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Experimental Temperature Compensation on Drop-On- Demand Inkjet Printing

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Abstract: The paper demonstrates the interest in using temperature compensation to stabilize drop-on-demand inkjet printing process. Experiments describing the influence of inkjet printing parameters on the droplet velocity and ejection stability are discussed. Experimental results have permitted to develop a relation between the printing parameters and the kinetic property of drops where a variation of temperature is compensated by an adjustment of pulse amplitude. This method allows to obtain stable drops velocity for a variation of 15°C, while without compensation the velocity increases by 5 m/s. Thus, drop ejection is stabilized and the print quality is optimized.

Keywords: Inkjet printing, drop-on-demand, droplets characteristics, temperature compensation.

INTRODUCTION

Inkjet printing developed in the seventies was first dedicated to office printers and industry of graphic applications. Nowadays its use has been extended to various applications such as sensors, MEMS [1,2], medical diagnostic [3], organic electronics (RFID, TFTs), or displays [4,5]. This technology is a non impact dot matrix printing technology in which droplets of ink are directly jetted from a small aperture to a specified position on a media. There are two methods of ink jet printing with many variations within each [6]. The first discovered ink jet printing method was continuous ink jet whereby a continuous ink stream is broken into droplets of uniform size and spacing [7]. The second method is drop-on-demand technology allowing the printhead to generate ink drops on request. On the application of voltage pulses, ink drops are ejected by a pressure wave created by mechanical motions of piezoelectric ceramic actuators. One of the potential performance advantages of drop-on-demand inkjet printing, which made it such an attractive technology, is a good print quality and a very high accuracy of layers positioning. Current researcher activities focus on ink jet printing technology and liquids behaviour (rheological properties) within inkjet printer heads [8, 9]. In this field, the control of the ejected drops properties (volume and velocity) is an important challenge. These properties depend on the rheology of the product (viscosity, density, surface tension) and of the electrical signal (frequency, pulse amplitude and impulsion width). The most important among the rheologic parameters of the fluid is the viscosity. This factor can be controlled by an external thermal regulation of the manifold of ink. Concerning piezoelectric actuator, because of a heating phenomenon due to high frequency printing ejection (1-10 kHz), having a stabilized temperature is hardly gained. This involves a decrease in the liquid viscosity and a change of drop characteristics. To stabilize this mechanism and to accurately deposit small volumes of liquid material over a long period of time, the objective is to compensate the thermal variations.

One solution proposed by Zapka *et.al* is to use the capacitance of the channel walls as a temperature sensor [10]. Temperature changes inside the actuator will cause a change in the dielectric permittivity which can be measured as change in the capacitance of the walls. The measurements were made with a printhead, on which the cover material has been changed from PZT to aluminum nitride (AlN). This material has almost the same mechanical characteristics as PZT but has a much higher thermal conductivity. This technique allows checking the magnitude of temperature changes inside the actuator and so to improve the homogeneity of the print. Nevertheless, inkjet printer material has to been modified and equipment to measure the capacitance is also necessary.

The aim of this paper is to propose another approach directly from an experimental study of the inkjet parameters influence on the drop velocity. The method allows determining a relation between the liquid temperature and the pulse amplitude is first described, then the temperature compensation effect is analysed and discussed.

EXPERIMENTAL

For drop-on-demand systems the most common technology is piezoelectric inkjet (used by e.g. *Xaar*, *Epson…*). Piezoelectric inkjet printers use the inverse piezoelectric effect, which causes ceramic materials to change shape when a voltage is applied across them. The inkjet printheads studied in this work are Xaar760® shear mode inkjet actuator, series "greyscale" where the printhead eject drops of variable volume. These are formed by producing sub-droplets at a much higher frequency and in groups. The number of droplets per group is variable according to the printhead specification (number of greyscale levels) [11]. These printheads, with 27µm nozzle aperture, use the deformation of piezoelectric actuators to cause an ink volume change in the pressure chamber. This volume change generates a pressure wave that propagates across the nozzle. This acoustic pressure wave overcomes the viscous pressure loss in the small nozzle and the surface

tension force from the ink meniscus so that an ink drop can be ejected from the nozzle. The actuator is composed of a base plate made of Piezoelectric lead Zirconate Titanate (PZT) ceramic, and an inactive cover plate (Figure 1). The base plate contains a multitude of ink channels. Metal electrodes are deposited on the upper half of both sides of the channel wall. The electrodes within one channel are connected galvanically at the wire bond area. The cover plate is glued onto the base plate [12].
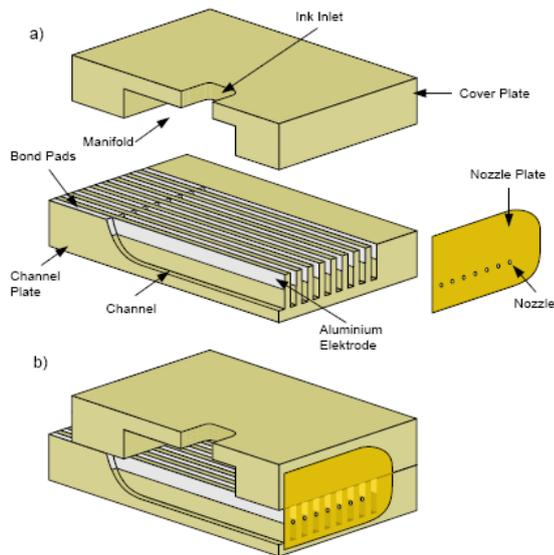

FIG.1. Exploded view of a *Xaar*-type actuator: a) components and b) an assembled actuator [12].

For drop generation, driving voltage signals are applied to the electrodes, generating fields perpendicular to the direction of polarization in the channel walls (Figure 2). This produces shear mode displacement in the upper half of the channel wall.
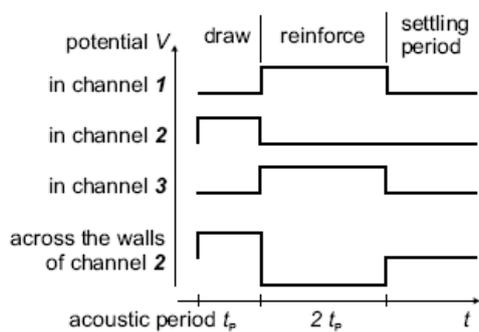

FIG.2. Typical waveforms of the driving voltage signal applied to the shear mode actuator for drop generation [12].

A negative signal pulse deforms the piezoelectric crystal which creates two acoustic waves of compression. During the positive pressure, the acoustic wave splits up and propagates in both directions. This causes a contraction of walls inside of the channel which is going to increase the phenomenon of overpressure within the liquid and to introduce the ejection of the drop. The reflection of the acoustic wave inverts the pressure at the manifold, what allows the breakup of the ligament. The depression, in the other extremity, also allows sucking up the liquid of the manifold to fill again the channel.

The liquid used is silicon oil DC 704 from Dow Corning. The viscosity of liquid to be ejected has to be in the range of 6-15cP for a temperature lower than 65°C. Measurements of silicon oil viscosity are made on a Brookfield cone/plate rheometer. The droplets formation has been visualized with a stroboscopic optical system composed of a CCD camera synchronized with a strobe LED system. The whole system is controlled by a computer, in order to store pictures of droplets during their formation. To calculate the velocity, two pictures are taken at different times. Knowing the delay between both pictures and measuring the distance, velocity can be estimated. In this work, we essentially focus on stabilization of the droplets ejection velocity. Thus, the experimental study consists in determining the variations of the drop velocity of Xaar760® printhead under the influence of (i) the shape of the waveform, (ii) the amplitude and pulse duration of the waveform, (iii) the viscosity of the liquid. Unfortunately, with Xaar® printheads it is not possible to change the shape of the waveform, so only the amplitude and impulsion width of the signal were able to be modulated. We have first tested the influence of impulsion width sent to the piezoactuator at two different temperatures; the pulse amplitude and frequency were fixed to 10 V and 2000 Hz, respectively.

The obtained results show that there is an optimum impulsion width (260 ns) which maximizes the drop velocity (Figure 3).
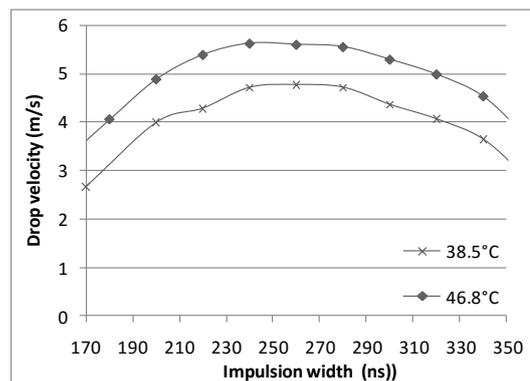

FIG.3. Drop velocity variations versus impulsion width with the Xaar760® printhead.

Once the optimal value of pulse duration was fixed we were interested in the effect of pulse amplitude. For all tests presented after, the frequency of ejection has been set up to 1000 Hz and to simplify the work, the binary mode (small drop size = 8pl) has been used.

RESULT AND DISCUSSION

Ink jet experiments have been performed on the DC 704 silicon oil in order to characterize the drop velocity according to the main process parameters: pulse amplitude and temperature. As shown in figure 4, the drop velocity increases linearly with pulse amplitude. Indeed, when higher pulse amplitude is applied to piezoactuator, its movements are emphasized and more kinetic energy is transferred to drops.
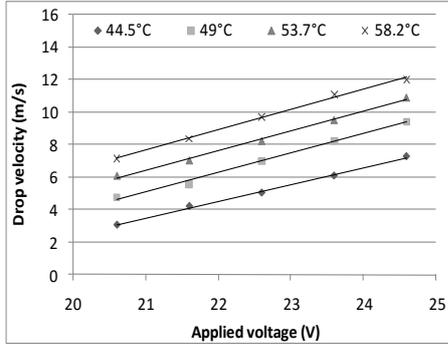

FIG.4. Pulse amplitude effect on the drop velocity of DC704 silicon oil at different temperature.

Additionally, a constant slope is evidenced for all curves. So, we can notice proportional variation of the drop velocity, in value of pulse amplitude:

$$v = C_1 \times U + C_1'$$
(1)

Where v is drop velocity, U is applied voltage, C_1 is a constant (curves slope are independent of temperature) and C_1' a variable depending on ejection temperature.

Experimentally the equation (1) becomes:

$$v = 1.18 \times U + C_1'$$
(2)

(root mean square = 0.09 m.s^{-1}.V^{-1})

On the same way, we observed the influence of the temperature of the head on the drop velocity. Figure 5 shows that the drop velocity increases with the temperature. Besides, the relation of dependence in temperature of the viscosity follows an Arrhenius law:

$$\eta = \eta_0 \ e^{E/kT}$$
(3)

Where η is the viscosity, η_0 a constant, T is the absolute temperature in ° K, E is the energy of activation, k is the Boltzmann constant.

Experimental values obtained by measuring DC704 silicon oil viscosity with Brookfield rheometer give:

$$\eta = 4.10^{-5} e^{4150/(\theta+273.15)}$$
(4)

θ is the temperature in Celsius degrees

Using equation (4), figure 6 illustrates the linear dependency of the drop velocity against viscosity:

$$v = C_2 \times \eta + C_2'$$
(5)

Where C_2 is a constant (curves slope are independent of pulse amplitude) and C_2' a variable depending on pulse amplitude.

The experimental values give,

$$v = -0.6 \times \eta + C_2'$$
(6)

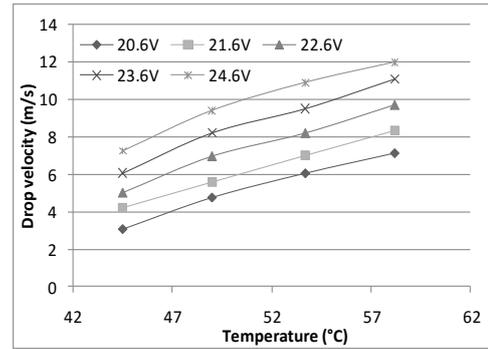(root mean square = 0.04 m.s^{-1}.cP^{-1})

FIG.5. Temperature effect on the velocity of DC704 silicon oil at different pulse amplitude.
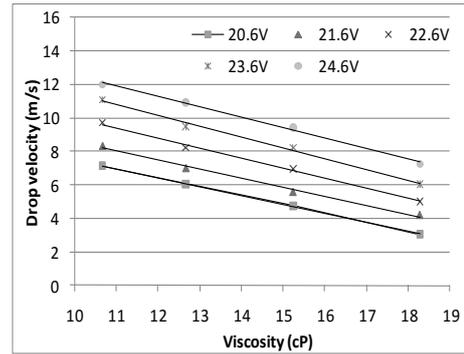

FIG.6. Viscosity influence on the velocity of DC704 silicon oil at different pulse amplitude.

The curves illustrated in figure 6 show that the drop velocity decreases linearly with increasing viscosity, evidencing a constant slope whatever the pulse amplitude is. In fact, the viscosity variation, due to change of temperature, minimizes the friction forces in the channel and makes the liquid flow easier through the nozzle aperture.

By combining the equations (1) and (5), we obtain the following global equation, expressing the drop velocity according to both parameters of printing that are the applied voltage U and the viscosity η:

$$v = C_1 \times U + C_2 \times \eta_0 \ e^{E/kT} + C_3$$
(7)

With C_1 and C_2 constant values depending on rheological properties of the liquid and printhead characteristics. C_3 is a constant independent from the applied tension and from the viscosity.

Finally, the experimental results of temperature dependency on the drop velocity give:

$$v = 1.18\,U - 2.4 \times 10^{-5}\,e^{4150/(\theta+273.15)} - 10.5 \qquad (8)$$

(estimated relative error 2%)

By using the dependency of drop velocity with inkjet parameters to control temperature variations during inkjet printing, we have proposed a method that consists in compensating the fluctuations in viscosity, due to the temperature variations, with a real time adjustment of the pulse amplitude. For that purpose, we chose to fix drop velocity to an optimum value v_0, for instance to have no satellites, (here $v_0 = 6$m/s), knowing the coefficients C_1, C_2 and C_3 we can express the pulse amplitude in function of the temperature (equation 9). In the case of silicon oil DC704 studied here, the temperature compensation is done by equation 10 and variation of voltage compensation versus temperature is represented in figure 7.

$$U = -\frac{C_2}{C_1}\,\eta_0\,e^{E/k(\theta+273,15)} + \frac{v_0 - C_3}{C_1} \qquad (9)$$

$$U = -2.10^{-5}\,e^{4150/(\theta+273,15)} + 14 \qquad (10)$$
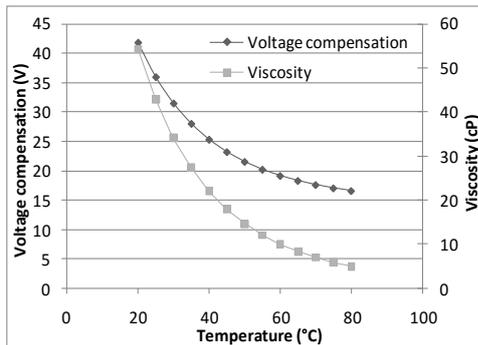

FIG.7. Pulse amplitude variation to compensate variations of temperature (drop velocity = 6m/s).

Variations of temperature in the fluid are now compensated by an adjustment of pulse amplitude. To apply such compensation during the printing process, a constant access to the liquid temperature inside the print head is necessary using thermal sensors. Simultaneously the amplitude pulse has to be adjusted. In consequence, the resulting variation of drop velocity with and without temperature compensation is observed and measured (Figure 8). Figure 8 illustrates the rapid increase of velocity without any compensation while with compensation the drop velocity is stabilized at the velocity aimed (6m/s). This method permits to have stable velocity for a variation of 15°C, during the print, while without compensation, the velocity increases by 5m.s^{-1} (almost twice velocity).
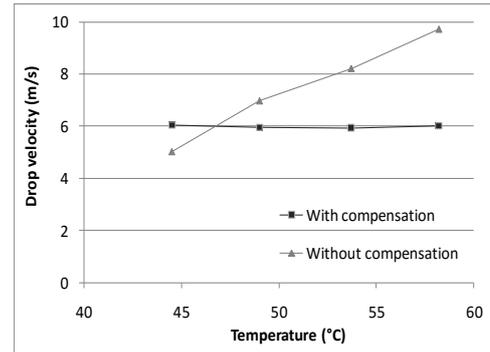

FIG.8. Velocity measurements comparison with and without temperature compensation.

In order to validate this experimental temperature compensation, we have realised measurements with a MJ style drop-on-demand single jet dispensing devices from Microfab® Technology. The integrated orifice and wetted surfaces are exclusively glass. Fluids with viscosity less than 20 cp and surface tension in the range 20-70 dynes/cm can be dispensed.

For the study the printhead used are nozzle orifice diameter of 80 µm. Measurements done with ethylene glycol, have permitted to obtain the following figures 9 and 10.
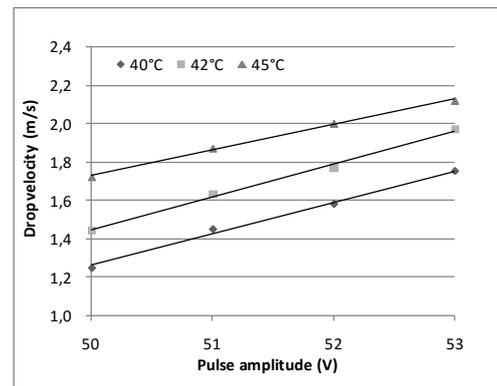

FIG.9. Velocity variation of ethylene glycol versus pulse amplitude at different temperature.
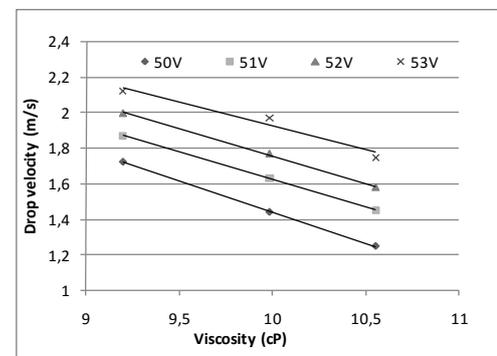

FIG.10. Velocity variation of ethylene glycol versus viscosity at different pulse amplitude.

Using the method of calculation described above and measuring experimentally the ethylene glycol viscosity, the following expression of drop velocity as a function of pulse amplitude and temperature is:

$$v = 0.16V - 5.6 \times 10^{-4} e^{2730/(\theta + 273.15)} - 3.3 \qquad (11)$$

This expression has the same form as the previous one obtained with the Xaar®760 printhead for the DC704 silicon oil. Even so, the constant values are quite different due to (i) the variation of ethylene glycol viscosity with temperature, which decreases more slowly than for the silicon oil, (ii) the geometry of the channel, and (iii) the piezoelectric properties of the actuator, which are different in both printheads. The effect of temperature compensation on the drop velocity variation was obtained only for two temperatures (Figure 11). With this technology, it is important to remind that the velocity decreases with the level of the manifold, because of the change of pressure into the channel. Therefore, to limit drop velocity variation the jetting has to be made with regulated ink volume. Unfortunately for this printhead, the ink manifold volume is very small (2ml) so a too long inkjet process disturbs the velocity.
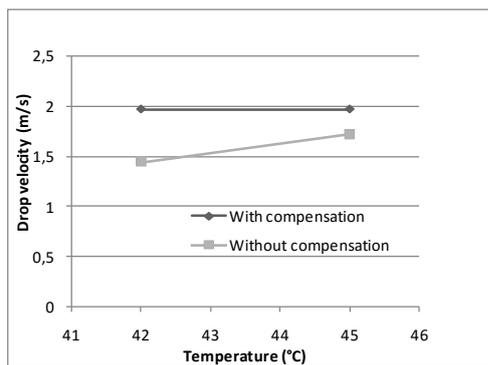

FIG.11. Velocity measurements comparison with and without temperature compensation.

CONCLUSION

A study of the influence of the inkjet parameters on the properties of drops allowed us to understand how to stabilize the print. First, we demonstrated that there is an optimal impulsion width of piezoactuator signal for each liquid. Afterward, we detailed the influence of the pulse amplitude and the liquid viscosity on the drop velocity. Experimental investigations lead to the calculation of temperature compensation expression. We have then found a method to stabilize ejection under uncontrolled temperature variations which could occur during inkjet process. Thus, this experimental temperature compensation increases the stability of drop ejection and consequently print quality. This tool could be used with other printheads but requires however to work on constant volume of manifold and to have optimized the ejection velocity.

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