

The Role Of Nozzle Geometry On The Break-up Of Liquid Jets

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Abstract

In this work we present the results obtained on jet break-up using two types of nozzles having the same nozzle aspect ratio but exhibiting different entry and exit holes. To further emphasize the effect of nozzle geometry, we use two different stimulations of the jet, respectively a piezoelectric transducer located upstream the orifice and an ElectroHydroDynamic (EHD) exciter which consists of an electrode situated downstream the nozzle. The different measurement techniques used are essentially a stroboscopic illumination of the jet and a laser photometry method which allow us to obtain information on both the break-up lengths and the spatial evolution of the jet shape. Spectral analysis combined with the laser photometric method shows the evolution of Fourier amplitudes of the jet radius and phase shifts between the fundamental and the harmonics for low and high initial perturbations. In particular, this method reveals drastic differences between nozzles which may be ascribed to the drop formation behaviour of jets.

Introduction

Continuous ink-jet printing largely relies on the production of uniformly sized and charged droplets caused by the break-up and charging of a periodically disturbed jet.

The parameters controlling the break-up of fluids are its physico-chemical properties (e.g. surface tension) and mechanical effects such as viscosity or velocity. Also of considerable importance are the amplitude and type of the excitation signal[1,2] and the nozzle geometry which has been quite overlooked until now except for the work by McCarthy and Molloy[3].

However these authors limit their investigation to the main geometrical factors influencing the velocity profile at the orifice exit and do not give details in their paper as to the method of evaluating the performances of different types of nozzles.

If an ink jet printer should work properly and reliably, it must be fitted with nozzles that are able to produce drops at a stable and repeatable frequency and be insensitive to small variations in fluid parameters and operating conditions. To decide if a nozzle is working appropriately the drops are usually viewed under stroboscopic illumination but this technique alone often proves to be insufficient[4]. Indeed, in order to discriminate between different types of nozzles it is necessary to obtain quantitative information on capillary wave dynamics which control jet break-up.

In this paper, we report results obtained for two types of nozzles using both the stroboscopic technique for measuring break-up lengths and a laser photometric method which has been shown to be adequate for non-intrusive measurements of the jet surface profile[5]. Spectral analysis is used in conjunction with the latter method to process the signals so as to recover the amplitudes of different Fourier modes and the phase shifts of the harmonics relative to the fundamental. This enables us to pinpoint the differences in the development of an initial disturbance applied to a jet issuing from a given type of orifice and thus to propose a method capable of evaluating in a quantitative manner nozzle performances.

Experimental

The different stimulation devices and measurement methods used in this study are presented and discussed. We also discuss the different technologies which may be used to manufacture nozzles for ink-jet applications.

Jet generation and stimulation

In this work, we have used either a piezoelectric stimulation technique[6] or an ElectroHydroDynamic (EHD) method[7] to impose a periodical disturbance onto the jet issuing from a nozzle. Temperature controlled fluid is supplied from a pressure-regulated reservoir to the fluid chamber. A vertical jet issues from the nozzle which has a length over diameter ratio of one. The diameter of the jet is

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roughly equal to that of the nozzle and the mean diameter of jets considered in this paper is of the order of 70 µm. Other details are shown on figure 1.

The piezoelectric stimulation technique essentially consists of a fluid chamber comprising a resonator at one end and a nozzle at the other. The resonator is made of a piezoelectric ceramic bonded to a steel rod. The expansion and contraction of the piezoceramic-rod assembly within the fluid chamber helps to create the initial disturbance (a velocity perturbation) which is then amplified along the jet and leads to drop break-up. Jet break-up either in presence or absence of satellites could be obtained by this technique.

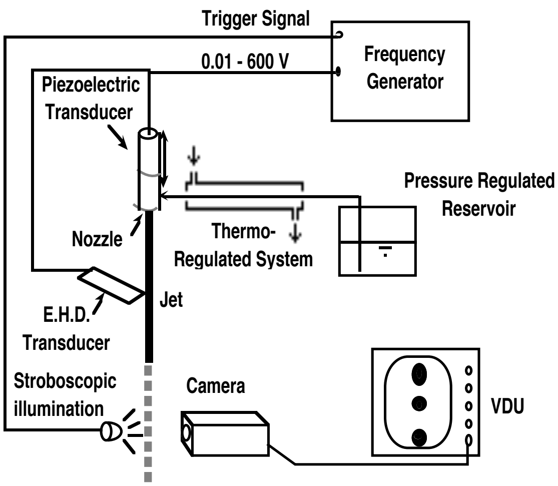

Figure 1. Schematic of the experimental set-up

The EHD stimulation method used in this work consists of a simple electrode (a thin metallic foil of 60 µm in thickness) which is located quite near the jet with a clearance of the order of 20 µm. In contrast to the piezoelectric stimulation technique, this method which induces a radial perturbation onto the jet can only generate drops interspersed with slow satellites. Indeed as shown in the next section, this type of stimulation is more than two orders of magnitude less efficient than piezoelectric excitation, so other disturbance waveforms have to be found[8] in order to eliminate these satellites.

A frequency function/amplifier generator is used to drive either the piezoelectric crystal or the EHD electrode with a periodically varying voltage comprised between 1 and 600 volts peak to peak. The amplitude and frequency of the function generator are manually operated. This generator also drives at the same frequency a LED which helps to capture still images of jet break-up. A phase scanning device set in-between the generator and the LED allows to introduce a variable phase shift between the transducer triggering signals and those of the LED[6] and thus to have a resolution of 1/10 of the wavelength (around 30 µm) in terms of break-up length measurements.

Nozzle configurations

As already stated in the introduction, the role of orifice geometry has seldom been considered in the case of capillary pinching (also called Rayleigh instability mode) which is the dominant mechanism of jet break-up in continuous ink-jet applications.

McCarthy and Molloy[3] made an attempt to form a qualitative correlation between the nozzle configuration and issuing jet shape. They were mainly interested in studying the efficient conversion of potential energy to kinetic energy and the effect of the nozzle aspect ratio L/d on the initial jet velocity profile and subsequent jet shape.

Other works relevant to the role of orifice flow patterns on jet break-up have been carried out in the domain of fluid atomization where the Taylor instability mode prevails In this field, the researchers have varied both orifice entrance configurations and nozzle aspect ratios[9] in order to change the internal structure of the core which controls the droplet size and velocity.

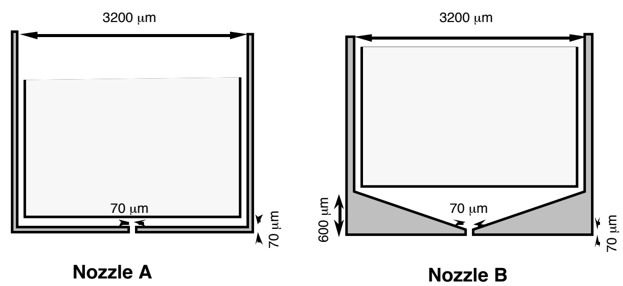

Figure 2. Nozzle configurations obtained using two different technologies

A number of nozzle manufacturing technologies can be found in the literature. Hershberg et al[10] proposed to use micro-punching and/or microelectric discharge machining. Kitahara[11] fabricated nozzles in a stainless steel foil using etching technology whereas Endert et al[12] found that excimer laser micromachining was an excellent tool for precision manufacturing.

In our study, we have used two nozzle set-ups which have been manufactured using some of the above cited technologies. They present the same aspect ratio L/D of one and differ by their entrance and exit geometries. Nozzle set-up A consists only of a cylindrical section having a diameter of 70 µm whilst nozzle set-up B combines both cylindrical and tapered sections. Due to the difference in the entry section, the piezoelectric transducer can be set much more closer to the orifice exit in the case of nozzle A as seen on figure 2. Our objectives in this work are to find the nozzle offering the highest efficiency in terms of stimulation (i.e. the shortest break-up length together with the lowest excitation voltage) and to understand the physical reasons underlying the phenomenon of jet instability.

In order to be sure that the effects identified were only due to differences in nozzle geometries, we checked that the fluid which was used in all our experiments was purely Newtonian over a large range of shear and deformation rates using different methods that we have described elsewhere.[13] The ink had a viscosity η of 4.4 mPa.s, a density ρ of 1172 kg/m^3, a static surface tension σ_s of 50 mN/m and a conductivity of 2500 μS/cm which is amply sufficient for using the EHD excitation method.

Laser shadow method

This method allows to perform non-intrusive measurements of the jet surface profile. This extremely accurate technique which has the capability to resolve relative diameter variations as small as 10^{-3} has been discussed in an exhaustive manner elsewhere[5] and therefore only the main features necessary for the understanding of the results given in the next section will be presented here.

Components of the measuring system are a laser diode and attendant optics which shape the beam into a thin laser sheet. A spherical lens which location can be varied according to the desired magnification factor (25 to 40) is also positioned behind the jet. In the course of the experiment the jet (which is opaque) is scanned from the nozzle to the break-up point using a motorized micro-positioner stage on which the drop generation system is mounted. The entire device including the translation stage, necessary optics, and detection means are mounted on a heavy granite optical table with self-levelling supports for vibration isolation.

The transmitted light which gives the jet profile passes through a diaphragm and a slit before being focused by a lens and projected onto a photodiode. The signal collected by the photodiode is amplified before being sampled using a digital oscilloscope. A Discrete Fourier Transform (DFT) procedure is used to expand the jet radius into Fourier modes and to extract information on both amplitudes of different modes and phase shifts between the fundamental and the harmonics.

Results and discussion

Break-up length measurements are performed at different excitation voltages using two types of nozzles. This allows to characterize the efficiency in terms of stimulation for both nozzles. Then tests are conducted using the laser shadow method. The data obtained gives the initial disturbance input to the jet and provides relevant information as to the differences between nozzles.

Disturbance growth and fluid dynamics

Before going into the details of this study, it is necessary to recall the basic relationships of the break-up of a liquid jet within the framework of linear stability analysis. Typically, controlled instability of a fluid stream is introduced by perturbing the jet with a sinusoidal waveform although other forms of disturbances have been considered[1,2,8].

For our purposes, we consider an axisymmetric jet emanating from a nozzle of radius R_0. The jet travels at a velocity V_0 (of the order of 20 m/s) which is much greater than the characteristic capillary speed $V_c = (\sigma / \rho d)^{1/2}$ and is perturbed using different methods with a frequency f of wavelength λ.

Rayleigh[14,15] developed the first linear stability analysis where he considered an infinite jet (inviscid[11] or viscous[12]) subject to a temporal disturbance growth. He showed that the surface waves grow exponentially in time as $e^{\beta t}$. In a subsequent study the temporal growth rate β was given by Weber[16] for a viscous fluid with aerodynamic interactions.

To be exact, one should consider a spatio-temporal disturbance for the jet break-up problem at hand since the jet is finite with a nozzle at one end but Keller et al[17]. have demonstrated that both analyses agree for $V_c << V_0$. In our case V_c, is of the order of 1 m/s which is about 20 times smaller than V_0 so a temporal analysis is justified.

Break-up length measurements

In order to study the effect of the nozzle geometry we have performed break-up length measurements using the two types of nozzles and the piezoelectric method described in the previous section. If we assume that the linear analysis is valid for the full jet then break-up is obtained when the perturbation is equal to the initial radius. If we assume further that the initial perturbation or disturbance is proportional to the excitation voltage then the spatial growth rate can be obtained from the slope of the curve (break-up length versus the logarithm of the excitation voltage).

Referring to figure 3, we can see that the slopes are the same for both types of nozzles which is consistent with the fact that the growth rate does not depend on the type of nozzle which is used to perform the experiments. Nevertheless, the break-up lengths for the jets issuing from these nozzles are different for one given voltage. If we consider the overall performances of the nozzles, we can attribute an higher efficiency factor to the nozzle A compared to nozzle B. Indeed as seen on figure 3, the break-up length of the jet and the excitation voltage are lower when using nozzle A. This difference in efficiency may be due to the fact that the transducer is closer to the exit as mentioned in the previous section, but as we shall see later on, other reasons namely in terms of flow might also explain this difference.

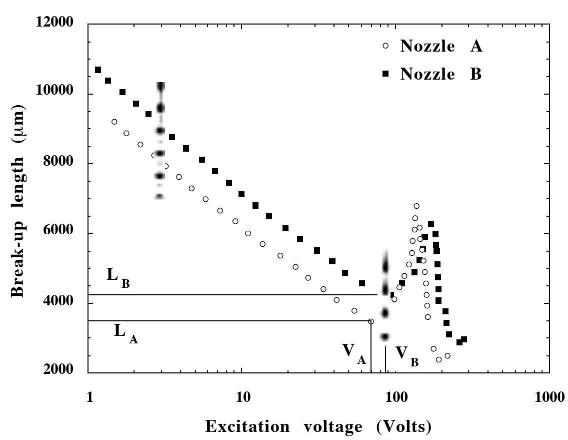

Figure 3. Break-up length measurements performed for two types of nozzles

Also shown as inserts on figure 3 are the stroboscopic photos of jets obtained for low excitation voltage (drops with slow satellites) and minimum break-up length (stream of drops devoid of satellites).

Low initial disturbance experiments

In this sub-section we perform experiments using both the piezoelectric and the EHD stimulation devices.

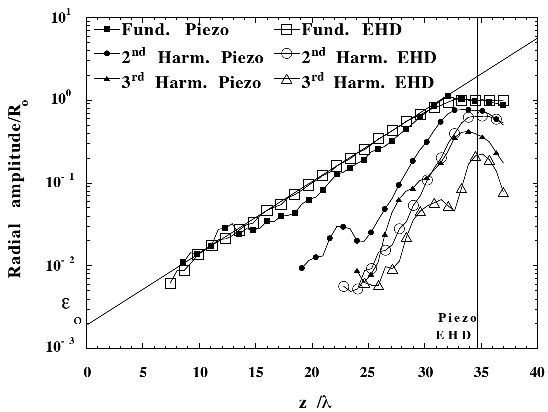

Figure 4. Normalized amplitudes for the fundamental and the two first harmonics using piezoelectric and EHD stimulations

The objective is to evaluate the influence of the nozzle in introducing harmonics into the jet so we have performed tests so as to obtain the same break-up length which is indicated by the vertical line on figure 4. For obtaining this break-up length (z/λ around 35) we used respectively 1 Volt for the piezoelectric excitation and 410 Volts for the EHD stimulation signal, so as said in the above section we find effectively a ratio of more than two orders of magnitude between the two types of stimulation.

The main advantage of EHD stimulation which is used in this work is its insensitivity to nozzle configurations since the electrode can be set at a location where velocity profiles have relaxed, i.e. typically at around 500 µm underneath the orifice. This value is taken as the zero on the horizontal axis (Figure 4) for the EHD measurements.

For the sake of legibility, only the amplitudes of the fundamentals (Fund. piezo and Fund. EHD) and the first two harmonics (respectively the second and the third) are reported in figure 4. The growth of the fundamental is very close to exponential as expected from linear theories. The slope of the fundamental is equal to the spatial growth rate from which we can calculate the temporal growth rate for comparison purposes with linear theories.

Taub[18] for example has reported that an averaged normalized growth curve agreed well with the Rayleigh's inviscid theory[14]. In all cases, this type of comparison is inappropriate so we have instead compared our data with Rayleigh's viscous predictions[15]. In this case there is a large discrepancy with the theory and we have to take into account the aerodynamic effects i.e. Weber's modification[16] to improve considerably the agreement between experiments and theory.

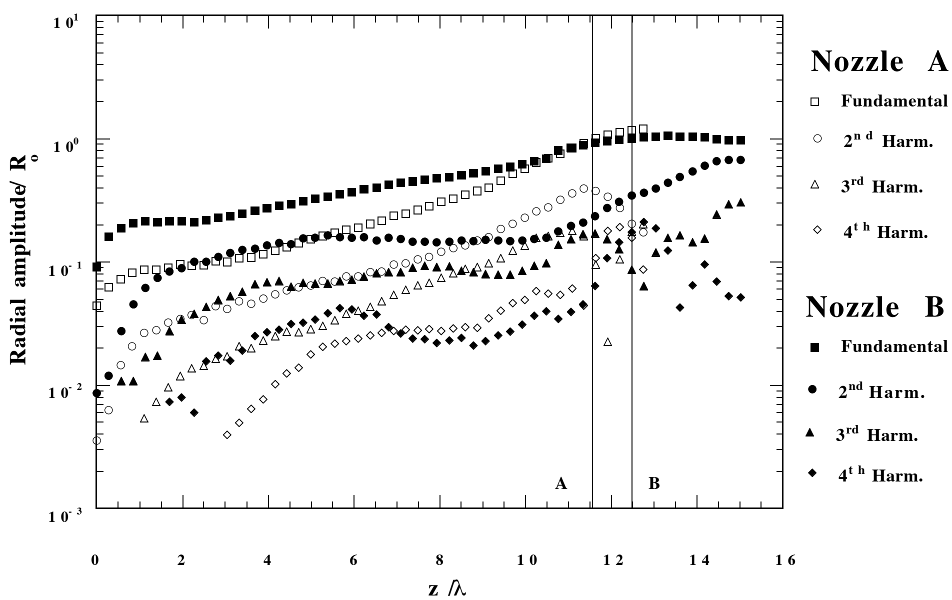

Figure 5. Normalized amplitudes of fundamental and the first four harmonics obtained when using the two types of nozzles

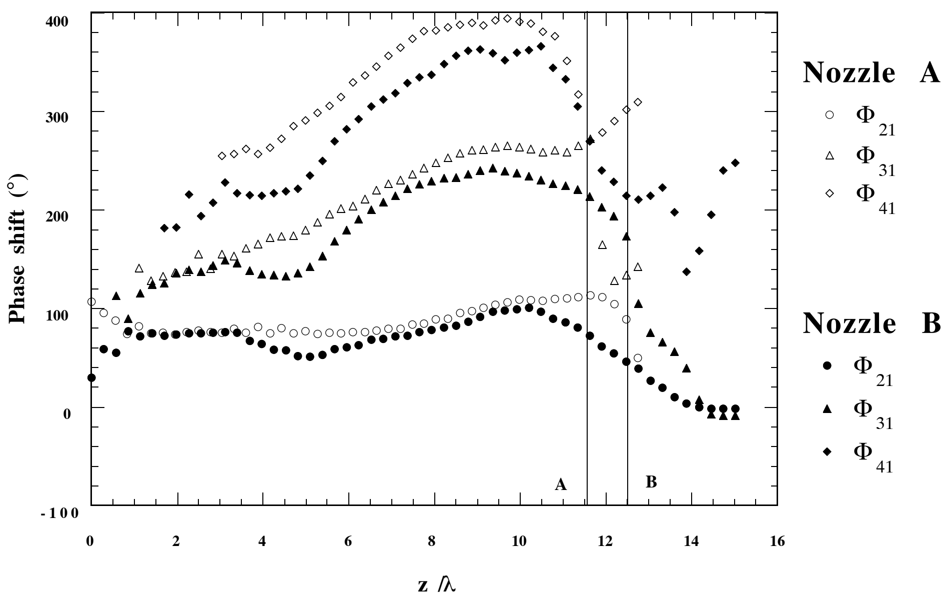

Figure 6. Phase shifts obtained when using the two types of nozzles

As can be seen on figure 4, there is no real difference in terms of evolution of amplitudes at least at first order between the disturbance input upstream the nozzle (piezoelectric excitation) and the excitation far downstream the nozzle (EHD). So, we can conclude, that nozzle effects are probably absent for low initial disturbances.

High initial disturbance experiments

As mentioned in the experimental section, the EHD stimulation is not sufficiently efficient to input an high initial disturbance onto the jet, so the experiments described in this sub-section have been performed using the piezoelectric transducer.

The excitation voltage was 69 Volts peak to peak (Vpp) for the experiment conducted with nozzle A and 89 Vpp for the one performed with nozzle B. This is due to the fact that we wanted to conduct the experiments at the minimum break-up length for both nozzles and as shown on figure 3, this leads to a lower excitation voltage for nozzle A. The results obtained for the amplitudes and phase shifts are shown respectively on figures 5 and 6 (on both figures blank symbols are used for nozzle A and filled symbols for nozzle B). As for figure 4, the vertical lines indicate the break-up points for the jets using the above mentioned nozzles.

In this high initial disturbance regime, which is of practical use in ink-jet printing with a short break-up length, the jet behaviours are seen to be quite different for both types of nozzles (Figure 5). The growth of the amplitude of the fundamentals are far from being exponential all along the jet and in contrast to the low initial disturbance results higher harmonics are present right from the exit of the nozzles. As discussed by Fagerquist[19], we demonstrate here that once the initial disturbance becomes large then the linear theory given by Rayleigh[15] does not apply any more since the periodic perturbation is described by a multi-frequency component.

Concerning the amplitude of the fundamental in the case of the jet issuing from nozzle B, one can observe a plateau. For this experiment, the amplitude of the second harmonic initially grows, then stabilizes and begins to grow again. Similar behaviour is also observed with other overtones. In contrast, the growths of the second to the fourth harmonic are monotonous for the jet exiting from nozzle A.

So, it seems that during the first part of the jet length ($z/\lambda<2$) other effects probably vorticity seem to dominate over capillary instability, so for high initial disturbance experiments there is an intricate mixing of kinematic and capillary effects. The practical consequence of this mixing is that jet break-up is delayed. This delay is much more important for the jet issuing from nozzle B than the one from nozzle A. Further experiments still need to be performed to understand why kinematic effects are more amplified for one geometrical configuration compared to another.

Finally concerning the phase shifts (Figure 6), one can notice that close to the nozzle ($z/\lambda = 0$) there is a large difference for ϕ_{21} (equal to 110° for the jet issuing from nozzle A and 30° for the other one) which is the phase shift between the fundamental and the second harmonic. To our opinion, this initial value can be assumed to be a characteristic of the nozzle and its flow geometry. This difference seems to die out slowly and along the major part of the jet ϕ_{21} is equal to 80°. However the initial difference in phase shift leads to two different jet profiles and consequently jet break-up behaviours which are not similar.

Conclusions

The role of the nozzle geometry on the break-up of liquid jets has been experimentally demonstrated in this paper. For this purpose we have used two types of jet stimulation and various measurement methods.

The break-up length measurements performed with a stroboscopic illumination permits to obtain efficiency values for different types of nozzles but is not able to provide any information on capillary wave dynamics.

The laser shadow technique used in conjunction with DFT analysis allows to extract values of the amplitudes and phase shifts of harmonics from the temporal variation of the jet radius. This method proves to be invaluable in characterizing the intricate surface phenomena and in pinpointing subtle differences between nozzles.

Finally to summarize, our study leads to conclude that nozzle effects are negligible for low initial disturbances and may become predominant for high initial perturbations which is of interest in most industrial applications.

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