Acoustic Ink Printing with Solid Ink

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Abstract

We have adapted the Acoustic Ink Printing (AIP) printhead for operation at 150C, and have demonstrated printing with solid ink for high image quality on plain paper. In AIP, an ultrasonic beam is focused on the free surface of the ink to eject discreet droplets of controlled diameter. The drop size is determined by the lateral dimension of the acoustic beam. Hence, AIP is a “nozzleless” drop ejection process that enables generation of extremely small drops. We have used 2.7 pl drops of a molten wax (i.e. solid ink) to produce images at a quality level exceeding xerography on plain paper. The printing is done at a spatial addressability of 600 spots per inch and the printed spot size can be varied by firing from 0 to 5 drops per pixel to achieve multiple gray levels at high resolution. For solid ink printing, we have modified the 1024-ejector aqueous AIP printhead materials and assembly process to enable 150C operation with a flowing layer of 13 cp molten wax.

Introduction

In principle, direct marking with ink jet printheads should offer significant advantages in cost and architecture simplicity relative to electro-photography. In practice, however, ink jet devices have not made significant inroads into the mid-volume (40-90 ppm) office market, due to the performance limitations of conventional aqueous inks which require high power dryers, and which exhibit image defects on plain paper.

Solid ink jet offers a breakthrough in plain paper office printing in that it employs molten wax droplets that freeze rapidly on impact with the substrate. The resulting images exhibit high saturation and fine line detail even on rough papers. The Xerox Office Printing Business Unit (formerly Tektronix Printer Division) Phaser series of solid ink printers[1] exploit this technique and exhibit excellent image quality on plain paper.

As described in another paper of this conference[2], AIP is a novel inkjet approach which uses focused ultrasonic beams to eject fluid from the free surface of a liquid[3-5] (see Figure 1.) After having successfully demonstrated photo quality images using room temperature aqueous inks, we adapted the AIP printhead for 150C operation, and used it to print with 2.7 pl drops of molten wax. Even on very rough “plain” paper (i.e Xerox 4024), the resulting images are of very high quality.

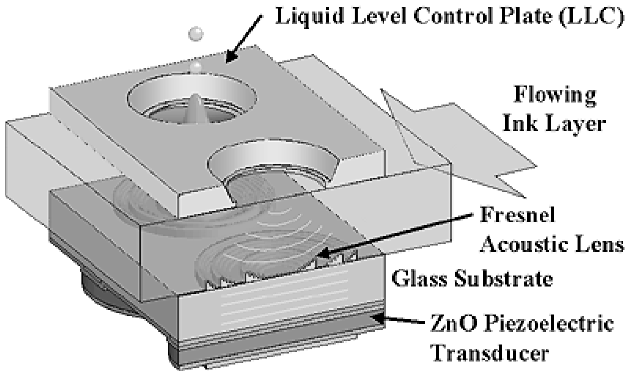


Figure 1. Perspective View of AIP Ejector

Printhead Design and Performance

Figure 2 shows a perspective view of the solid ink AIP printhead. In most respects, the device is similar to the aqueous printhead that operates at room temperature with water-based inks. The key differences are in the materials of construction, and the addition of heaters to maintain a 150C temperature. For the solid ink printhead, the “stack” (a multilayer structure of etched alloy-42 shim stock) is laminated together using an epoxy with a glass transition temperature slightly greater than 150C. The active transducer/lens array is embedded in this stack using a precision tool, such that the lenses are at a precise distance from the free surface of the liquid. The liquid surface is defined by apertures in a liquid level control plate (LLC), each of which holds a meniscus of ink via surface tension. These apertures are sufficiently large (85 x 180 um) that the ejection process is still "nozzleless." As with the aqueous AIP design, there are 8 staggered rows of lenses to provide for full 600 spi marking with a single pass of the printhead.

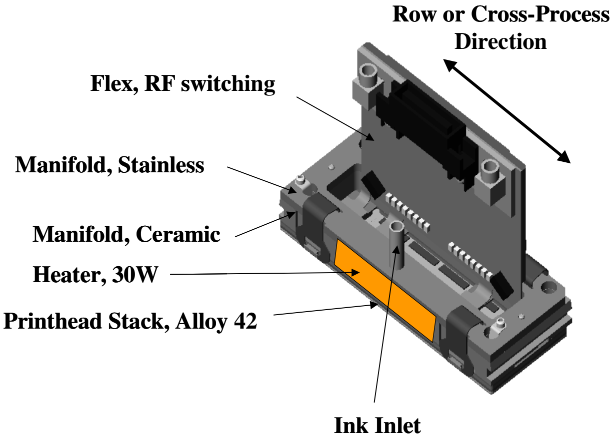


Figure 2. Perspective View of 1024 Ejector Printhead

In order to achieve the best possible directionality, an electric field was applied between the printheads and the substrate. This paper describes the case of direct marking, in which the droplets are ejected directly onto a sheet of paper, which has been tacked down to a metal platen. The platen is heated to enable adequate spreading of the ink droplets before they freeze, and is maintained at a high voltage to achieve the desired E-field. For the printing results reported in this paper, the gap between substrate and printhead was 1.5 mm, and the applied voltage was 1.5kV. The Phaser 840 ink was found to have sufficiently high electrical conductivity to allow for full charging of the ejected droplets.

In operation, the ink is forced to flow into the inlet using a gear micropump, and a low level of suction is pulled on the symmetrically disposed outlet. The suction is achieved using a siphon effect, as the ink is made to fall through a tube of approximately 8" in height before returning to the external ink reservoir. In typical operating conditions, the pressure at the center row of ejectors is approximately –1.5" of water. The ink pressure must be negative everywhere within the active zone of the printhead, in order to maintain a concave meniscus in all of the LLC apertures. Typical ink flows are between 20 and 40 ml/min. The entire fluid flow circuit (reservoir, pump, delivery and return lines) must be heated, and these temperatures must be kept well controlled (± 4C), in order to maintain constant flow resistance and hence constant pressure conditions in the printhead.

Across the 8 staggered rows of ejectors (630 um center-to-center spacing between rows), the pressure drop is approximately 1.4" of water. With an ink surface tension of 26 dynes/cm, the meniscus position in the LLC apertures varies from approximately –8 um to –25 um. Given the strong sensitivity of the acoustic power on the liquid surface height relative to the acoustic focus, the lens design was adjusted from row 0 to row 7 in order to compensate for this known surface height variation.

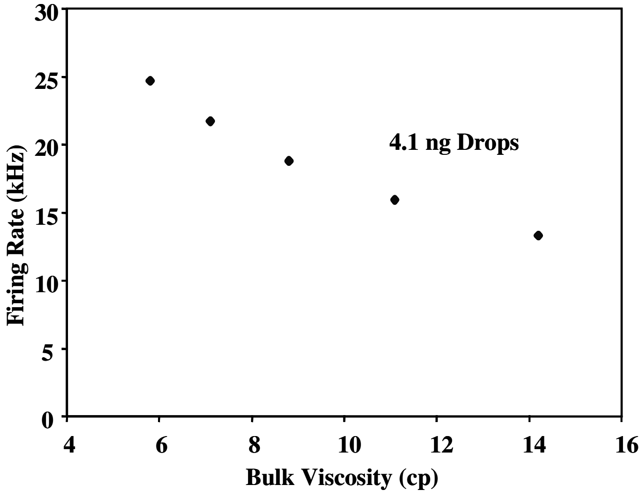


Figure 3. Chaotic Limit Versus Viscosity

The "chaotic limit" for the 13 cp ink is shown in Figure 3. This is the firing rate at which there is a dramatic change in the character of the ejection and the trajectories of subsequent droplets become chaotic. With aqueous AIP, it is possible to achieve high quality printing at ejection rates as high as 70-80% of the chaotic limit. With solid ink, there appears to be a more subtle loss of directionality at firing rates below this value, even with an applied E-field. In order to achieve the highest quality prints, the initial printing reported in this paper was done at an individual drop firing rate of 2.4 kHz. With 5 drops per pixel, this corresponds to a pixel rate of 480 Hz, and a process speed of 0.8 ips.

Printing Results

Printing was done using a precision breadboard with an XYZ stage capable of 2 um accuracy and 30 ips motion. Printing conditions are summarized in Table I. Three printheads (CMY) were used to make these images. Figure 4 shows a comparison of bitmaps printed with AIP solid ink, and with a Xerox DocuColor 40 (laser xerographic machine.) The AIP images show very fine detail, even on the relatively rough 4024 paper. The AIP image shown in the Figure is comprised of multiple narrow print swaths, which was necessary to avoid the image artifacts associated with runout between the LLC apertures and the acoustic lenses (see Technical Challenges section.) In order to hide the stitch boundaries, a "puzzle cut" algorithm[5] was used.

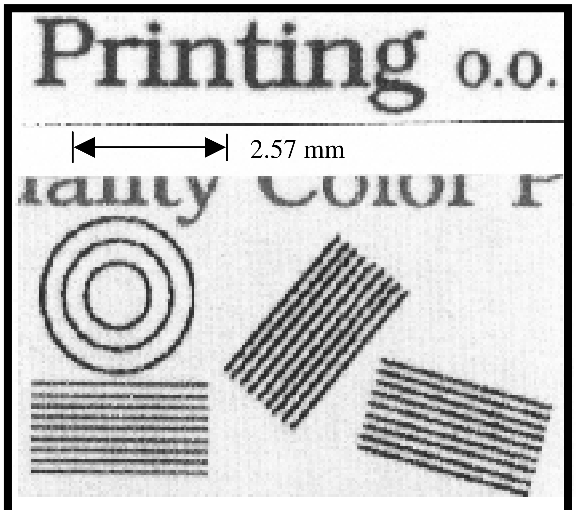
Table I. Summary of Printing Conditions

Resolution	600 SPI
Pixel size	42 microns
Print zone width used	5.1 mm
Number of ejectors used	120
Ejector pitch per row	336 microns
Number of staggered rows	8
RF frequency	110 MHz
Acoustic pulse width	15 us
Drop volume	2.7 pl
Max drops per pixel	5
Max volume per pixel	13.5 pl
Individual drop ejection rate	2.4 kHz
Pixel rate	480 Hz
Paper Type	4024
Paper Temperature	40C
Gap to Paper	1.5 mm
Applied Voltage	1.5 kV

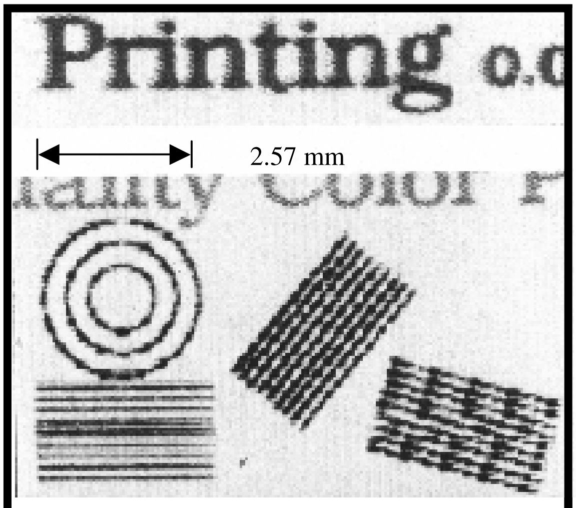
Technical Challenges

For these initial printing studies, we used a standard aqueous AIP printhead, and made only minor modifications to allow for operation at high temperature. Most of the technical challenges listed below result from the high viscosity of the ink (13 cp at 150C), and the variations in the viscosity with temperature. With proper redesign of the printhead, most of these problems could be addressed.

For the high viscosity ink, we found that slight misalignments of the LLC apertures with respect to the acoustic focus resulted in mis-directionality of the ejected droplet, and this effect became more pronounced as the meniscus curvature became larger. In the printing results presented in this paper, the LLC apertures were rectangular, with an orientation that was not ideal. The apertures had dimensions of 180 um in the cross-process direction, and 85 um in the process direction (direction of printing.) This particular design gives rise to high meniscus curvature in the cross-process direction, and this direction is the most sensitive to streaks. The measured sensitivity for this particular aperture shape was quite high, giving rise to runout of the printed image in the cross-process direction in response to runout between the aperture centers and the lens centers. For this particular generation of printhead, the aperture to lens runout (due to manufacturing errors) was 9.5 um, and the resulting print width runout was 163 um. Modeling of apertures with a more ideal size and orientation suggested that with tight manufacturing control, it would be possible to reduce these runout problems to an acceptable level. Given the runout issues with this particular generation of printhead, it was necessary to limit the printing zone to be 15 columns (120 ejectors) in width.



AIP Solid Ink on 4024 Paper



Xerox DocuColor 40 on CX Paper

Figure 4. Solid Ink AIP vs Xerox DocuColor 40

Solid ink has both higher viscosity and lower surface tension than aqueous ink, and both of these reduce the margins for operation in a recirculating system. The lower surface tension results in a larger meniscus displacement at the same pressure, and the higher viscosity leads to larger resistive pressure losses. Figure 5 shows the fluidic margins that were experimentally observed. The x-axis shows the suction level that was applied to the outlet of the printhead in inches of water. The y-axis is proportional to the voltage applied to the gear micro-pump, which is roughly proportional to flow rate. The top curve indicates values of suction pressure and flow rate at which the first row of apertures spills ink, while the lower curve represents the values at which the last row of apertures ingests air bubbles. The middle curve represents the values at which the first row meniscus starts to become concave. In practice, it is necessary to operate in the narrow region between the center curve and the lower curve. The consequence of these tight fluidic margins is that the control system for ink temperature and pressure must be stable.

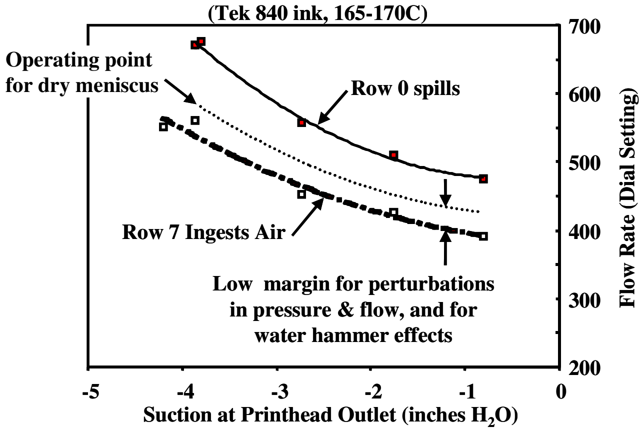


Figure 5. Fluidic Stability Margins

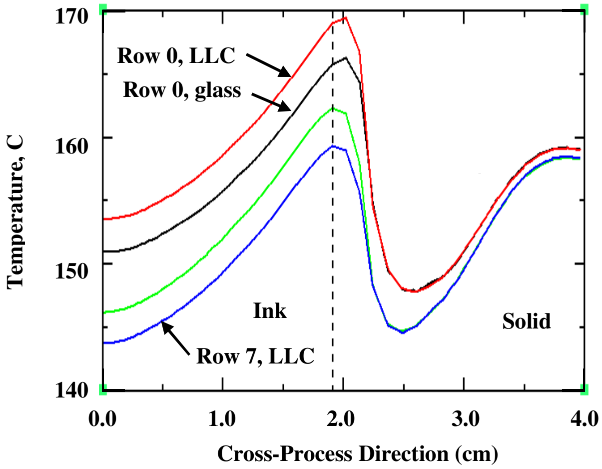


Figure 6. Thermal Simulation

Another technical challenge with the first generation of solid ink AIP printhead is its power uniformity. Modeling results suggested that the printhead would be reasonably uniform (≤ 1 dB), particularly given the compensation of lens focal lengths that was made for known effects (meniscus sag variation, deformation of the LLC plate, etc.) However, the actual printheads were substantially less uniform, with power non-uniformities up to 3dB. Thermal modeling revealed this problem to be the result of non-uniform ink temperatures across the printhead. Referring to Figure 2, the ink enters through the inlet tube, spreads out in the manifold under the heater, and then flows in a thin sheet between the LLC plate and the glass surface on which the lenses have been patterned. The ink that flows to the outer edges of the printhead has a longer dwell-time under the heater. The thermal modeling results of Figure 6 indicate the magnitude of the problem. The x-origin is the center of the printhead, and the vertical dashed line represents the end ejectors in the cross-process direction. A large difference exists in temperature, with the end ejectors being as much as 15C hotter. For these solid inks, a 15C temperature difference will give rise to an additional 2 dB of non-uniformity. These problems could be eliminated through a custom design of the heater and ink flow path.

Conclusion

We have demonstrated high quality solid ink images on plain paper with an AIP printhead modified for operation at 150C. Initial experiments indicate a number of technical challenges, and modeling suggests that these could be addressed through changes in the fluidic and thermal design.

References

1. S. Korol, "The Effects of Ink and Media Parameters on Offset Solid Ink and Xerographic Halftoned Image View Quality", *Proc. of IS&T PICS Conference*, 210 (1998)
2. R. Sprague et al, "Acoustic Ink Printing: Photographic Quality Printing At High Speed", *NIP 17: International Conference on Digital Printing Technology*, p. 660 (2001)
3. B. Hadimioglu, S. A. Elrod, M. Lim, D. L. Steinmetz, J. C. Zesch, B. T. Khuri-Yakub, Eric. G. Rawson and C. F. Quate, "Acoustic Ink Printing: Printing by Ultrasonic Ejection," *Proc. 1992 IST's Eighth International Congress on Advances in Non-Impact Printing Technologies*, 411 (1992).
4. S. A. Elrod, B. Hadimioglu, B. T. Khuri-Yakub, E. G. Rawson, E. Richley, C. F. Quate, N. N. Mansour, and T. S. Lundgren, "Nozzleless Droplet Formation with Focused Acoustic Beams," *J. Appl. Phys.* **65**, 3441 (1989).
5. B. Hadimioglu, E. G. Rawson, R. Lujan, M. Lim, J. C. Zesch, B. T. Khuri-Yakub and C. F. Quate, "High-efficiency Fresnel Acoustic Lenses", *Proc. 1993 IEEE Ultrason. Symp.* Vol. 1, 579 (1993).

Biography

Scott Elrod is manager of the Document Hardware Laboratory at Xerox PARC. While at PARC, he has led a number of printing hardware projects, including a novel ink jet technology based on focused ultrasonics. He has also contributed to ubiquitous computing research, including the invention of novel input devices for large area displays and the development of smart office environments. Elrod holds a PhD in Applied Physics from Stanford University, where he built the world's first low temperature tunneling microscope. In addition to his contributions at PARC, Elrod served as a director of Environment, Safety and Health at SEMATECH, the consortium of semiconductors manufacturers.