Using Ultrasonic Energy to Improve the Ink Drying Process: A Feasibility Study

Yehoshua Socol, Yitzhak Meshorer, Larisa Berenstein, and Arie Zaban*

Department of Chemistry, Bar-Ilan University, Ramat Gan, Israel

It has recently been proposed to use ultrasonic energy to dry ink jet printed materials. This work presents the results of a feasibility study of such technology. Both calculations and experiments show that direct heat transfer may be of significant influence only for MHz range ultrasonic frequencies. Thus, any attempt to use ultrasonic energy to speed drying on non-absorbing substrates should involve moving to MHz frequencies, and this move may prove useful.

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Introduction

Over the last decade, considerable progress in digital printing, and ink jet printing, in particular, has been achieved.[1,2] One of the goals of ink jet research and development is to achieve printing at high speed and quality which are close to that of laser printing, at a relatively low cost. The increasing printing speed, together with the fact that it uses wet ink, leads to a situation in which the drying speed of the printed materials becomes the bottleneck of the process in many applications. For example a printing speed of 400 m/min (as in wallcover printing machines) means that a drying process lasting one second demands about a 6 m long facility, and one would probably try to minimize this size by increasing the drying speed.

Simultaneously, different high power ultrasonic techniques have evinced a rapid development. Sonochemistry is a rather young, but an important field of chemical research and technology, which began to grow significantly about 15 years ago.[4] The ink jet printing industry itself has proposed to use focused ultrasonic beams in nozzle-less printers,[4] and ultrasonic drying has been used in the food industry.[5] Recently, two groups independently[6] proposed to use ultrasonic energy to dry ink jet printed materials.

Ultrasonic energy has several advantages with respect to other forms of energy. What makes it extremely promising for use in the printing industry is its nearly absolute absence of inertial effects, since, as soon as the source of ultrasonic vibration is turned off, the vibration (and the heat release caused by it) stops. This is an extremely relevant issue for the printing industry, which normally works with flammable materials.

There are several ways in which ultrasound can influence the drying process. The first is direct heat transfer, i.e., ultrasonic energy dissipating into heat and evaporating the ink solvent. Second, one can think about ultrasonic stirring inside the ink drops (or layer), facilitating evaporation in case it is diffusion limited. Additionally, such stirring can influence the shape of the printed dots in a positive way.

In this work we report the results of an ink jet ultrasonic drying study performed by our group. Our theoretical calculations show that the direct heat transfer may be of significant influence only for rather high (of the order of MHz) ultrasonic frequencies, and the experimental results confirm this statement. Other possible impacts of ultrasound on drying are discussed.

Estimation of Heating by Ultrasound

Energy Considerations

The first question to be addressed while analyzing the perspectives of using ultrasonic irradiation for speeding the drying process relates to the required energy amount. We constrain the analysis to the case of non-absorbing substrate, which is the most problematic from the point of view of drying. In this case, the solvent does not penetrate the media and therefore should be completely evaporated. This process requires a relatively high amount of energy, which leads to a long drying time. So we estimate the amount of energy that should be transferred to the ink in order to evaporate its solvent. It is not important whether the ink is of a soluble dye type, or whether it is a colloidal dispersion of pigment.

The problem of drying time is of primary importance for water based inks. The reason is that organic solvents (like ethylene glycol, acetone, etc.) have a much lower heat of vaporization than water (generally by a factor of around five). That means that the drying time of organic solvent based inks is much shorter.

The typical volume of a single ink drop is around 10 – 20 pL[1]. At 600 dpi resolution (which is about 240 points/

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* Corresponding author. Tel.: +972-3-531-78-76; fax: +972-3-535-12-50; E-mail: zabana@mail.biu.ac.il

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cm), 100% coverage by 20 pL dots translates to about 5.6×10^4 points/cm^2, i.e., to 1.1 µl/cm^2. For water based inks, the estimated amount of water to be evaporated is therefore about 1 mg/cm^2 (usually somewhat less, since water based inks contain, nevertheless, 10 – 30% of organic solvents,[2] and an additional 5 – 10% of solids). Since the heat of vaporization for water is about 2.5 kJ/g (temperature dependent), we have to apply an energy of about 2.5 J/cm^2 in order to dry a 100% coverage printed sheet. In order to achieve full drying within 1 second, the estimated required power is about 2.5 W/cm^2. We note, however, that the required power will increase if larger printed dots are used and therefore the ink layer is thicker. Higher power would be also required if drying time shorter than 1 sec is needed as part of the effort to decrease the size of the drying facility. As mentioned above, a printing speed of 400 m/min (as in the case of wallcover printing machines) means that a drying process lasting 1 sec requires a 6 m long facility.

Now we estimate two values: ultrasonic power emitted from the oscillating print substrate, and ultrasonic power dissipated into heat inside the ink.

Radiated Ultrasonic Power

The ultrasonic power I emitted from an oscillating surface is given by the formula (65.6 of Ref. 7) :

$$I = + \rho\, c_{air}\, \nu_0^2, \qquad (1)$$

where ρ is air density, c_{air} is sound velocity in air, and ν_0 is maximal velocity of oscillations.

Since $\nu_0 = 2\pi{+}\nu\, a_0$ (a_0 is displacement amplitude),

$$I = 2\pi^2\, \rho\, c_{air}\, \nu^2\, a_0^2. \qquad (2)$$

For air, the density $\rho = 1.2$ mg/cm^3, and sound velocity $c_{air} = 345$ m/s (at 25C). With the $\nu = 20$ kHz, a typical ultrasonic frequency, and displacement amplitude $a_0 = 0.1$ mm, the formula yields $I = 2.5$ W/cm^2. If this energy would dissipate in the ink, it would be sufficient to evaporate the solvent in 1 second. However, this amount of power is radiated and generally lost, since a high Q ultrasonic resonant cavity with printed material traversing it, can not practically be built.

Dissipated Ultrasonic Power

Comprehensive estimation of ultrasonic energy dissipation in a liquid layer (or liquid drops) is much more problematic and will be reported separately. At least three different means of applying vibration – via air, direct coupling to the paper, or via a solid supporting base – should be considered separately. We will only mention that for the above values of layer width and ultrasonic power, cavitation in the liquid layer cannot occur. The main mechanism of ultrasonic power dissipation is viscous dissipation[7], the appropriate dissipation rate, W, per unit volume being proportional to the average square of the velocity gradient (formula 16.3 of Ref. 7). We consider the case where the liquid is uniformly distributed on the substrate and oscillates with it. In this case, the resulting formula is

$$W = \eta k^2\, \nu_0^2/2, \qquad (3)$$

where η is dynamic viscosity, k is the wave vector length $2\pi/\lambda$, and ν_0 is the velocity amplitude. Shifting to more convenient terms, frequency, maximal displacement, a_0, and oscillation propagation velocity, c, we obtain:

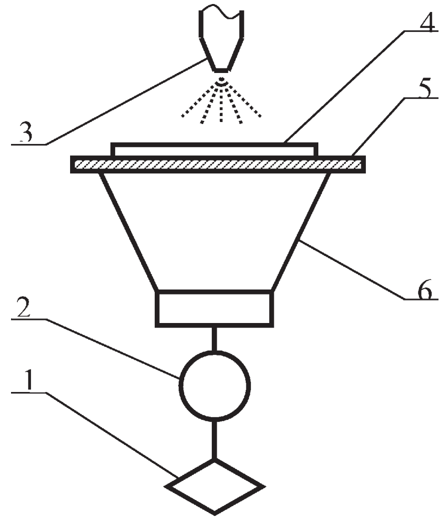


Figure 1. The sonic driver. 1 – signal generator, 2 – broadband (20 Hz – 22 kHz) amplifier, 3 – glass pipette tip, 4 – the print substrate, 5 – supporting table, 6 – transducer.

$$W = 8\, \eta\, \pi^4\, \nu^4\, a_0^2/c^2. \qquad (4)$$

Let us take the viscosity $\eta = 0.1\, g/(\mathrm{cm} \cdot \mathrm{s})$, which is 10 times the viscosity of water and an upper-limit estimation of values for real inks[2]; $\nu = 20$ kHz, a typical ultrasonic frequency and $a_0 = 0.1$ mm, as above; $c = 345$ m/s, sound velocity in air. We obtain thus $W = 0.1$ W/cm^3. Taking into account the thickness of the liquid layer (about 0.01 mm), we come to a very small value of about 0.1 mW/cm^2 of evaporation power.

One can argue about the validity of substituting the sound velocity in air for the velocity of oscillation propagation in our case. It is not really clear that ultrasonic waves propagating in air will cause forced oscillations of the printed media, which is assumed by the above substitution. However, a very different calculation, taking into account the oscillation propagation in a thin sheet (the media itself, or its supporting base) leads to the same order of magnitude for the propagation speed, c, and therefore for the dissipation, W.

Summary

In summary, the lost power is higher by about four orders of magnitude than the power used for water evaporation. This huge inefficiency should prevent efficient use of common high power ultrasonics for speeding printed media drying due to direct heat transfer. The experimental verification of this statement and the possibility of increasing the frequency will be discussed later in the paper.

Experimental

As shown above, we should not expect shortening of the drying time by direct heating when ultrasonic vibration is applied to a printed medium. However, it might be possible that stirring induced by the vibration will have an effect. Specifically, we refer to the dot quality in terms of uniformity and roundness.

The experimental set-up is shown in Fig. 1. The sonic driver included a signal generator (1), a broadband (20 Hz – 22 kHz) amplifier (2) and a transducer (6). To simulate the ink jet printing process, the ink was injected

TABLE I. The Drying Time of Sonicated and Reference Samples. No Significant Changes Are Achieved.

	Sonicated	Reference
Avery Dennison	7.4 ± 0.4 min	7.3 ± 0.5 min
Ink jet Paper	20 ± 10 s	20 ± 10 s

onto the substrate by means of a glass pipette tip (3), which was vibrated with ultrasonic (20 kHz) frequency, onto the print substrate (4). Such injection produced drops of 10 – 60 pL each and proved to be a good lab simulation for ink jet printing (see a separate report[8] for further details). Several hundreds of dots were injected. Each print substrate had a size of a microscope slide (2.5 × 7.5 cm) and was glued to it. The slide was glued onto the ultrasonic table (5), which was coupled to the transducer.

In all experiments, we used water based cyan ink, containing 30% ethylene glycol and propylene glycol. Two types of substrate were studied: Avery Dennison, and an ink jet paper. The former is a paper-backed vinyl: it is hydrophobic, non-absorbing, and very homogenous. The latter is a clay-coated paper, used as a reference in many jobs of ink jet printing. The total electric power applied was about 50 W. The sonic pressure was adjusted to be 0.1 mbar corresponding to a surface density of ultrasonic radiation of about 1 W/cm^2 .

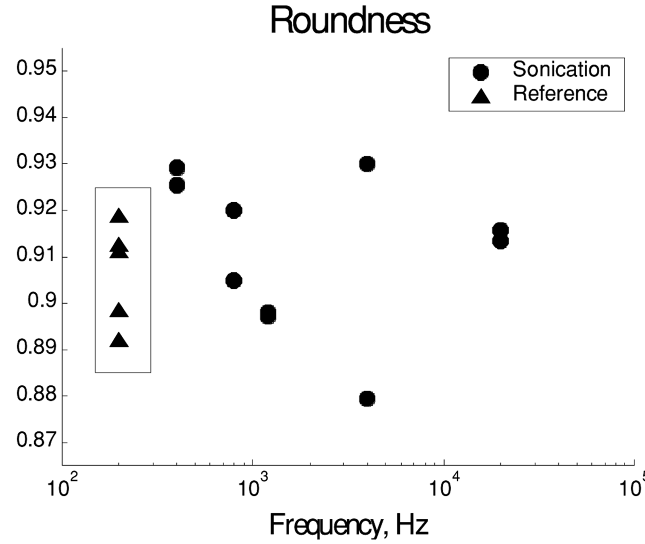
All of the experiments were performed in the laboratory at a temperature of 22°C and humidity of 70 – 75%. In order to measure the ink drying time, we put a control sheet on top of the printed substrate, while applying constant pressure. The drying process was considered to be complete, if no traces of ink were observed on the control sheet.

When studying the influence of sonic irradiation on the quality parameters of printed drops, we exploited the technique described elsewhere.[8] Pictures of printed dots were taken with an Olympus PROVIS microscope, fed to a computer, and processed by image processing software especially developed for this system using the MATLAB package.[9] The software enables interactive viewing of the obtained images together with quantitative characterization. Each ink dot was characterized by several parameters, out of which two proved to be the most representative of the overall printed dot quality: roundness and non-uniformity.

A typical measure of roundness would be the minimum annulus (region between two concentric circumferences) containing the drop boundary. Numerically, we define roundness as ratio of inner to outer radii of the annulus: the roundness is therefore equal to unity for a circle and zero for a straight infinitely thin line. Non-uniformity was defined as the root mean square deviation of the ink density distribution within one drop.

Results

The results of the study of the drying time of printed drops are given in Table I. The study confirmed the theoretical estimation: no significant difference between sonicated and reference (non-sonicated) samples was observed. Specifically, one can see that for the sonicated Avery Dennison substrates, the drying time was 7.4 ± 0.4 min, while the reference dried after 7.3 ± 0.5 min. As shown above, the ultrasound intensities used in these experiments should lead to the total evaporation of the solvents in course of a few seconds at most, provided that the ultrasonic energy would be adequately absorbed. As for the ink jet paper substrates, the drying



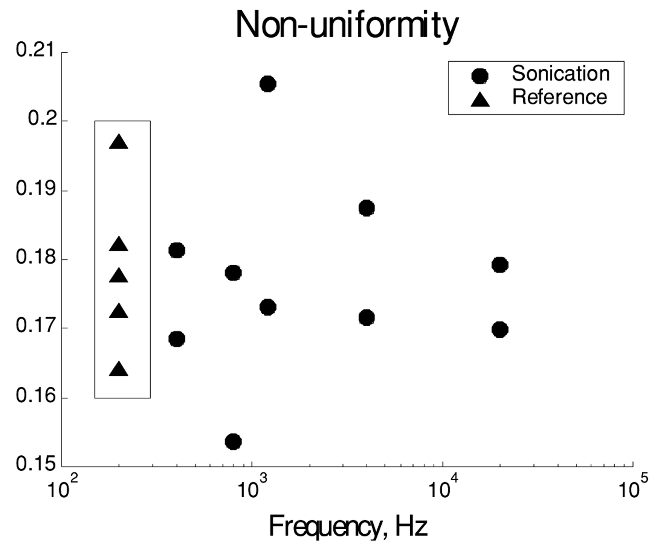


Figure 2. Non-uniformity (top) and roundness (bottom) of sonicated (circles) and reference (triangles) printed dots. No significant trend can be seen.

time was 20 ± 10 sec, also without any dependence on the fact of sonication. We should mention here, that in case of porous substrates like the ink jet paper, the solvent does not evaporate, but penetrates into the substrate volume. This process is not limited by the applied heat and therefore transpires much faster.

For the study of the influence of vibration on the quality of the printed drops, the experiments were performed with the Avery Dennison vinyl substrate at five different frequencies of 0.4, 0.8, 1.2, 4.0, and 20 kHz. For each frequency, two different experiments with a sonication duration of 3 and 5 min. were performed. Five reference experiments, i.e., without vibration, were also performed. To exclude possible artifacts, the experiments were performed in a random order. Figure 2 presents the results regarding the two most representative drop quality parameters – roundness and non-uniformity. One can readily see that no significant effect, either positive or negative, is observed.

Discussion

Full *a priori* description of the behavior of ink drops on substrate is an unsolved problem for any practical system. One of the key issues is the problem of the ink-substrate adhesion. Our first principles energetic analysis enabled us to make definitive predictions regarding the drying time. However, it is not clear whether such estimations can be made for the shape of the printed dots.

For absorbing substrates, the main mechanism of drying is wetting, i.e., penetration of the solvent into the bulk of the substrate (paper). Ultrasonic oscillations can enhance wetting and thus shorten the drying time.[10] On the other hand, just the opposite effect can also take place[10] if ultrasound-produced bubbles block the substrate pores. Anyway, in our experiments we did not see any significant effect.

Several more words should be said about the possibility of ultrasonic acceleration of the drying process on non-absorbing substrates. Oscillation dissipation W is proportional under very general conditions to the second power of frequency (see par. 79 of Ref. 7). Thus, increasing frequency by two orders of magnitude yields a four-orders-of-magnitude increase in dissipation. Thus, for MHz ultrasonic frequencies, the efficiency of ultrasonic energy transfer to ink can be significant, especially if ultrasonic resonators (even low Q) are used to "recycle" radiated power. MHz range ultrasonic equipment is not as wide-spread in industry as the common one working at 20 – 40 kHz. But it is commonly used for research and imaging purposes, and high power MHz ultrasonics (called "megasonics") is a standard technology in the semiconductor industry where it is used for cleaning silicon wafers. (See Ref. 11 for further references). Thus any attempt to use ultrasonic energy to speed drying on non-absorbing substrates should involve MHz frequencies, and this move may prove useful.

Conclusions

Both calculations and experiments show that, due to the inherent inefficiency of ultrasonic-to-heat energy conversion in given conditions, common 20 – 40 kHz ultrasonic irradiation cannot be of technical value for speeding ink drying on non-absorbing substrates. For absorbing substrates, the principal possibility exists, but experimentally no drastic effect was observed. Additionally, no effect of ultrasonic irradiation on the printed dot quality was observed. Any attempt to use ultrasonic energy to speed drying on non-absorbing substrates should involve moving to MHz frequencies, and this move may prove useful.

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