Stimulation of a Conductive Liquid Jet Directly Heated by an Electric Current

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Abstract

This paper presents experiments performed on a conductive liquid jet stimulated by an inner volume heating. The stimulating device consists in a couple of plain stainless steel electrodes located within the channel feeding the nozzle, the liquid flowing through the electrode clearance being heated by Joule effect. By applying an appropriate electrical signal, the stimulating device significantly reduces the jet break-up length and produces a very stable stream of droplets. The break-up length varies semi-logarithmically with the applied electric power. We emphasize on printer applications by performing experiments on typical continuous ink jets of small diameter (~ 50 µm). Finally, the physical mechanisms giving rise to the stimulation are briefly discussed.

Introduction

When a liquid jet naturally breaks up, uneven droplets are formed at a variable distance from the orifice. In a continuous ink jet printer, the jet disintegration is carefully controlled by means of a stimulating device to produce drops of equal size, regularly and at a well-defined rate. Most droplet generators rely on piezoelectric transducers to produce jet velocity disturbances[1] which are amplified downstream through the capillary instability phenomenon.[2] Although acoustic excitation can be readily implemented, it involves the occurrence of sound waves in the whole structure of the drop generator leading to narrow window of operating conditions in particular in multi-jet devices.

Other stimulation techniques have been studied to overcome this problem. The ElectroHydroDynamic (EHD) excitation consists to apply an electrical voltage on an external electrode close to the grounded jet[3,4]; the electrostatic pressure induces a regular jet surface deformation which allows to control droplet formation.[5,6] Previous work devoted to an external thermal stimulation demonstrated the possibility of controlling the jet break-up[6,7]: a laser beam of time modulated intensity is focused on the jet surface and the surface temperature modulation results in a surface tension modulation which induces the expected jet surface disturbance through the Marangoni effect. The main disadvantages of these two external stimulation techniques are their rather low efficiency, and the difficulties to implement the driving devices within the print-head.

In this paper, we report results on the internal thermal stimulation of a continuous jet through Joule heating. After presenting specificity of the driving electrical signal, the experimental arrangement and procedures used in this investigation are detailed. Then, we present results obtained on a scaled-up jet and on jets of a few tens of micrometers in diameter. Finally, we discuss the stimulation mechanism.

Technique for Ink Volume Heating

The basic idea here is to heat the ink flowing in the channel by the Joule effect due to the flow of electric current. Figure 1 gives a schematic view of a device built to achieve such a heating. In a duct of rectangular cross-section two plane electrodes facing each other define a zone of uniform electric field. Applying a sinusoidal potential difference leads to an axial modulation of the temperature of the ink flowing through the duct and hence, to the expected stimulation of the jet issuing from that duct.

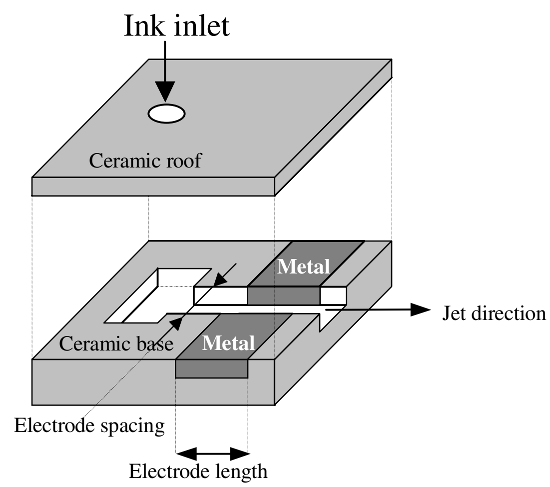

Figure 1. Schematic view of the stimulation device

By applying an appropriate low frequency F_L, one can observe a well characterized jet stimulation, but above a voltage threshold depending on the nature of the electrode metal, the break-up length suddenly increases and the jet exhibits rather random perturbations. This behavior is due to the generation of small bubbles at the surface of the electrodes resulting in a marked decrease and a chaotic behavior of the electric current. The bubble generation arises from electrolysis of the ink which is a mixture of glycerine, water and conductive dyes.

In order to prevent bubble formation, it is necessary to eliminate the electrochemical reactions at the electrodes. This was achieved by using a high frequency F_H signal, the amplitude of which is modulated at the (low) frequency of drop generation (Figure 2). Indeed the over-voltages on the double layer at the metal/ink interfaces induced by the electric current must have an amplitude η_0 lower than the smallest over-voltage η_i characterizing the possible electrochemical reactions; this leads to an estimate of the appropriate high frequency F_H.

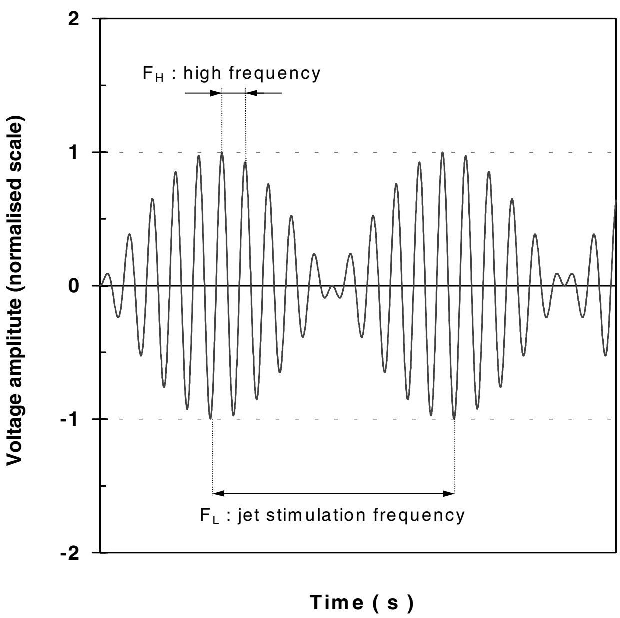

Figure 2. Voltage pattern applied onto the stimulating electrodes

Denoting by C_l the capacitance per surface unit of the compact double layer and by J the current density in the ink, the amplitude η_0 of the over-voltage is :

$$\eta_0 = J / (\omega_H C_l) = (\gamma_e V_0) / (d \omega_H C_l) \quad (1)$$

γ_e being the ink electrical conductivity, V_0 the peak value of the applied voltage and d the electrode spacing. By taking the typical value $C_l = 10^{-1}$ F/m^2 and $\eta_i = 1$ V (potential of electrochemical reactions), the condition $\eta_0 < \eta_i$ leads to :

$$\omega_H > 10 \gamma_e V_0 / d \quad (2)$$

It is clear that the high frequency $F_H = \omega_H / 2\pi$ must be increased when the ink conductivity or the applied voltage is increased or when the jet diameter is decreased. In the case of our scaled-up jet, $\gamma_e \cong 10^{-1}$ S/m , $d \cong 300$ µm and $V_0 \cong 100$ volts, one obtains :

$$\omega_H > 3\ 10^5\ s^{-1} \quad \rightarrow \quad F_H > 50\ kHz \quad (3)$$

A test performed at constant voltage amplitude V_0 by varying the high frequency F_H shows that there exists a sudden jump of the break-up length at $F_H \sim 100$ kHz (Figure 3). Clearly, for $F_H > 100$ kHz, the stimulation is very stable whereas at lower frequencies the stimulation is much weaker and the electric current is very noisy revealing the occurrence of disturbing small bubbles. Note that relation (2) predicts the good order of magnitude of the transition frequency.

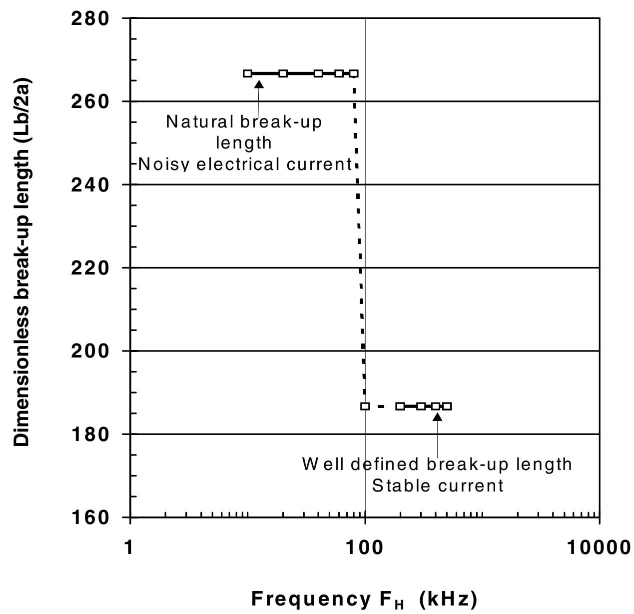

Figure 3. Dimensionless jet break-up length (“L_b“ and “a” being jet breakup length and jet radius) as a function of the high frequency (F_L is kept constant).

Experimental Method and Observations

Experimental Set-Up

The experimental set-up is shown in Figure 4. The stimulating device (see for instance Fig. 1) is fed with ink maintained at a constant regulated pressure. A high voltage amplifier driven by the amplitude modulated high frequency signal supplies the stimulating device. An analog voltage generator generates such a signal, the expression of which is :

$$V(t) = (V_0/2) * [\ 1 + Sin(2\pi F_L\ t)\ ] * Sin(2\pi F_H\ t) \quad (4)$$

The electrical power dissipated within the ink writes (after integrating over one period of the high frequency signal) :

$$P(t) = \frac{V^2(t)}{R} = \frac{V_0^2}{8R}\left[\frac{3}{2} + 2\sin(2\pi F_L t) - \frac{1}{2}\cos(4\pi F_L t)\right] \quad (5)$$

R being the ink volume resistance in between the electrodes. The mean power delivered to the ink is $\overline{P} = 3V_0^2/(16R)$ and the power modulated at the frequency of drop generation F_L has an amplitude :

$$P_I = V_0^2 / (4R) \quad (6)$$

(it is assumed in the following that the dimensionless wave-number k is such that $0.5 \le k < 1$).

The ink-jet break-up was studied using a stroboscopic technique ; the voltage generator triggers a strobe light (LED) which allows one to observe the magnified jet profile on a video screen. The mean jet velocity U_0 is determined from the relation $U_0 = \lambda F_L$ (λ is the drop formation wavelength). In order to determine accurately the jet break-up length L_b, the phase shift between the triggering signal and the pulse applied to the LED can be tuned. The used ink is a dyed glycerine-water mixture (the dye also provides for the conductivity γ_e of the ink).

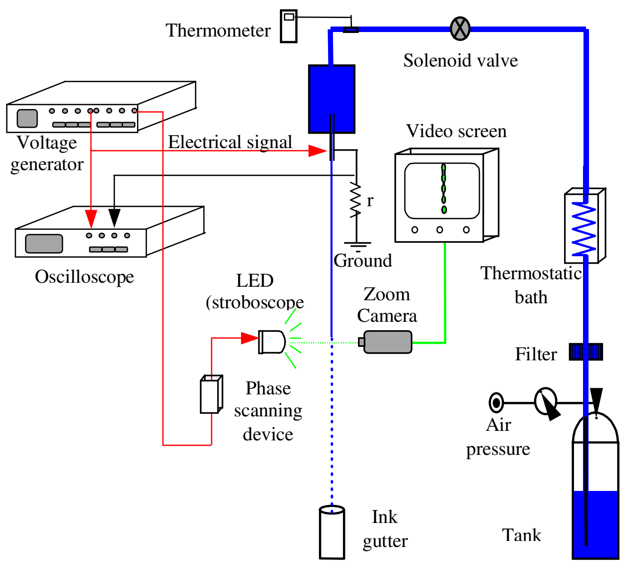

Figure 4. Schematic diagram of the experimental set-up

Results on the Scaled-Up Jet (300 µm in Diameter)

As a first step experiments were performed on a scaled-up jet because the stimulation device (Fig. 1) is easy to machine. The electrodes length L_e is 740 µm, the cross-section of the channel is 300 x 350 µm^2 (d = 350 µm being the spacing between electrodes, the channel height being 300 µm). The jet emerging from the channel rapidly relaxes towards a circular cross section of diameter $2a \cong 300$ µm.

At a given voltage amplitude, the shortest break-up length is obtained by tuning the low frequency F_L (the expected frequency corresponds to the highest growth rate of perturbations). By increasing the voltage amplitude, one observes a significant reduction of the jet break-up length as shown in Figure 5.

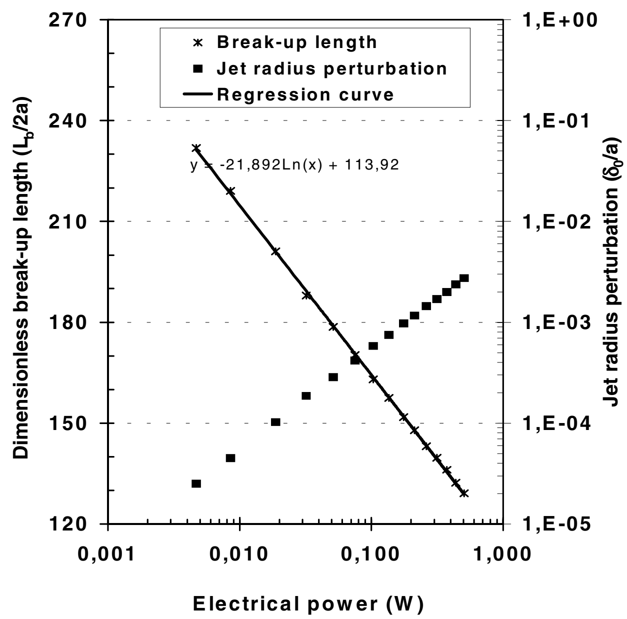

Figure 5. Non dimensional jet break-up length $L_b/2a$ and initial radius perturbation δ_0/a versus the electrical power input. U_0 =6 m/s , F_L = 3200 Hz, F_H = 400 kHz, ink viscosity μ = 23 cps, ink electrical conductivity γ_e = 0.12 S/m.

The break-up length varies semi-logarithmically versus the electrical power dissipated into the conductive ink. According to the linear stability analysis, the break-up length L_b is related to δ_0, the equivalent initial perturbation of the radius, through :

$$\frac{L_b}{2a} = \frac{\sqrt{We}}{2\gamma} \; Ln\left(\frac{\delta_o}{a}\right) \quad (7)$$

where $We = (\rho U_0^2 a/\sigma)^{1/2}$ is the Weber number, σ = 60 mN/m the ink surface tension, ρ = 1182 kg/m3 the mass density and γ the dimensionless growth rate.

The straight line obtained in Figure 5 suggests that the amplitude δ_0 of the initial jet radius perturbation is proportional to the electrical power dissipated by Joule effect. From the slope obtained by fitting the experimental data and by using relation (7), the measured value of the non-dimensional growth rate is $\gamma_{exp} \cong 0.28$ for the dimensionless wave-number $k = 2\pi a F_L/U_0 \cong 0.68$. These values are in very good agreement with the ones predicted by the linear theory taking into account the viscous effects.

We see from Fig. 5 that δ_0/a takes the value 3 10^{-3} for P_I = 0.8 W. We purposely compare this efficiency to those of other stimulating techniques such as EHD ($\delta_o/a \cong 10^{-4}$-10^{-3}), external thermal stimulation by laser ($\delta_o/a \cong 10^{-5}$-10^{-4}) and finally acoustic excitation ($\delta_o/a \sim 10^{-1}$). Accordingly our direct ink heating technique is clearly more efficient than the EHD or laser techniques which appear to have a weak stimulating effect.

Results on Industrial Jets (50 µm and 30 µm in Diameter)

In the scope of continuous ink jet applications, we investigated the volume thermal stimulation onto jets of 50 µm and 30 µm in diameter. As a first attempt, we built a stimulating device as depicted in Figure 1. The jet denoted #1 of 50 µm in diameter was issuing from a channel of about 50 x 50 μm^2 in cross section and the electrode length was 100 µm.

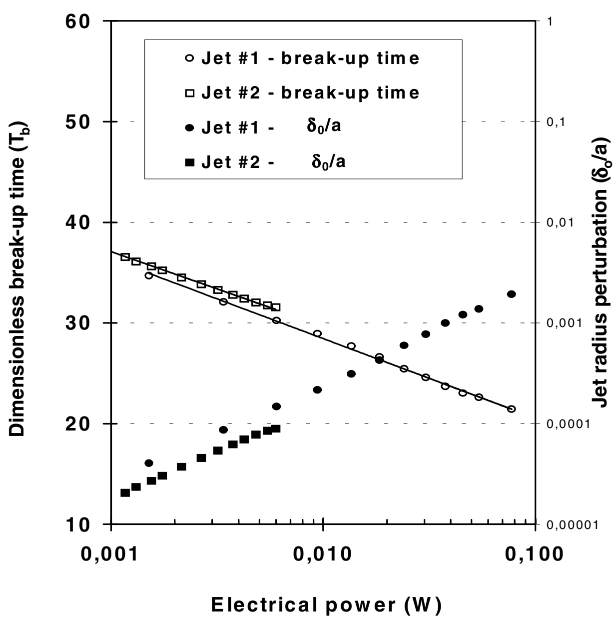

Figure 6. Non dimensional jet break-up time T_b and initial radius perturbation δ_0/a versus the electrical power input for k = 0.7. Ink : water-glycerine-dye mixture, μ = 3.6 cps, ρ = 1050 kg/m^3 , σ = 60 mN/m, γ_e = 0.56 S/m (jet #1: 2a = 50 µm, U_0 = 12 m/s, F_H = 1 MHz; jet #2: 2a = 30 µm, U_0 = 15 m/s, F_H = 1.3 MHz).

Figure 6 shows the variations of the dimensionless break-up time ($T_b = L_b / 2a\sqrt{We}$) versus the electrical power input. Clearly the stimulation stage and then the growth stage are similar to those characterizing the scaled-up jet; there is a rather strong excitation proportional to the power input and the experimental growth rate and optimum wave-number are also in good agreement with theoretical predictions.

The main drawback of this device arises from a jet orientation varying from time to time. We suspect that such instabilities were due to both thermo-capillary flows in the meniscus at the channel exit and the rough shape of the outlet because the device is built with two different ceramic parts.

Another stimulating device denoted jet #2 was designed based on a set of 3 foils as shown in Figure 7. This device which is easier to machine than the first one consists of a polyimide foil of 80 µm in thickness drilled by Excimer laser to form a convergent hole of 40 µm inlet and 30 µm outlet diameters. The two metal foils are plain 304 stainless steel drilled to form holes of 40 µm and 30 µm in diameter. The whole set is then carefully aligned, glued and finally sealed to a pressurized ink reservoir. The modulated high frequency signal is applied on the uppermost plate whereas the lower plate is grounded and plays the role of the well-known nozzle plate. A study of the break-up time versus electrical power input (Fig. 6) shows that this jet #2 exhibits an efficiency similar to that of device #1. The advantage of this second technique of device implementation is that the jet is very well calibrated in diameter and perfectly stable in direction.

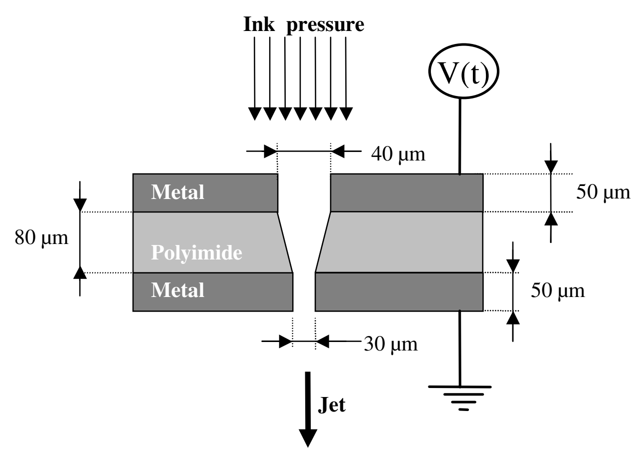

Figure 7. Schematic cross section of the direct ink heating stimulating device based on a set of 3 foils

Discussion

The afore presented results establish that the inner thermal stimulation by modulated Joule heating works well and exhibits an efficiency higher than the EHD or outer thermal stimulations. The physical mechanisms responsible for the stimulating action, however, are not clear.

The only obvious conclusion concerning this (or these) mechanism(s) is that the generation of bubbles is not involved in the stimulation process. Firstly we operated in such a way as to eliminate electrolysis of the water-glycerine mixture (no gas generation). Secondly, by determining an approximate solution for the ink mean temperature distribution T_s in the channel, it is found that T_s rises by at most 5 degrees for the highest electrical power input used with our jets. Such a temperature increase is far too small to produce a local vaporization of the ink.

The thermal stimulation presumably arises from the variations with temperature of the physical properties of the liquid, namely the mass density ρ, the viscosity μ and the surface tension σ. The magnitude of the temperature modulation (at frequency F_L) can be easily estimated. The power P_1 delivered during about half the period results in a temperature increase of the liquid lying between the electrodes of the order of

$$\Delta T_{mod} \sim \frac{P_I}{2\pi F_L \rho\, c_p L_e\, a^2} \qquad (8)$$

c_p being the specific heat (this relation is derived from the equation of energy conservation). This leads to $\Delta T_{mod} \sim$ 0.8 K for the scaled-up jet and $\Delta T_{mod} \sim 1$ K for the small jet #1 under maximum power input.

We do not think that surface tension plays a dominant role in this stimulation process. Indeed as the heating occurs inside the channel, we expect only very small temperature gradients (of the relevant wave length) at the jet surface downstream the nozzle.

Considering the effect of the ink expansion, we have, to a rough approximation :

$$\frac{\delta_0}{a} \cong \frac{1}{2}\frac{\Delta U}{U_0} \cong \frac{1}{2}\frac{\Delta\rho}{\rho} \approx \frac{1}{2}\frac{1}{\rho}\frac{d\rho}{dT}\Delta T \qquad (9)$$

This gives estimates of δ_o/a between 20 and 100 times lower than the measured values. Expansion therefore plays a negligible role in the stimulation.

The influence of the modulation of the ink viscosity is much more difficult to scale. We developed an order of magnitude analysis of the modulation of the flow between plane parallel electrodes based on the assumption that there is a modulation of the wall shear stress. This approach led to estimates for δ_o/a between 3 and 10 times lower than the measured values. A detailed numerical investigation proves to be necessary in order to determine the influence of the viscosity modulation and to draw a conclusion concerning the physical mechanism of the volume thermal stimulation.

Conclusion

Experimental study was performed on a thermal stimulation technique in which electrical conductive ink is directly heated by electric current (Joule effect) by mean of a couple of electrodes located inside the nozzle on the fluid path. The key point in this technique is to use a high frequency voltage whose amplitude is modulated at the frequency of drop generation. The high frequency modulated signal avoids the formation of any electrolysis bubble. The amount electrical energy dissipated is significantly increased leading to rather short break-up length i.e. a good stimulation efficiency. Moreover, this type of stimulation was investigated on jets of a few ten microns in diameter with consistent results with respect to preliminary ones obtained on a scaled-up jet. Furthermore, we have discussed the physical mechanisms involved in the stimulation technique, viscosity variation with temperature is supposed to be the main driving phenomenon although a numerical analysis is mandatory to clarify its influence

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Biography

Bruno BARBET is a research engineer within IMAJE S.A. He received his PhD. in Physics from Grenoble University (France) in 1997. He is a co-author of several papers published in the area of ink-jet printing.

Pierre Atten received his PhD. in Physics from Grenoble University (France) in 1969. Since 1963 he has worked in the Laboratory of Electrostatics and Dielectric Materials (LEMD) of Grenoble. His studies concerned space-charge modified electric fields, the behavior of dielectric liquids subjected to electric fields and electrohydrodynamics with Coulomb force. He published extensively on various EHD instability problems (linear, nonlinear, transient), electroconvection, transition to turbulence, etc... Since 1991 he is working on electro-capillary instabilities and on the electrorheological effect.