Capillary Instability of a Jet Induced by Surface Tension Modulations

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Abstract

This paper presents experiments performed on a fluid jet stimulated by an external thermal device which in our case is a laser diode. The investigation considers both sinusoidal and harmonic excitation signals. We demonstrate that in the case of a purely sinusoidal excitation the break-up length varies semi-logarithmically versus the optical power of the laser diode. In the case of a harmonic excitation, the excitation frequency, the amplitude and phase of the signals are independently controlled, leading to a variety of drop break-up patterns. Finally, the most suitable conditions for printer applications are emphasized and the physical mechanisms of thermal stimulation are discussed.

Introduction

Continuous ink-jet technology requires the formation of drops, from a jet, at a well-defined rate. Generally, piezoelectric stimulation producing velocity disturbances which grow through surface tension forces until the jet breaks up into uniform drops has been used[1]. Other stimulation techniques might be used, in particular for designing multi-jets devices. The ElectroHydroDynamic (EHD) exciters, which appear to be easy to design because the stimulation stage is downstream the nozzle have been considered[2,3]. With fluids of rather low vicosity, all techniques which result in a sinusoidal stimulation of low amplitude of the jet lead to a break-up with satellites which are deleterious for appropriate printing since they lead to drop placement errors. In order to obtain a stream of drops devoid of satellites, it is necessary to impose a complex periodic signal. This has been successfully performed for the EHD stimulation technique by introducing two modes which are further amplified by the capillary effect[4,5]. A disadvantage of the EHD stimulation is the necessity of rather high electrical fields which lead to both high voltages and small clearances between the electrode and the jet. So there is incentive to find other stimulation means which operate downstream the nozzle similarly to the EHD excitation.

In this paper, we present results on the thermal stimulation of a continuous jet using both sinusoidal (frequency f) and harmonic (two modes of frequency f and $2f$) signals. First of all, we detail the experimental arrangement and procedures used in this investigation. Secondly, we present selected results obtained for both single and two mode excitations. In particular, we present a discussion of the different régimes of break-up obtained, and we emphasize the operating conditions which allow or suppress the formation of satellites. Finally the physical mechanisms of the thermal stimulation are examined.

Experimental Set-Up and Procedures

The experimental set-up is shown in figure 1. The jet (diameter = $2a$ = 72 μm), emerges from a standard printing head with an orifice having a length over diameter ratio $l/2a \cong 1$. The jet velocity ($U_o \cong 12$ m/s) is carefully controlled by means of a pressure regulated tank containing the fluid. The stimulating device consists of a laser diode emitting in the red radiation of 680 nm with a maximum power of 30 mW. At the exit, the emitted laser beam is divergent. Using appropriate lenses, we obtain a laser spot of about 30 μm in diameter which is then focused on the jet surface at about 1 mm downstream the orifice. The optical power of the laser diode is modulated at a frequency approximately equal to 40 kHz. By using a customized software, the modulated signal is synthesized on a micro-computer and converted to a analog one which is then sent to the laser diode driver.
The optical energy applied onto the jet reads:

$$P(t) = P_0 + P_1 \cos(2\pi f t) + P_2 \cos(2 * 2\pi f t + \varphi) \quad [1]$$

where P_0 , P_1 , P_2 are the continuous, the first and second mode of the optical power, φ is the phase shift between the fundamental and the second mode. In contrast to Nahas and Panton's work[6], we control carefully the modulation of the light and consequently the disturbances applied onto the jet. Moreover we are able to obtain a much greater efficiency in our stimulation compared to their's. This is mainly due to the fact that we were particularly careful in choosing a very absorbing ink. The typical absorption thickness is of the order of a few microns, thus a very thin outer layer is heated and this enhances the stimulation efficiency.

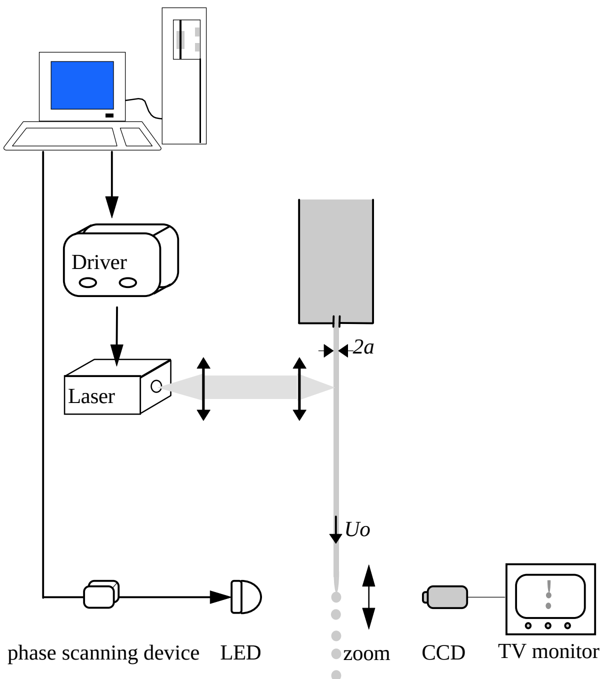

Figure 1 Schematic representation of the experimental set-up

The inkjet break-up is studied using a visualization technique described elsewhere[3]. The microcomputer used to generate the signal also triggers a strobe light (LED) which allows us to observe the magnified jet profile on a video display. The mean velocity U_0 of the jet is determined from the relationship $U_o = \lambda f$ (λ the wavelength $\cong$ 350 µm). In order to observe closely the break-up of the jet, the formation and lifetime of the satellites, we introduce a variable phase shift between the diode triggering signals and those of the LED. This allows to strobe the jet at different relative times, i.e. at different axial locations.

The fluid used is a dyed glycerine-water mixture with viscosity $\mu \cong 6.35$ mPa.s, with a dynamic surface tension σ of $65{\cdot}10^{-3}$ N/m and mass density $\rho \cong 1130$ kg/m^3 at room temperature.

One mode thermal stimulation

Thermal disturbance of the jet

As a first step, we stimulated the jet using only the fundamental mode (i.e. we limited ourselves to the first two terms appearing in equation 1). In order to have the maximum efficiency, we performed our measurements at the optimum wavenumber $k_{opt} \cong 0.7$ with corresponds to the minimum break-up length. First of all we observe, by putting on and off the laser diode a clear variation in break-up lengths, indicating a thermal stimulation of the jet. When the laser diode is on, we also observe the formation of drops and satellites with a well defined frequency giving a very stable picture on the TV monitor. This picture is identical to the ones obtained by sinusoidal stimulation through weak piezoelectric or EHD excitations. This demonstrates unambiguously that the thermal modulation imposed onto the jet induces surface tension modulations which constitute the initial disturbance amplified by the capillary instability. Note that although the laser spot falls only on one side of the jet, because the circular jet is unstable the axisymmetric mode is amplified leading to the break-up of the jet.

Effect of the optical power

Figure 2 shows that the break-up length varies semi-logarithmically as a function of the optical power peak to peak which can be changed readily using the driver.

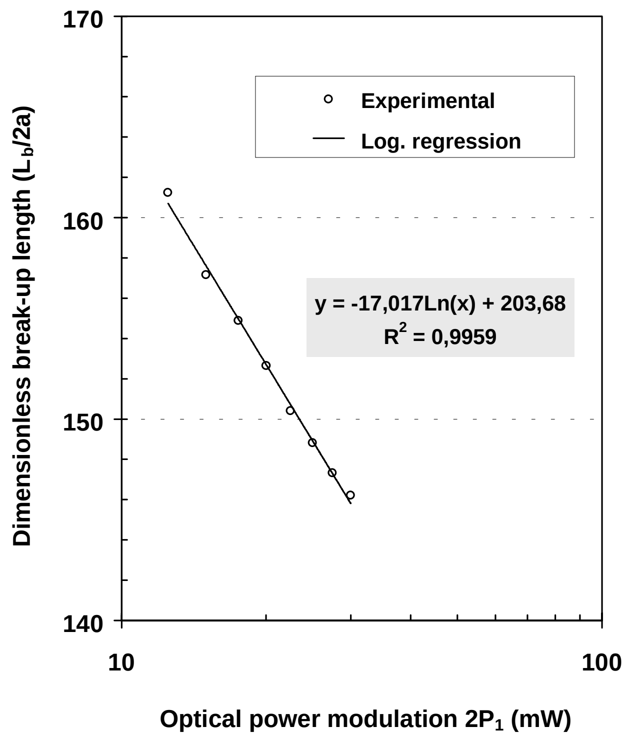

Figure 2 Jet break-up length as a function of the laser diode optical power, k = 0.71, We = 102, $P_1 \in [10\text{-}30]$ mW

According to the linear stability analysis the break-up length L_b is related to the equivalent initial radius perturbation of amplitude ε_o through:

$$\frac{L_b}{2a} = \frac{\sqrt{We}}{2\gamma} Ln\left(\frac{\varepsilon_o}{a}\right) \qquad [2]$$

where We = $(\rho U_0^2\ a/\sigma)^{1/2}$ is the Weber number and γ the dimensionless growth rate.

The modulation of the surface tension is proportional to the modulation of the temperature at the surface which itself is proportional to the amplitude of modulation of the laser diode power. It is natural to expect ε_0 to vary in proportion to P_1 as shown in figure 2. From the slope obtained by fitting the experimental data and using relation [2], we obtain an experimental value of the growth rate $\gamma_{exp} \cong 0.30$ for $k = 0.70$ in good agreement with the linear theory taking into account the viscous effect in the jet and aerodynamic interactions [7]. From the experimental operating conditions, it would be interesting to evaluate the order of amplitude of the temperature modulation ΔT on the jet surface and the energy Q required for the formation of a drop. We find:

$$\Delta T \cong 1°\mathrm{C} \qquad\qquad Q \cong 1\ \mu\mathrm{J}$$

Finally from the value of the break-up length, we deduce the ratio (ε_o/a) which is approximately equal to 10^{-4} close to the values obtained using EHD stimulation[2,3]. Therefore these thermal and EHD stimulations are considered to be rather weak types of stimulation compared to the acoustic one. Using one mode thermal excitation, one always observes the formation of one drop and one satellite per wavelength (figure 3). From the results obtained using EHD stimulation[4,5], we expect to control the break-up pattern using a two-mode thermal stimulation and thus to obtain a stream of drops devoid of satellites.

Two mode thermal stimulation

Operating conditions

The complex signal retaining two modes (3 terms of equation (1)) is first synthesized using our customized software and then sent to the laser diode driver.

The frequency f for our two mode thermal stimulation measurements was 19.5 kHz. As for the EHD stimulation, we choose to work at a dimensionless wavenumber $k = (2\pi a/\lambda) < 0.5$ (λ is the wavelength) in order for the second mode to be amplified. As seen on figure 3, when the fundamental is predominant we find one drop with a slow satellite per period whereas when the stimulation signal consists of only the second mode we find two drops and two satellites. In order to investigate the behaviour of the jet between the above cited patterns we choose to vary the ratio P_2/P_1 (optical power ratio of the two modes) and the phase shift φ.

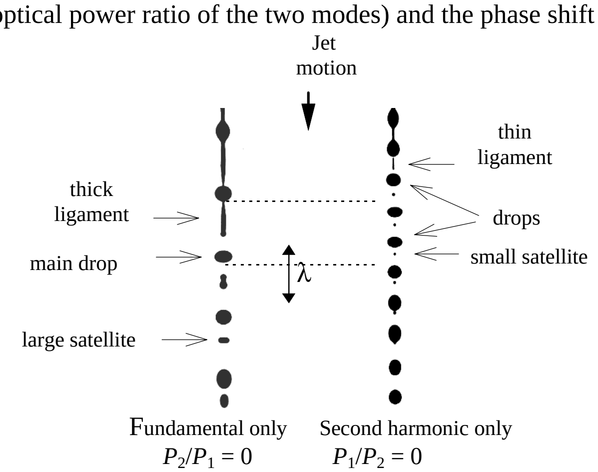

Figure 3 Typical jet break-up patterns

General map of the different régimes

Figure 4 shows the general map in the P_2/P_1-φ plane exhibiting the different zones where the break-up generates one, two, three or four droplets per wavelength. This type of behaviour is very much reminescent of the one which has been obtained with EHD stimulation [4,5]. The only difference is a phase shift of about 180° with respect to the map obtained using EHD stimulation. This point will be discussed in the next section.

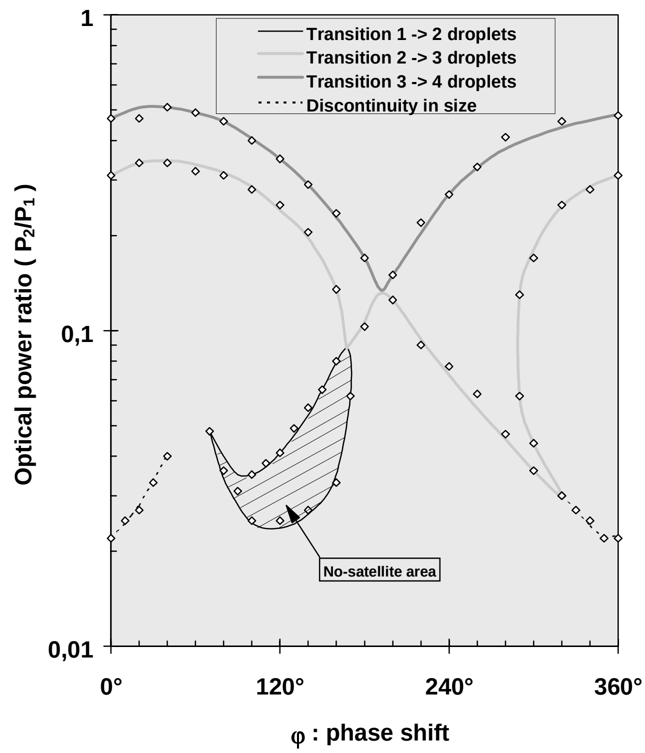

Figure 4 Jet break-up diagram at wave-number k = 0.40 and jet velocity U_0 = 11.1 m/s

Break-up zones without satellites

It is an essential requirement for technological reasons to obtain a stream of drops devoid of satellites. The operating conditions in the case of figure 4 ($k = 0.40$ and $U_0 \cong 11$ m/s) give rise to a single no-satellite area corresponding to a fore-side break-up. In order to obtain several no-satellite zones with both aft and fore-side break-up, as it was shown by using EHD stimulation[8] it is necessary to increase the wavenumber and/or the jet velocity which are the relevant parameters.

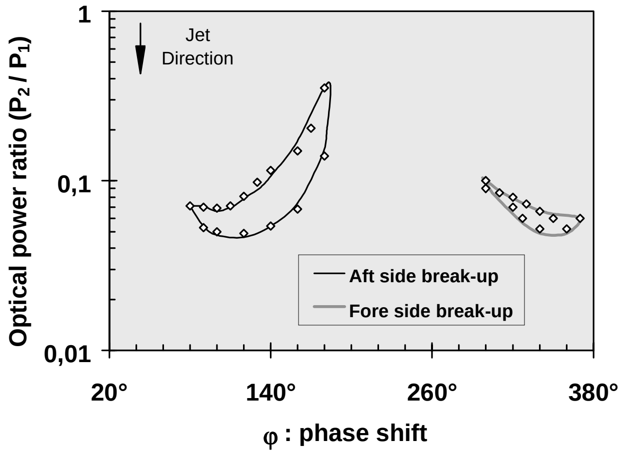

Figure 5 No-satellites areas at wave-number k = 0.43 and jet velocity U_0 = 13.9 m/s

Figure 5 exhibits the existence of the two expected no-satellite areas for the conditions k = 0.43 and $U_0 \cong 14$ m/s. The aft-side break-up area is smaller than the fore-side one, but we have shown for EHD stimulation[8] that one can obtain a rather good balance of the size of the two areas by further increasing the jet velocity.

Mechanisms of thermal stimulation

In the present part, we wish to examine liquid zones subjected to axial temperature gradients which induce axial flows that may generate the initial radius perturbation This perturbation can be subsequently amplified by the capillary instability phenomenon. We begin by considering an infinitely long axisymmetric column of liquid bounded by a free surface of radius $r = a$. The interface possesses surface tension which is assumed to vary linearly with the local temperature:

$$\sigma = \sigma_0 - \beta(T - T_0) \qquad \beta = -\left.\frac{d\sigma}{dT}\right|_{T=T_0} > 0$$

Considering a sinusoidal variation of the temperature imposed on the surface along the axis x of the column, the axial surface tension gradient induces flows driven by thermocapillarity:

• the normal stress (capillary pressure) due to the curvature of the jet reads:

$$P = \sigma_{\mathrm{T}} \frac{1}{a} \qquad [3]$$

For a lower value of the surface temperature, the pressure inside the jet is higher, therefore we expect a bulk flow from the colder regions to the heated ones i.e. a pinching of the cold surface and swelling elsewhere. In that case, the deformation of the jet surface would be in phase with the stimulating signal as it is the case for the EHD stimulation where the electric field promotes a decrease of the net pressure inside the jet and a local swelling of the jet.

• Due to the surface tension gradient, the shear stress (Marangoni effect) induces a surface flow from the heated regions towards the colder ones because in these zones the value of the surface tension is higher:

$$\mu \frac{dU}{dr} = \frac{d\sigma_{\mathrm{T}}}{dx} \qquad [4]$$

One would then expect to have the thermal disturbance out of phase with the perturbation of the free surface corresponding to a necking at the heated area.

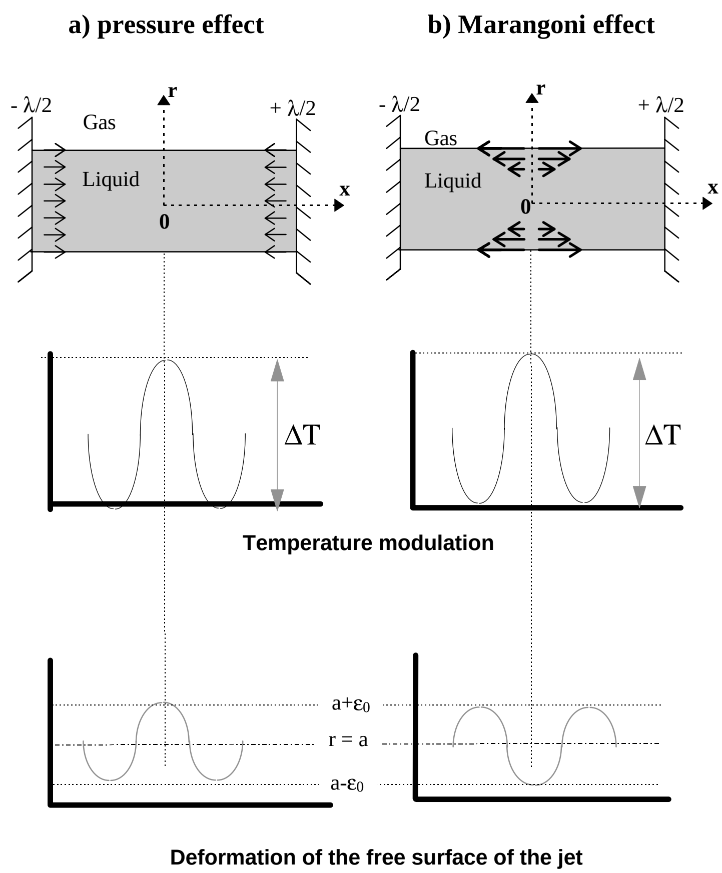

Figure 6 Schematic representation of the jet surface deformation induced by a pressure or Marangoni effect

Considering that the second mechanism is dominant over the first one, we thus explain and understand the phase shift of 180° in the abscissa axis between the 2 mode thermal and EHD stimulations as formely noticed. This is also in agreement with the numerical modelling of Mashayek and Ashgriz[9].

Conclusions

An experimental investigation of the break-up of an ink-jet subjected to one and two mode external thermal stimulations located downstream the nozzle have been presented in this paper. We have demonstrated that a small power laser diode is sufficient to force the capillary instability of the jet. By using a multiple harmonic thermal stimulation we have been able to control the jet break-up patterns. This allows us to obtain streams of drops devoid of satellites which is an essential requirement for ink-jet printing. Moreover, this type of stimulation is very much similar in terms of results to those obtained elsewhere using EHD excitation, and thus represents a viable alternative to the former. Furthermore, we have identified the Marangoni effect as the main driving phenomenon for the external thermal stimulation of the jet.

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