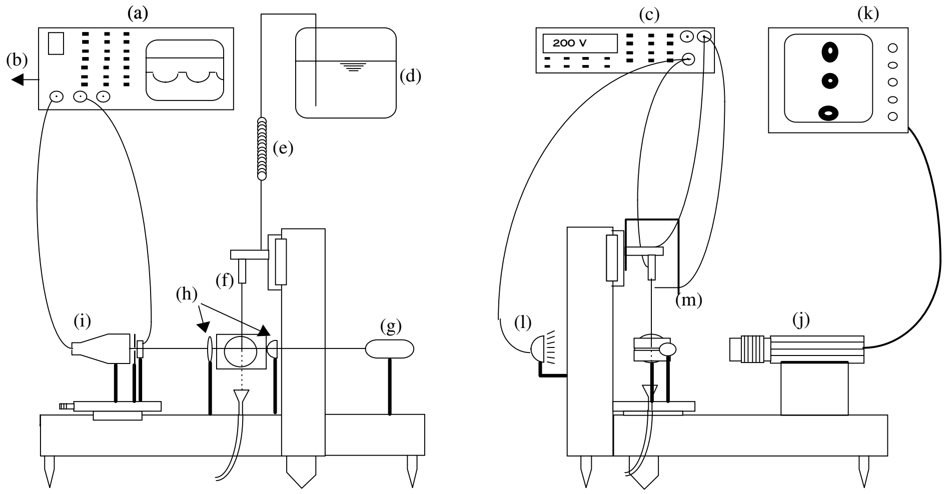

Figure 1. Industrial continuous ink-jet head with associated measurement techniques

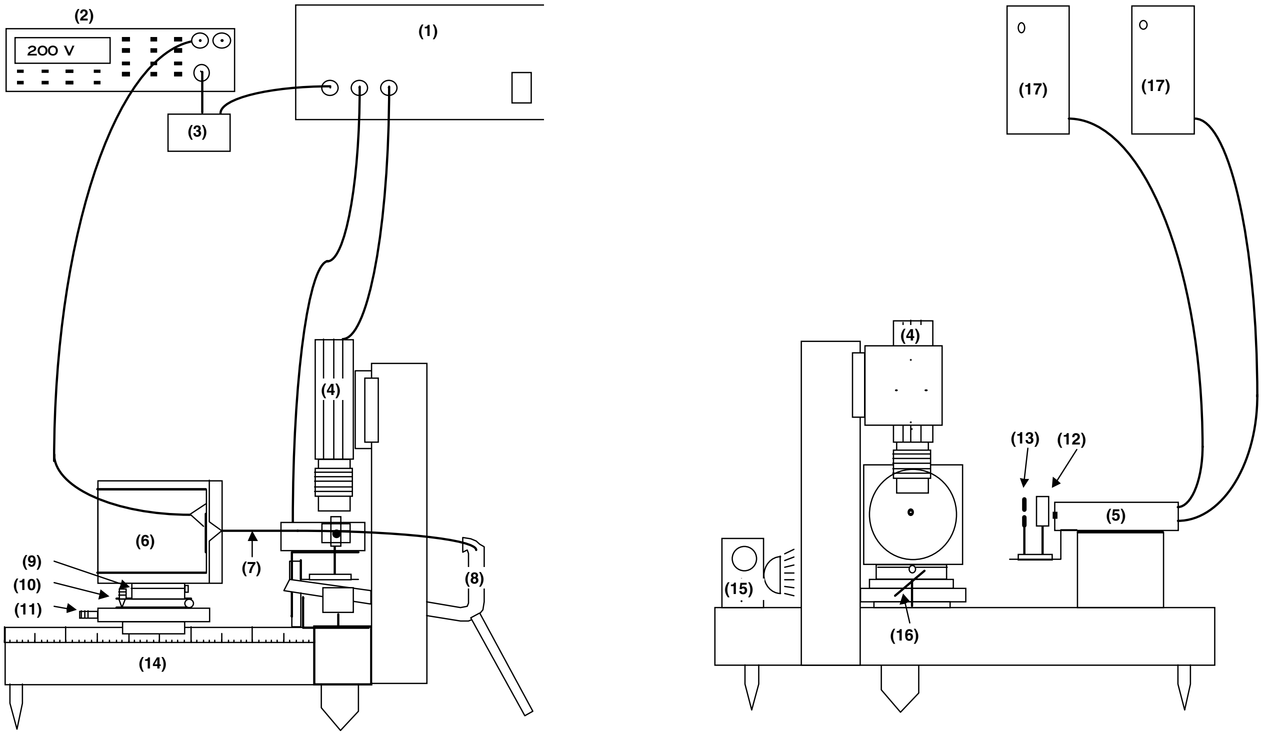

Figure 2. Scaled-up model head with associated measurement techniques

The measurement technique associated with the scaled-up model head is digital particle image velocimetry (DPIV). The methods used for the measurement of velocity fields in flows can be distinguished into single-point techniques, aiming at the determination of the velocity vector at one point with high temporal resolution and multi-point techniques aiming at the simultaneous determination of multiple velocity vectors. DPIV is a technique of the latter type and has been chosen both because of its large processing speed and the possibility of synchronization between transducer and laser triggering signals, which is a critical point for us. The source of illumination is a 532 nm wavelength double head pulsed Nd:Yag lasers (5, 17) which work at a frequency of 15 Hz (see Figure 2). Each laser provides powerful and very short pulses of the order of 8 ns and the double head allows very short time interval between the two pulses. Attendant optics (12, 13) comprising a cylindrical lens shape the laser beam into a thin sheet. Located orthogonal to the laser sheet is a PIV dedicated CCD camera (4) with a pixel array size of 768×484. This camera can record two images with a very small time interval and thanks to the processor (1) has also the ability to perform cross-correlation measurements, which is an essential requirement in our case. All other details can be found in figure 2. Finally the last but not the least of the features of this set-up is the original phase-locking system,[25] which allows the synchronization between DPIV measurements and the triggering signal of the piezoceramic transducer. Our phase locking system is moreover sufficiently versatile to be interfaced with any device comprising an external trigger auto-synchronization input.

Results and Discussion

As in the preceding section, we will again split this section into two parts. The first one will concern the spectral measurements of the surface profile, whilst the second one will detail the DPIV results.

Spectral Measurements

We show in figure 3 hereinafter the expansion of the surface profile into Fourier modes for a high initial perturbation similar to that found in ink-jet printing.

The amplitudes of the different modes are squared and plotted versus z, which represents the distance from the nozzle. The reason for taking into account the amplitudes squared is essentially due to the fact that we follow closely Torpey[10] in writing the different equations describing the jet dynamics. As indicated in the insert, Figure 3 gives the behavior of the continuous component (CC), the fundamental and the harmonics upto the fourth one.

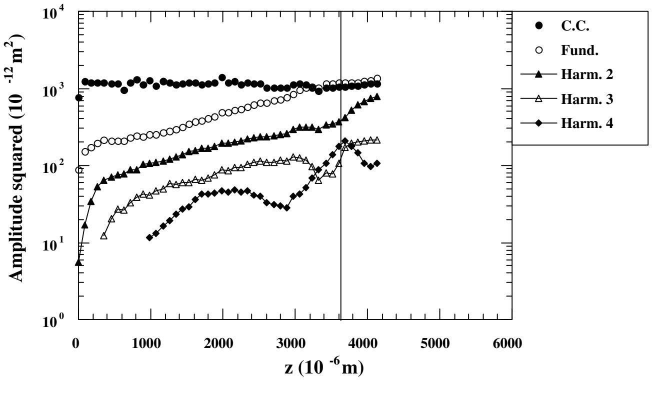

Figure 3. Amplitudes of the different Fourier modes for the industrial jet

Since higher harmonics exist right at the exit of the nozzle, the initial perturbation, which was periodical and monochromatic, has become a multi-frequency component. It is to be noted that the different modes are quite similar in shape and have more or less three régimes. The first régime ($0<z<6.10^{-4}$ m) with the highest slope close to the nozzle exit is probably representative of kinematics of the flow within the nozzle where the perturbation tends to be greatly amplified. The second régime quite limited in length is characterized by the fact that competitive effects namely kinematic and capillary seem to take place since the measurements of the surface profile show a plateau for the different modes. Finally, we find a third zone which extends from z equal to 10^{-3} m to about 3 10^{-3} m. This zone has Fourier modes with an exponential growth very similar to what would happen just with the capillary instability effect.

Digital Particle Image Velocimetry Results

In the discussion part in the above sub-section, kinematic effects which are probably due to shape of the velocity profile are conjectured but not demonstrated. In this sub-section, we will present the first available results of velocity profiles of forced liquid jets and explain them with respect to the spectral measurements.

Before presenting in figure 4 the final results, it is useful to mention some of the operating conditions with the scaled-up model head. The fluid used has a viscosity close to 25 mPa.s, the velocity of the jet is 3.15 m/s and the working frequency is 250 Hz. With these parameters fixed, the important dimensionless numbers given in the above section are maintained.

A sequence of forty-two DPIV images has been recorded in order to obtain the velocity field for the whole jet. They are not represented here for the sake of brevity. We give in figure 4 the processed results for three different parts of the jet. The middle picture (a) which is probably the most important since taken close to the nozzle exit is from 8.6 mm to 24.6 mm, the one on the left (b) is for 21.4 mm to 37.4 mm and the third one on the right (c) represents the velocity behavior from 34.2 mm to 50.2 mm. The vectors appearing in the three different snap shots of figure 4 represent the dimensional relative velocity vectors which are obtained by subtracting the mean velocity. The latter value has been measured using the DPIV technique on an unperturbed jet once that the velocity profile has relaxed i.e. at several tens of millimeters from the nozzle exit.

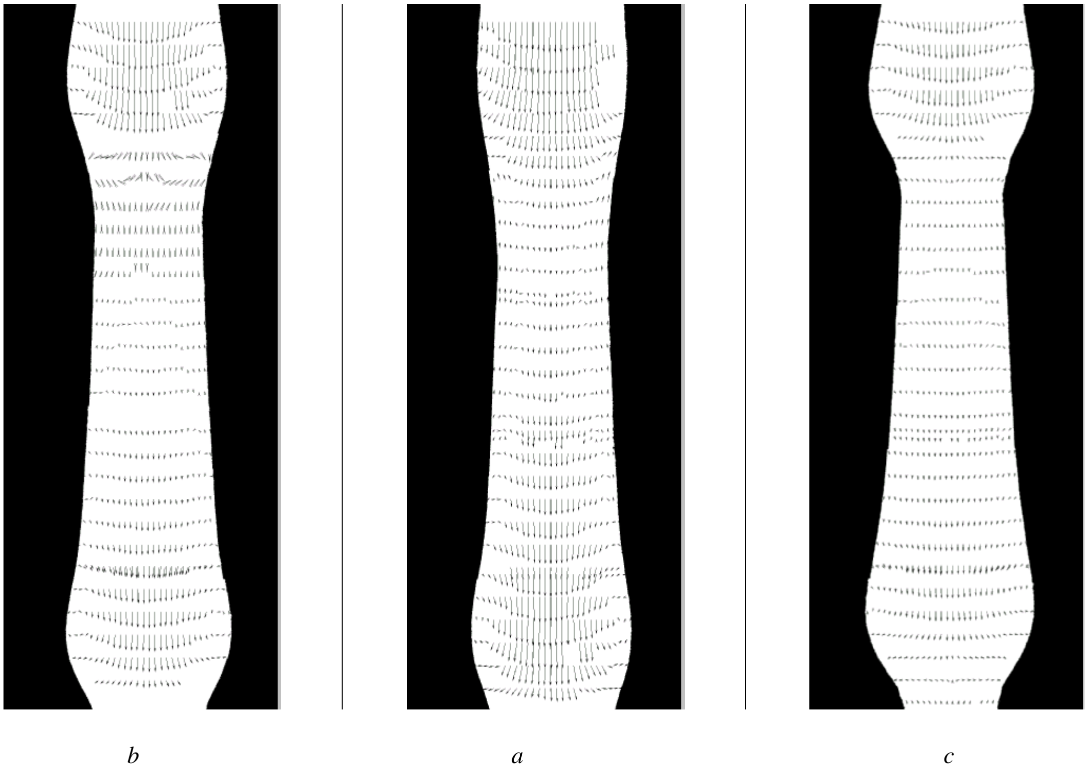

Figure 4. Velocity field for the scaled-up perturbed jet. Note the evolution of the velocities versus the distance from the nozzle exit

We demonstrate that at the exit of the nozzle the velocity profile is not flat which is in discrepancy with the usual assumptions for the numerical modeling of the jet break-up process. Moreover, we also show that although the radial velocities are significantly smaller than the axial ones, they are far from being negligible. The observed gradient of the longitudinal velocity (see the middle picture) induces an accumulation of the fluid in some zones and can be held for primarily responsible for the formation of the swells. This explains the very steep growth of the Fourier modes in the so called first régime. The small radial velocity gradient, which can be calculated from our DPIV measurements, can probably be attributed to the passage of the fluid in the nozzle. Overall, the flow kinematics are shown to be predominant at the exit of the nozzle as hypothesized in the above sub-section. One can note that farther from the exit (see the picture on the right), the velocity profile tends to flatten and the damping of the kinematics coincides with an enhancement of radial perturbations. From a physical point of view, the attenuation of velocity effects allows the surface tension to become the predominant mechanism leading to jet break-up. This explanation is in agreement both with the spectral measurements (third régime in the above sub-section) and some of the results which have been reported very recently.[26]

Conclusions

The problem, which has been studied here, is a challenging one because of the existence of moving complex free surfaces. It particularly places stringent requirements of temporal and spatial resolution and accuracy on the experimental techniques used.

The laser photometric method used in conjunction with DFT analysis allows us to extract values of the amplitudes of the fundamental and the harmonics from the temporal variation of the jet radius. The results obtained prove to be important in characterizing the intricate surface phenomena and in pinpointing the different flow régimes.

The improved digital particle velocimetry technique used with the phase-locking system leads to the first available measurements of instantaneous velocity field in a jet with an initial perturbation similar to that found in industrial applications. The results obtained with this technique complement the spectral measurements and prove unambiguously for the first time the importance of flow kinematics for highly forced jets. They also provide an explanation for the non-appearance of satellite drops since the arrangement of the velocity profile is such that there is one single pinching location in the jet which leads to a single drop. Finally these measurements show that a non-flat velocity profile should be considered as initial conditions in the future modeling of drop formation in continuous ink-jet processes.[27]

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