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Breakthroughs required in piezo-on-demand inkjets for production printing: satellite drops, ink penetration and evaporation

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Abstract

A high-speed digital production printer using an aqueous piezo-on-demand inkjet is considered in terms of its high-speed applicability to electrophotography, which also enables digital printing. Further enhancement of the printing speed and improvement in the image quality will require control of the satellite drops that are generated during ink jetting. Further versatility is necessary for use of paper types that require printing without ink penetration, and as a result, the reliability of moisture evaporation in ink becomes increasingly important.

Introduction

In the 1990s, inkjet printers grew rapidly in popularity with the increasing prevalence of computers, and these printers were enabled by properties such as high image quality production by multi-pass printing, penetration control of both ink and paper, and high reliability with respect to evaporation control of the water by addition of moisturizing agents to the ink.

In the 21st century, along with the progress in Internet technology, there has been remarkable growth in production printers enabled by inkjets and also by electrophotography, which enable realization of on-demand and variable digital printing. [1]

At present, printing jobs are completed using inkjet paper with medium image quality; however, it is natural that the customer may require higher image quality. Simultaneously, to ensure compatibility with other printing jobs, it is necessary for the printer to be compatible with offset coated paper, which is slowly permeable; additionally, applicability to nonpermeable media is expected to be a requirement for industrial package printing in the very near future. To meet these expectations, technologies that operate at a higher level than the established performance levels of conventional inkjets or revolutionary breakthroughs that transform the current operating principles are required.

Inkjet vs. Electrophotography

Table 1 presents a comparison between the world's fastest (by author survey) electrophotography machines and typical continuous-feed inkjet printers [2]. In inkjet printers, the printheads are aligned to the page width and the driving frequency is enhanced to be close to the response limit, resulting in printing speeds of 100 m/min. While there is no major difference between this speed and that of monochrome electrophotography, which is 91 m/min, inkjet printers can easily be enhanced to speeds of 200 m/min by doubling the number of printhead bars and the paper speed.

Figure 1 compares the printing principles of electrophotography and inkjet printing. Because the process numbers are small in inkjet printers, and also because there is no contact process such as the"transfer"stage in electrophotography, it is thus easier to increase the printhead numbers; this, combined with the independence of the process from the paper motion, enables faster operation in inkjet printers.

Additionally, the ink begins to penetrate immediately after landing on the paper and is then fixed, while toner remains unstable on the paper until the fusing process. Inkjet printing should therefore be recognized as the principal high-speed-applicable process.

Satellite

In inkjet printing, the streaks that occur because of nozzle clogging or jet misdirection are critical issues and multi-pass printing methods are thus generally applied. The number of passes is decided based on a balance with the required printing speed, allowing for only one pass to be used by a production printer to meet market requirements.

When multi-pass methods cannot be used, the dot placement and shape must be precise to obtain high image quality. Because the flying jet that becomes a dot is in a column configuration, there are time differences between the head and the tail of the jet, resulting in image defects such as dot splitting; therefore, faster jetting velocities are preferred.

Table 1 Specifications and structural elements of high-speed printers

Products	Colors	Colorant	Res. (dpi)	Width (inch)	Printing fixtures	Speed (m/min)
EP color	4	Toner	600	18.5	1	69
EP mono	1	Toner	600	18.5	1	91
IJ 100	4	Ink	600	20	1	100
IJ 200	5	Ink	600	20	2	200

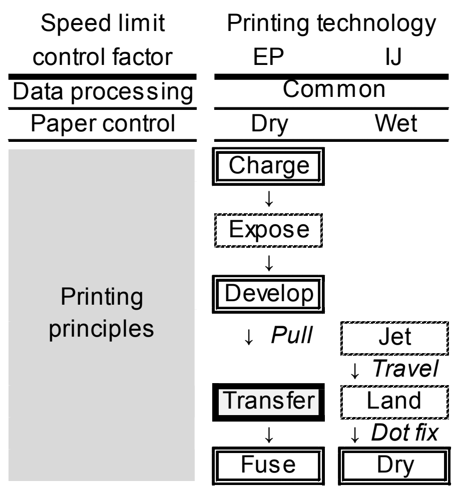

***Figure 1** Factors in high-speed printing and fundamental process comparisons between electrophotography and inkjet printing (dotted line: contactless; solid line: contact; double lines: either type)*

Additionally, the occurrence of the satellite drops that commonly form in inkjets are a particularly critical issue. As the paper transportation speed increases, the distance between the locations on the paper where the main drop and the satellite drop land also increases, and thus adversely affects print quality.

The printer described above [2] has a jetting frequency of 40 kHz at 600 dpi, which is equivalent to a repetition period of 25 µs. The market requires a higher resolution of 1200 dpi while maintaining the same operational speed, which would mean a jetting frequency of 80 kHz or a period of 12.5 µs. Therefore, in the printhead, a shorter piezoelectric waveform period that would eliminate the satellite drops is allowed, thus resulting in a minimum of two (double) pulses for the jetting drive.

Figure 2 shows the piezoelectric waveform used for jetting by double-pulse driving that consists of the driving (operating) voltage (V_{op}), the first (main) pulse width (T_{main}), and the pulse interval (T_{int}) as adjustable parameters, and the second (post) pulse width (T_{post}) as a fixed parameter at 2 µs.

Figure 3(a) and (b) show the jetting conditions achieved with double-pulse driving when observed (a) 300 µm and (b) 1 mm from the nozzle with a main pulse width of 3.4 µs and an interval time that varies from 1.0 to 10.0 µs. When the interval time is shorter than 1.6 µs, as shown in Figure 3(a), it is considered that the main drop becomes small while the satellite drop becomes large because the post-pulse is applied too early, thus resulting in inadequate oscillation.

When the interval time exceeds 6.0 µs, the second drop is jetted because the post pulse is applied after jetting of the main drop is complete. Figure 3(b) shows that a satellite-free range is obtained, and additionally shows that the most suitable conditions are a main pulse width of 3.4 µs and an interval time ranging from 2.6 to 5.0 µs until the second drop appears.

Figure 4 presents an observation of the jetting from the nozzle to a distance of 1 mm with a time step of 8 µs under satellite-free jetting conditions. The jet separates from the nozzle meniscus and the main drop and the filament then remain connected as the main drop "tugs" on the filament for approximately 8 µs. Subsequently, the filament separates from the main drop and becomes a spherical satellite before finally merging with the preceding main drop. The filament is considered to separate and become spherical because of the surface tension of the ink.

In general, satellite drops do not appear when the drop velocity is low but tend to gradually appear as the drop velocity increases. Therefore, the required drop velocity (V_d) for high-speed printing is assumed to be more than 6 m/s in this experiment and the jet observations were thus made at drop velocities of 6, 8 and 10 m/s by adjusting the driving voltage and the waveform; the parameters were varied as shown in Figure 3 at a distance of 1 mm from the nozzle. The duration of the tugging action of the filament, as described above, is considered to be affected by the filament velocity; therefore, this dependence was investigated with the expectation of collection of multiple data to aid in understanding of the overall trends.

Figure 5(a), (b) and (c) present the dependence of the filament tail velocity on the tugging time, where each plot was measured for different pulse parameters; crosses indicate that the satellite remains separated, while filled circles indicate that the satellite drop moves forward and merges with the main drop. The filament velocity becomes higher than that of the main drop; this means that the satellite merges when the tugging time exceeds 5 µs and the main drop travels at 6 m/s, as shown in Figure 5(a), and also when the tugging time exceeds 10 µs and the main drop travels at 8 m/s, as shown in Figure 5(b).

However, the filament velocity does not reach the main drop velocity and the satellite drop is thus not free when the main drop velocity is 10 m/s, as shown in Figure 5(c).

Based on the extrapolated line in Figure 5(c), it is predicted that the filament velocity will reach the main drop velocity at a tugging time of 20 µs. However, the filament velocity does not increase with an increase in the main drop velocity, while simultaneously the satellite drop velocity does not increase and

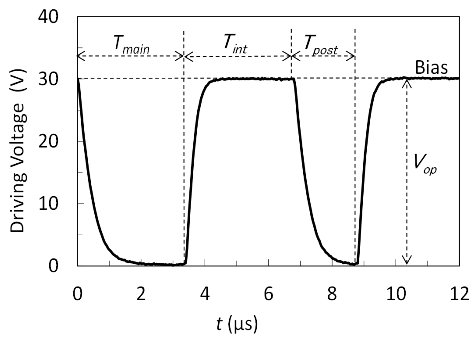

***Figure 2** Driving waveform applied to a piezoelectric actuator*

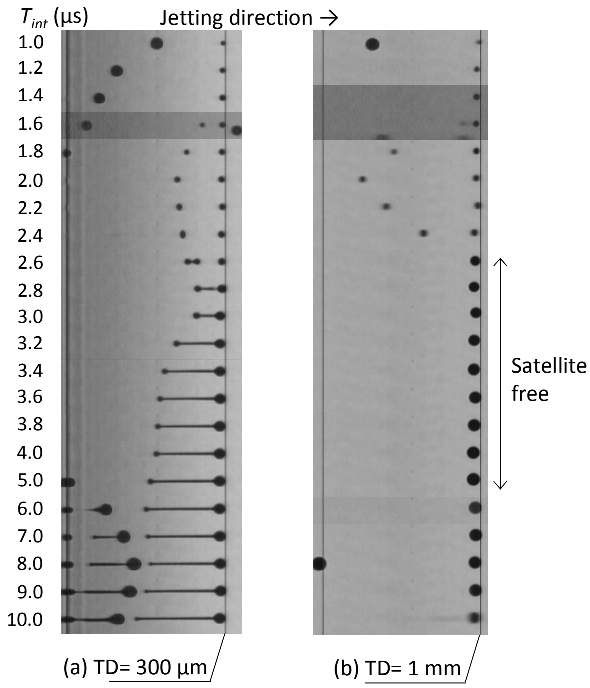

***Figure 3** Jetting observation versus main pulse width and double-pulse driving interval for T_{main}=3.4 µs*

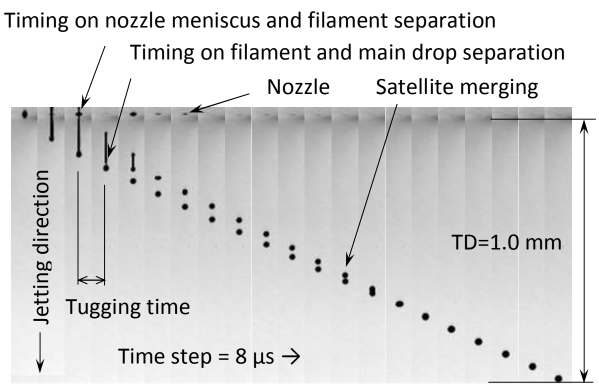

***Figure 4** Jetting in the forward merging condition (time steps of 8 µs)*

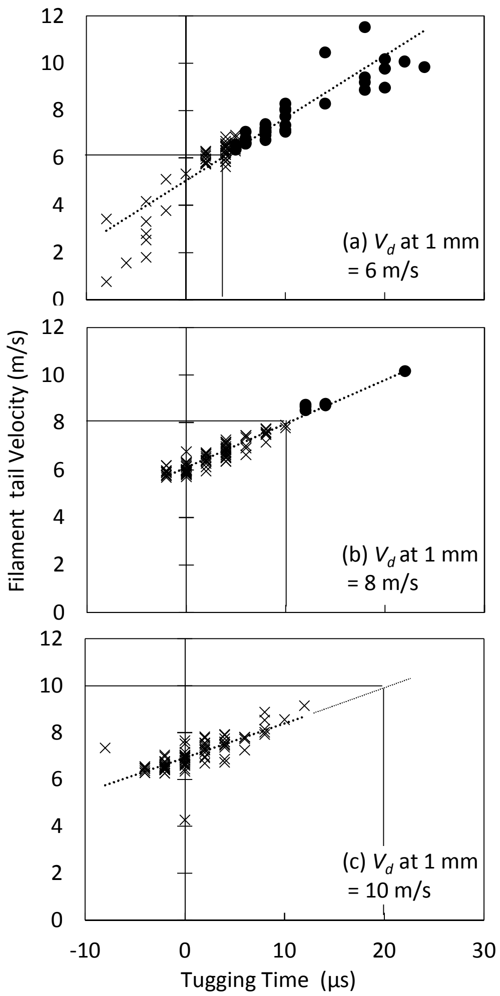

***Figure 5** Drop merging observation at various main drop velocities at a 1 mm distance: (a) 6.0, (b) 8.0, and (c) 10.0 m/s*

the tugging time decreases. This means that for this printhead, an increase in the drop speed and satellite-free conditions are not compatible in the control of the waveforms [3].

Penetration

Coloring of the paper by ink penetration is the basic principle of inkjet printing. Bleeding occurs on plain paper because the ink penetrates along the fibers; SiO, CaCO3 and water soluble polymers are therefore added into or onto the paper and the image quality, including aspects such as the sharpness of characters and the color gamut area, are then improved. Additionally, conventional printers do not need a dryer because the ink is designed to dry naturally. Therefore, the use of coated paper, which is slowly permeable, in offset printing goes against the principle of inkjet printing.

Figure 6 shows the observed results of the penetration of two continuous ink drops on (a) inkjet paper, where the penetration is completed in less than 0.1 s, resulting in printing of separated dots on the paper, and (b) offset-coated paper, where the penetration requires more than 1 s, and where two ink drops are also coalesced within a millisecond and shifted on the paper, resulting in printing of the single large and uneven dot shown in Figure 6(b).

Therefore, when printing on coated paper, the dryer must eliminate all ink solvents rapidly; this means that moisturizing agents such as glycerin, which have a higher boiling point than water and are conventionally contained in the ink to prevent nozzle clogging due to evaporation, are limited in their use.

The coalescence of ink drops that is shown in Figure 6 occurs naturally on high coverage areas. When compared with Figure 7(a), which is printed on inkjet paper, Figure 7(b), which is printed on coated paper, shows the "mottling" problem that occurs in color images in particular because of the coalescence and shifting of undried drops.

To manage these characteristics, drying of the water mentioned above on coated paper is actually possible because the dryer incorporated in the production inkjet printer itself is powerful, and adhesion of the pigments to the coated paper is also possible because the dispersing agent of the pigments contains resin or latex, which basically acts as an adhesive. Consequently, monochrome images can be printed on the coated paper using the optimized and compatible ink without changing the printer hardware; for example, additional printing of personal and/or variable information on offset pre-printed paper can be provided as outputs for transpromotional marketing purposes.

Mottling, which occurs when the color and density are high, is prevented by the pre-coated layer on the paper, which is conventional in inkjet technology, and which allows the ink pigments to be coagulated and anchored.

As demonstrated at the drupa 2016 exhibition, future candidate solutions include: the ink itself, which can print on nonpermeable media; the coated paper itself, which is applicable to aqueous inkjet printing as a plain paper in production printing; and the supporting system, which uses intermediate stages, heating and other solutions. After these improvements have been made, it is expected that inkjet printing will be able to overcome the issue of inkjet bleeding on plain (low cost) paper over a period of a year.

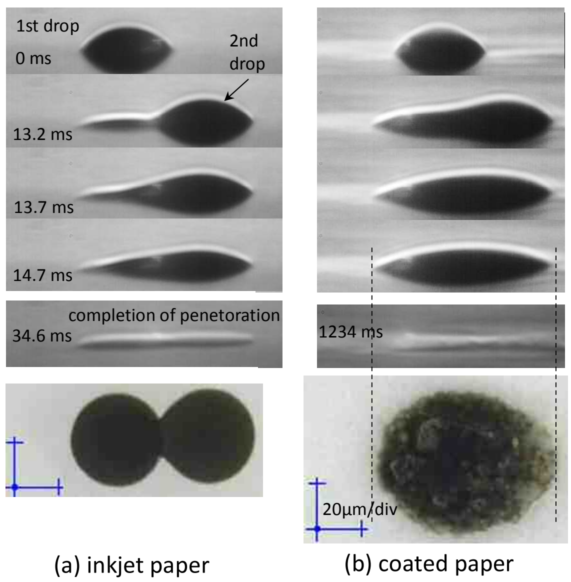

***Figure 6** Ink penetration differences relative to paper permeability*

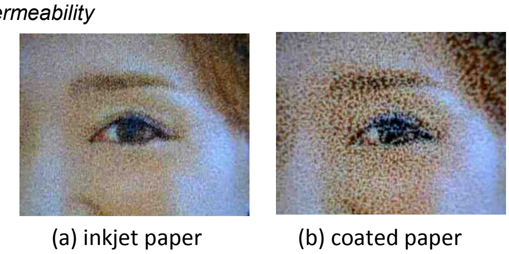

***Figure 7** Ink dot coalescence on coated paper, resulting in mottling problems*

Evaporation

Elimination of the moisturizing agents from the ink leads to a recurrence of the reliability concerns related to natural ink dehydration. Conventional piezo-inkjet printing uses its ability to make the nozzle surface vibrate to dilute condensed inks and also refreshes the ink around the nozzle by recirculation; this results in a highly reliable system [4], in which the jetting phenomenon observed as "V-shape recovery" has also attracted the interest of ink researchers [5].

Research activity into water evaporation, and particularly into understanding of the evaporation from micro nozzles, is also considered to be increasingly important; the authors have previously demonstrated that it is possible to estimate both the surface tension and the viscosity of the flying drops [6].

A method to estimate the vibration caused by the collision of the satellite drop with the forward main drop was demonstrated based on the experiments on observation of satellite drops in this report and the evaporation experiments that are described above. Figure 8(a) shows the results of observation of flying drops using a time step of 1 μs, where the vibration behavior corresponds well with the results of simulations performed using Flow 3D, which are presented in Figure 8(b). In other words, the relationship between the properties of the liquid and the vibration phenomenon [7] is well understood; i.e., in the case of a simple second mode vibration, the vibration period is controlled by the surface tension of the liquid, and the damping is controlled by the viscosity.

Figure 9 presents the results for the surface tension relative to the non-jetting time that were obtained by jetting of deionized water that contained a surfactant and measurement of the resulting vibration cycle. The reduction in surface tension in this experiment occurs 0.3 s later than that of water; this is thought to be the time required for the surfactant to coordinate with the liquid surface.

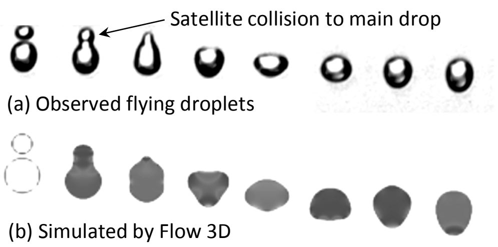

***Figure 8** Ink drop vibrations caused by satellite collision with main drop (time step: 1 μs)*

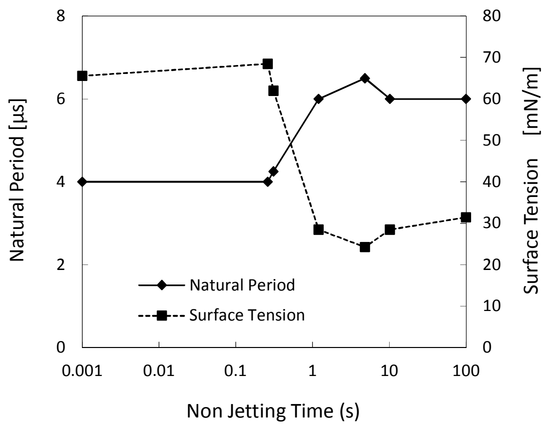

***Figure 9** Periodicity changes and estimated surface tension measured using drop vibration (water + 0.2 % surfactant)*

An ink film around the nozzle that shuts the air passage and that also breaks easily when pushed by the jetting oscillation has long been desired and discussions have recently started with regard to the actual configuration of film forming agents at the ink-air interface [8]. Such an ink, where the evaporation is controlled by the ink itself, is the ideal for inkjet printing.

Summery

The breakthroughs required for use of aqueous inkjets in production printing are considered to be high-speed satellite-free jetting, printing on nonpermeable media and evaporation control by the ink itself.

While inkjet technology has long been established and used for home/small office, photographic and wide format printing applications, there is another chance to innovate in this technology by facing the challenges in production printing, which are rather different from the challenges faced in microfabrication and 3D inkjet applications.

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Naoki Morita received his ME (1983) and his PhD (2002) in thermodynamics from Yokohama National University. Since 1983, he has worked on inkjet research and development at Fuji Xerox. He has engaged in the development of a continuous inkjet with traveling wave propagation, a thermal inkjet with rapid boiling, an acoustic inkjet with wave convergence, a solid (melting wax) inkjet and a piezo-on-demand page-width high-speed inkjet.

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