Method for In situ Measurements of Ink Jet Printed Ink Drops

Y. Socol, L. Berenstein, O. Melamed, and A. Zaban*
Dept. of Chemistry, Bar-Ilan University, Ramat-Gan, Israel

B. Nitzan
Aprion Digital Ltd., Netanya, Israel

A laboratory simulation technique that is able to study in situ drying of ink jet printed ink drops and to predict results of ink jet printing on a given substrate before mass production has been developed. The technique includes drop formation (ink jetting), imaging, and data processing. The imaging and data processing parts of the system also enable analyzing industrially-printed materials. A possibility to predict mass production results using less then 1 ml of ink is demonstrated. High flexibility makes the system applicable for different optimization tasks such as ink-substrate matching, ink formulation optimization, drying technology development, etc. By analyzing different quality parameters we give a rigorous definition of roundness and show its importance in evaluating print quality.

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Introduction

Over the last decade, considerable progress in digital printing, and in ink jet printing[1,2] particularly, has been achieved. One of the goals of ink jet research and development is quality printing at a high speed, which approximates that of laser printing, at a relatively low cost. Ink development is considered at present to be the main task,[2] and the ink-substrate interaction is one of the crucial problems of this task. This problem is probably the most complicated issue from the theoretical point of view. A full hydrodynamic analysis of the drop spreading process is at this point an impossible task.[3] For comparison, we can mention that hydro- and aerodynamic algorithms model the processes of drop formation and flight with fair accuracy (see, e.g., Ref. 4 and references therein). Therefore there is a need for experimental simulations of the ink jet printing process that would facilitate preparation of new ink formulations and the testing of their interactions with particular substrates in a matter of minutes. Moreover, in order to make the development process more cost effective, one will want to be able to use small quantities of each ink formulation.

We report here on the development of an analytical method—using the drop formation, imaging and data processing—that proved to be able to predict the results of printing on a given substrate before mass production. We show that it is possible to predict the mass production results using less then 1 ml of ink. The system also enables analyzing industrially-printed matter and drying technology development.

Technique

This technique involves two independent steps, the first being the drop injection, and the second is imaging and data processing.

Drop Injection

To simulate the ink jet printing process, the ink was injected from a distance of 1-2 cm onto the substrate by means of a glass pipette tip, which vibrated with an ultrasonic frequency. The tips were hot-pulled to obtain an inner diameter of about 30 μm. Such injection produces drops with an average volume of about 20 pl, at a velocity of 8-15 m/s. The injection velocity was determined by measuring the flight distance of the drops in air while taking into account their diameter and the air viscosity. The method therefore proved to be a good lab simulation method for industrial ink jet printing, where the ink drops are usually 10-20 pl and the injection velocity is around 10 m/s.[1]

Several advantages of this method should be mentioned. The injection can be done directly under a microscope, enabling the monitoring of the drops' evolution from the first moment of the ink-substrate contact. The glass tips can be changed in a fast and cheap way, with no interference between subsequent injections. The amount of ink required is very small – theoretically of the order of μl, practically about several ml.

For an ultrasonic generator, we used the 30 watt "Pro Scale" system having a frequency of 20 KHz. The injection application was achieved by attaching the glass pipette tip

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to the tip-shape ultrasonic transducer of the "Pro Scale". A short (up to several seconds) pulse of ultrasonic vibration was transferred to the tip yielding fine ink drops. The generator was operated at maximal output.

Imaging and Data Processing

The imaging system is based on the Olympus PROVIS microscope. Reflection, transmission and fluorescence modes are available. The images are read by a CCD camera and stored in a computer via ATI hardware/software as a pixel-to-pixel map of light intensity. The reading of images can be done one-by-one or continuously, with a frequency of up to 30 frames per second. This frequency was found to be fast enough for changes taking place during the drying of the ink drops: as shown below, a typical time scale for a drop evolution is of an order of seconds. Both color and grayscale imaging are possible. For all the studies reported in this article, grayscale imaging was performed. The measurements were performed in a narrow wavelength interval (10 nm) using bandpass filters in order to distinguish the ink from the other system components. Moreover, the semi-monochromatic light simplifies the image analysis in terms of the ink spectrum.

In each experiment, the image of substrate was first taken, then the injection was performed and a second image was taken. We define two types of characterization; "per pixel" that refers to each pixel in the image and "per drop" that refers to the whole drop area. For each pixel, we defined the following parameters:

Transmission (t) – ratio of ink drop image intensity (I) to intensity of substrate image (I_o),

$$t = I/I_o$$

$$\text{Absorption (a): } a = 1 - t.$$

Absorbance (A) – logarithm (base 10) of intensity extinction (with respect to the substrate). This parameter represents the amount of absorbing material (ink) at any given point; the intensity decreases exponentially with the amount of the absorbing medium.

$$A = -\log t$$

Each drop was characterized by several macroscopic parameters that were calculated by averaging the pixel-to-pixel characteristics. For each drop, we defined the followed parameters:

Average Absorbance $<A>$, the average absorbance of all pixels within a single drop.

Root mean square deviation (σ) of the absorbance distribution: $\sigma = (<A^2> - <A>^2)^{½}$. This parameter is one of the possible characteristics of nonuniformity of absorber (pigment or dye) distribution.

Quality Factor (QF) – ratio of total absorption a to maximal possible absorption for this amount of absorber (ink). The maximal absorption is achieved if the absorber is distributed uniformly.

Total Ink Drop Area (S) - directly measured from the image. Total amount of absorber (ink) was defined as the product of area, S, and $<A>$.

Roundness–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: Roundness = $R(in) \ / \ R(out)$. The roundness is therefore equal to unity for a circle and zero for a straight line.

We must elaborate more on the description of two of the parameters defined above:

QF – when absorbance is small ($A << 1$), the quality factor (QF) does not significantly depend on distribution. This is no more than a manifestation of near-linear behavior of an exponential function around zero. On the other hand, when the absorbance is large ($A > 1$) and the absorber's spatial distribution has the form of "black" and "white" areas, QF is close to the ratio of black areas to the total area. For example, let us consider two cases with the same amount of absorber. In the first case, the absorber is distributed homogeneously with $A = 1.0$ across the unit area: the total absorption $A_1 = 0.9$. In the second case, the same amount of absorber was used, spread only on one half of the area. Thus one half has absorbance, $A = 2$, and the other half has $A = 0$. The total absorption is $A_2 = 0.5\ (0.99 + 0.0) = 0.495$. The quality factor is 0.55.

However, from a practical point of view, it turns out that QF is not a sensitive parameter. One should keep in mind that for real ink jet printed dots the actual values for the absorbance (A) are around $A = 0.3$, i.e., the single-pass light attenuation is a factor of about two. Figure 1 presents the dependence of QF on the ratio of the covered area to the total area, for three values of average absorbance (essentially the total amount of absorber). One can see that, e.g., for $A = 0.25$, if all of the absorber is concentrated on one half of the total dot area, this causes only 20% decrease of QF. And even if absorbance is large ($A > 1$), only extreme lack of homogeneity (such as zero absorbance holes within the printed dots) leads to a significant decrease of QF. Figure 2 illustrates this point, e.g., even for $A = 1$, when the distribution of ink between two equal areas is 1:3, the quality factor decreases by only 8%.

Roundness: This parameter should be of principal practical importance, since the printing is calculated based on regularly shaped dots. One can invent many different quantitative definitions of roundness, e.g., exploiting the Fourier spectrum of the drop boundary shape.[5] Our definition comes from the field of computational metrology. It is in fact the measure used by the American National Standards Institute and International Standards Office.[6] This definition seems the most relevant from the point of view of printed pattern formation (this parameter was used by Heilmann et al.,[7] though its rigorous definition is absent in their article).

Image Processing

The image processing software was written especially for this system using the Matlab[8] package. It enables interactive viewing of the obtained images together with the macroscopic parameters mentioned above. In order to calculate the parameters of the drop itself, we defined the drop as being all of the recorded pixels with absorption above the background level, i.e., with transmission lower than the given threshold. Empirically, we found that this threshold was $t = (0.85 - 0.95)$.

In order to calculate the roundness, we used the following algorithm. First, the drop center of gravity (COG) is calculated. Then, we calculate separately the distances from the COG to every pixel with absorbance above the threshold ("ink"), and to those pixels with absorbance below the threshold ("background"). Finally, we define the outer radius of the annulus as the maximal value of all the distances between the COG and the ink pixels. Correspondingly, the inner radius of the annulus was

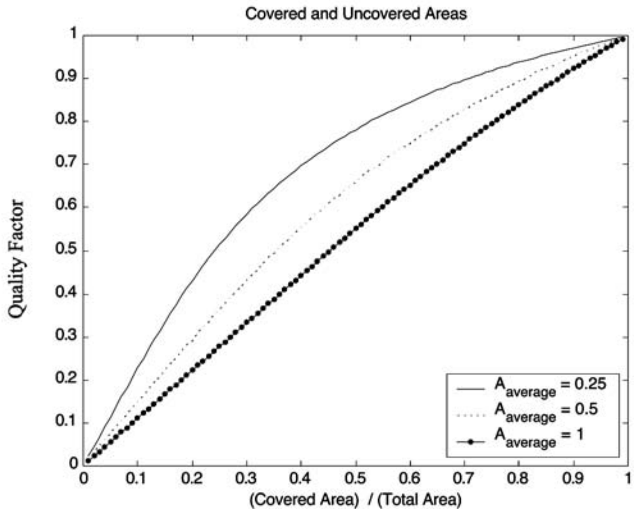

Figure 1. Drop with no-ink holes: the dependence of the quality factor, *QF,* on the ratio of the area covered by ink to the total drop area. The covered area is considered to be strictly uniform.

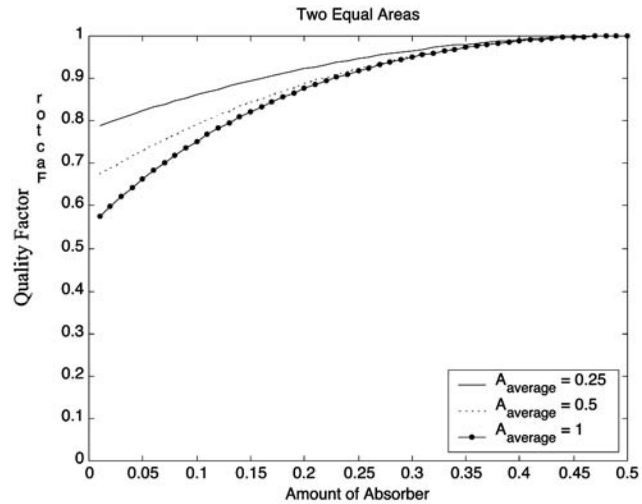

Figure 2. Drop with two equal areas of different absorbance: the dependence of the quality factor, *QF* on the amount of ink in one area.

defined as a minimal value of all the distances between the COG and the background pixels.

Materials

In all of the experiments, we used a water-based (57%) cyan pigment ink, containing 20% of dipropylene glycol, additional 10% of liquid and 13% solid components.[9]

For the feasibility study we used eight different substrates used in the wall-covering production industry. The substrates can be divided into three major groups: vinyls, papers and non-wovens.

Vinyl is a generic name for specialty polymer films. These substrates have a low surface energy (hydrophobic) and are non-absorbing, though they differ from each other in their surface chemistry. We studied cotton backed vinyl (180 g/m^2) manufactured by RJF, USA; CP 90/90, vinyl coated wallpaper manufactured by Chamberlin Coating Ltd., UK; and standard PVC coated (90 g/m^2) mechanical pulp (80 g/m^2) manufactured by Forbo CP Ltd., UK.

Papers are absorbing substrates. Coating can significantly vary their properties, and this topic is beyond the scope of this report. For the feasibility study we took uncoated substrates Superfine 150 g/m^2/60 mesh paper, manufactured by Horton Kirby, UK; Keshet Matte 135 g/m^2, manufactured by AIPM (Hadera Paper Mill), Israel.

Non-woven is a generic name for non-woven fabric made of synthetic fiber. Their fiber structure is generally more coarse than paper's fiber structure. These substrates can be highly absorbing, depending on the type of fiber used and on whether they are coated or not. Printing on these substrates by ink jet technology is generally problematic due to their coarse fiber structure that affects dot uniformity. We studied "Borastapeter Moment" – manufactured and coated by Borastapeter, Sweden and Ahlstrom 4811 and 7032, manufactured by Ahlstrom Lystil, France.

Each sample was glued onto a microscope slide (26 × 76 mm), which was fixed onto the microscope. Several samples of each substrate were studied in order to check reproducibility. Several hundreds of dots were injected onto each sample in 3-5 series. One or two dots (within one field of view) of each series were monitored in situ, and 20-50 were examined afterwards to check macroscopic trends.

Our system enabled us to observe some interesting features of ink drop behavior typical to the different types of substrate. Though each substrate has its particular details, each type, i.e., vinyls, papers and non-wovens, has its characteristic features. Here we present the results obtained on Forbo substrate as an example of vinyl, Keshet Matte – paper, and Ahlstrom 4811 – non-woven fabric. We emphasize that beyond the specific illustrative results presented in the next section, the goal of this report is to present the power of the new technique that enables monitoring of the drop evolution at high resolution under printing conditions.

Results

For all substrates studied, the correlation between the printed dots obtained with an industrial printing machine[9] and by the described technique of ink jet simulation was very good. The main distinguishing feature of the simulation technique is its rather broad range of ink dot sizes (generally from 20 to 70 μm in diameter). This feature can be viewed as a drawback in some applications, but since one can select the sizes relevant to each specific machine it is possible to study the ink behavior in different systems at once. Furthermore, in some cases one can utilize the extremely small dots to obtain information regarding satellites.

Figure 3 shows the time evolution of an ink drop on Forbo. The figure reveals the regular circular shape of the drop, which is preserved during the entire evolution. We note that the *z*-axis in this presentation is absorbance, which depends linearly on the absorber concentration. Thus it represents relative amount of pigments on the surface. Figure 4 (top) shows the high values of roundness. The absorbance histogram (the right column of Fig. 3) shows that the drop homogeneity increases during the evolution. Namely, the mean width of the absorbance distribution decreases by a factor of about two. However, the quality factor does not change, as expected based on our theoretical analysis discussed earlier.

We should also mention here that although the drop is "frozen" after at most 1 minute, i.e., no further evolution is observed, the drying time at room conditions (25°C, 70%

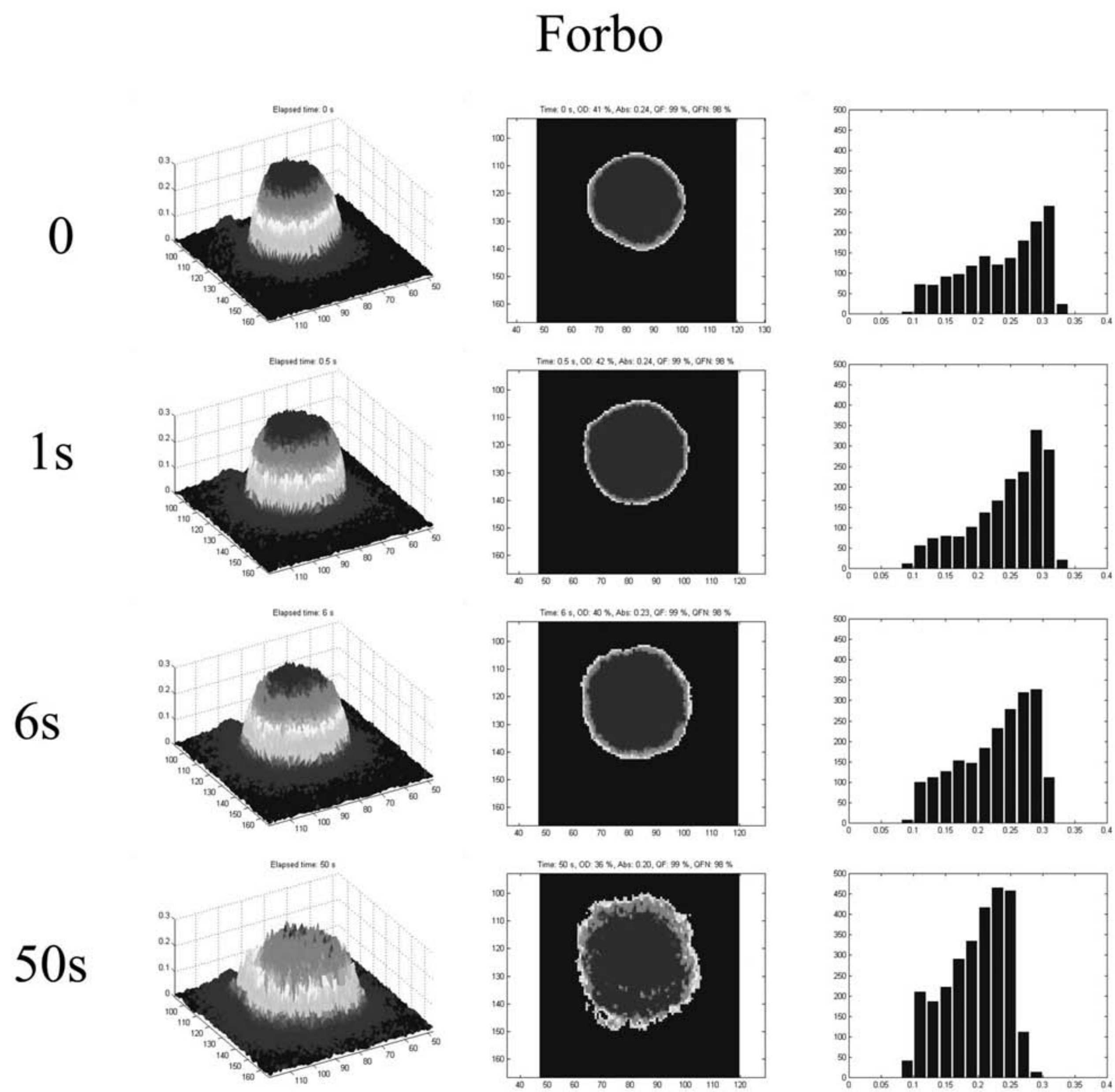

Figure 3. The time evolution of ink drop on the "Forbo" (vinyl) substrate. The regular circular shape of the drop is preserved during the entire evolution, which is typical for vinyl substrates. The absorbance histogram (the rightmost column) shows that the drop homogeneity increases during the evolution. *Supplemental Materials—Figure can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

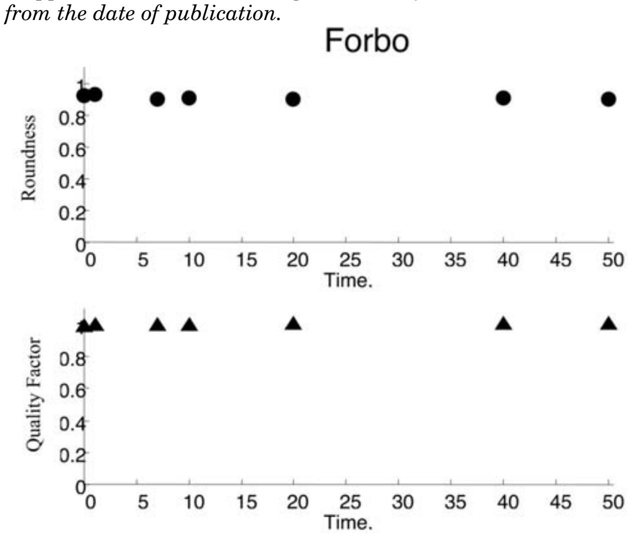

Figure 4. The "Forbo" (vinyl) substrate, time-dependence of parameters. Top: roundness. Bottom: the quality factor. Note that the quality factor does not change, though the mean width of the absorbance distribution decreases by a factor of about two (see Fig. 3).

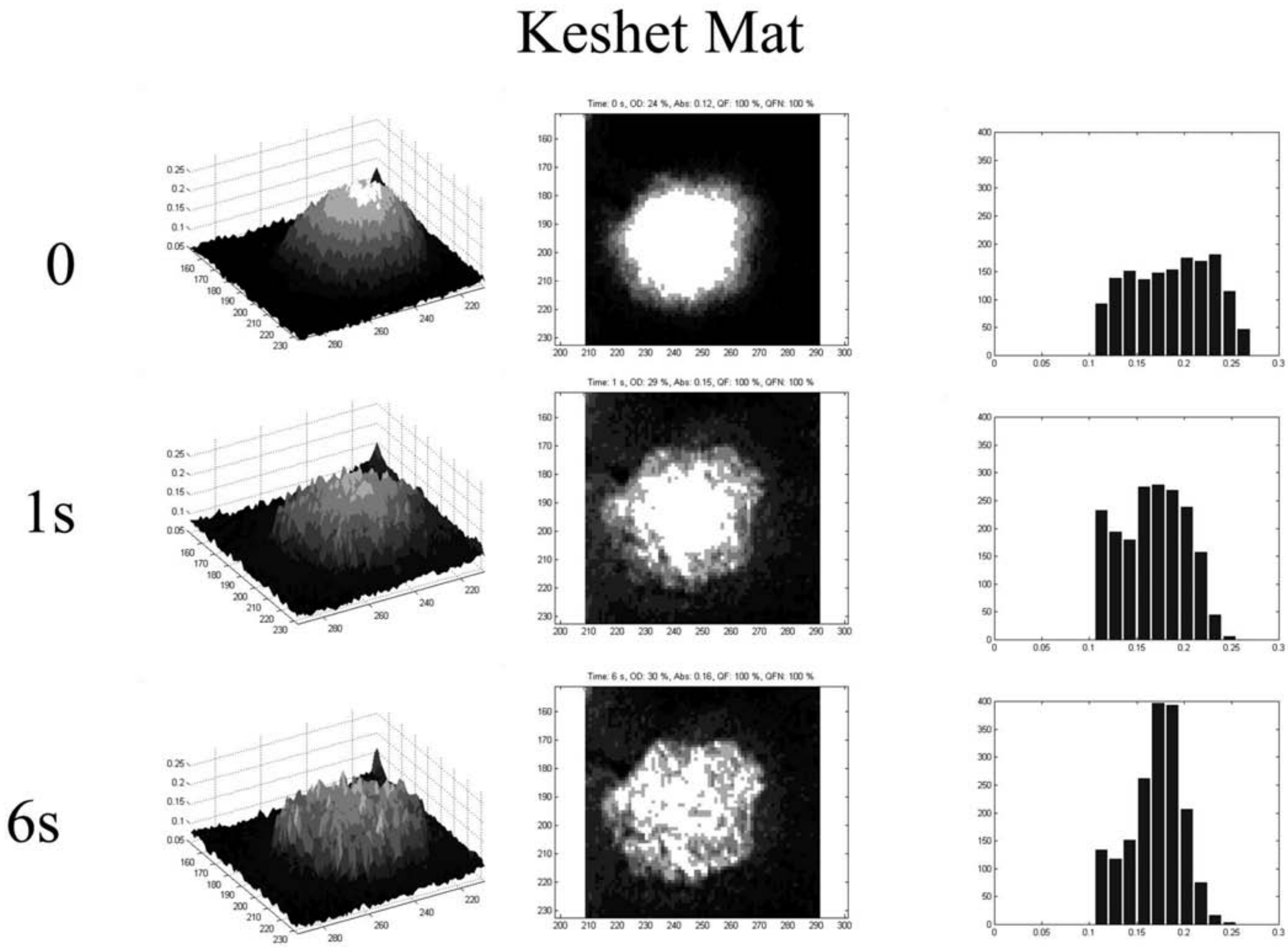

Figure 5. Substrate: "Keshet Matte" (paper). The absorbance profile is not as smooth as on "Forbo". The evolution time is much shorter and there are no essential changes after about 10 seconds. The latter is connected with the fact that the solvent (water) penetrates the porous substrate (paper) much faster than it is evaporated in the case of non-penetrable substrate (vinyl). *Supplemental Materials—Figure can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

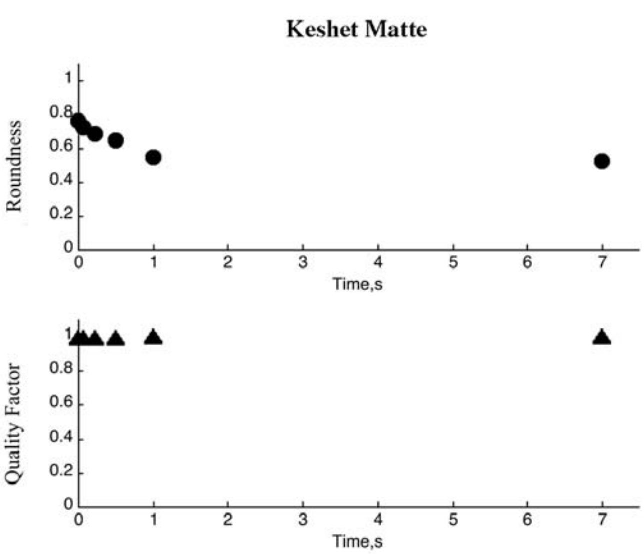

Figure 6. Time-dependence of parameters on "Keshet Matte" (paper). The roundness is somewhat lower than on "Forbo".

humidity) is approximately 10 minutes. The latter was measured by putting a paper sheet on top of the printed pattern and applying constant pressure of 0.5 g/cm^2. This behavior is usually attributed to viscosity increase.

Figures 5 and 6 provide similar information about drop evolution on Keshet Matte paper. The absorbance profile is not as smooth as on Forbo, and the roundness is somewhat lower. The evolution time is much shorter: there are no essential changes taking place after about 10 seconds. This is because with the fact that the solvent (water) penetrates the porous substrate (paper) much faster than it is evaporated in the case of a non penetrable substrate (vinyl). Moreover, non-calendared paper such as the Keshet Matte tends to create a feathering phenomenon, which increases the ink flow unevenly on the surface.

Figures 7 and 8 demonstrate the problematic effect due to coarse fiber structure of non-wovens. Specifically, the evolution of a drop on a non-woven substrate, Ahlstrom 4811, is shown. One can readily see the process when a drop is moving along a fiber, resulting in a very irregular shape. Such a shape has a near-zero roundness (see Fig. 8). However, the quality factor parameter is as high as in cases of regularly shaped drops, since its calculation does not take the shape into account. Consequently, this

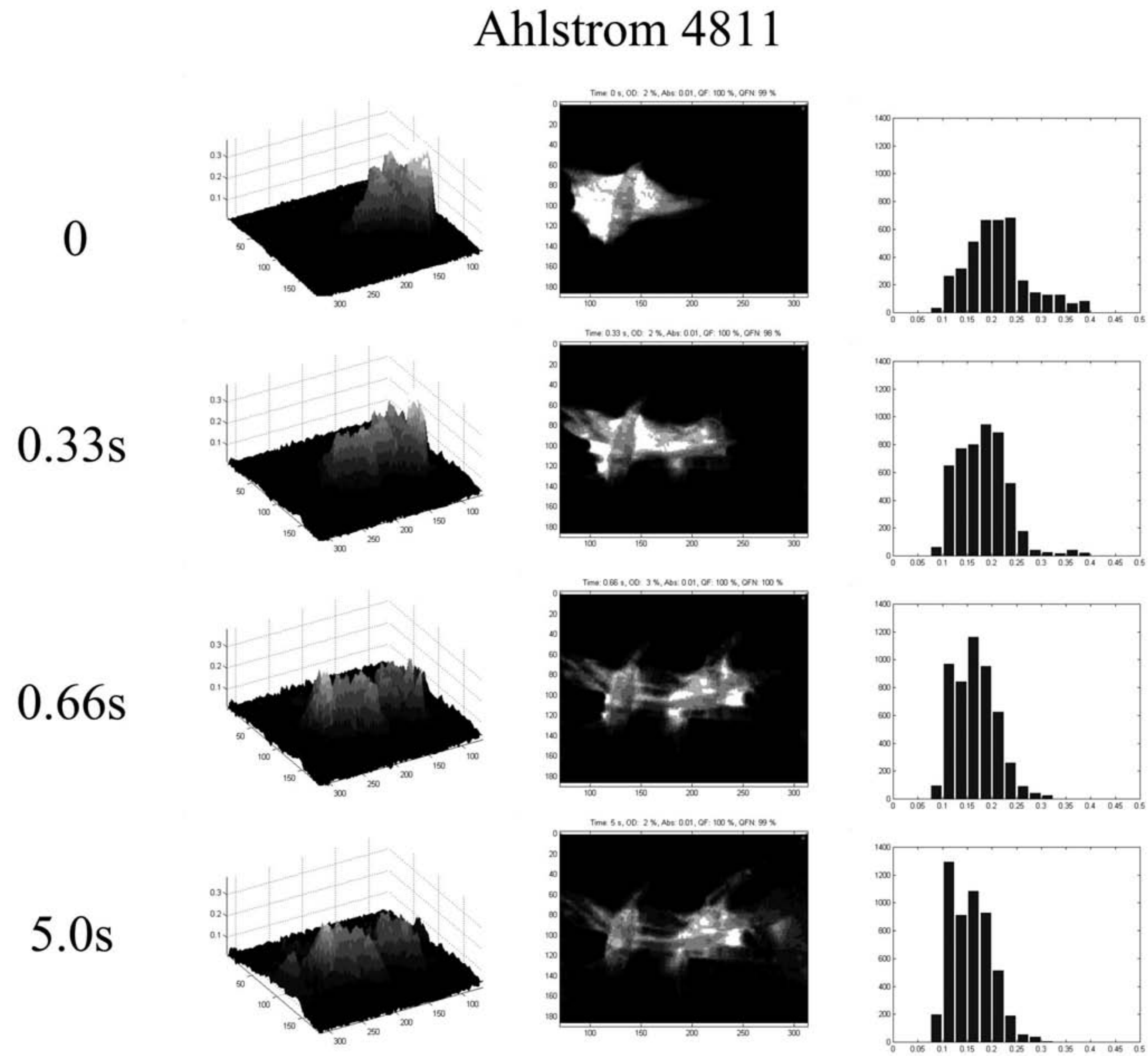

Figure 7. Substrate, Ahlstrom 4811 (non-woven), with a clearly seen fiber structure. One can readily see the process when a drop is "moving" along a fiber, resulting in very irregular shape. *Supplemental Materials—Figure can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

parameter cannot be considered important in judging the printing results.

Discussion

As shown above, the technique thus far developed can give valuable information about ink-substrate interaction in a matter of minutes. Several applications have been listed as examples, some of them having been reported in other works:

1. General understanding of the behavior of ink drop – substrate interaction under different conditions.
2. Finding the optimal ink composition for any given substrate. That is, a high resolution study of the ink composition is possible owing to the fact that only small volume of ink is needed.[10]
3. Verifying the results of printing before mass production.[9]
4. Studying the impact of external parameters, e.g., heating, on the process of ink drying, and therefore drying technology development.[11]

The present ink jet simulation method proved to be simple and reliable. As for the image analysis, though many such systems have been reported in the literature (see, for example, the work of Tse et al.,[10] and references therein), most of them are of quality assurance type. That is, they are designed to measure small deviations of parameters during mass production. In addition, such systems are oriented towards the macroscopic end quality features, such as line sharpness, color matching, etc. In contrast to quality assurance, the tasks of research and development may be quite different. Instead of multiple and continuous measurements, it is important to examine

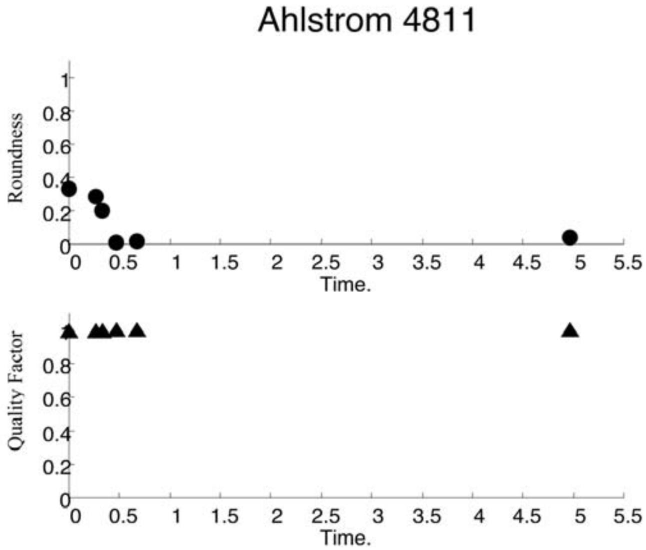

Figure 8. Time-dependence of parameters on Ahlstrom 4811 (non-woven). The roundness has a near-zero value. However, the quality factor parameter is as high as in cases of regularly-shaped drops, demonstrating in a very clear way that this parameter cannot be considered important in judging the printing results.

variations in working parameters, e.g., different inks and substrates. In addition, the single dot parameters become relevant. Therefore, both the flexibility of experiments and the ability to study the behavior of single drops are principal issues. Indeed, a few very flexible techniques[3] have been developed, but they are rather complicated and expensive.

Summarizing, we demonstrated a powerful system for the study of ink jet drop evolution. The system is flexible and inexpensive. It requires only small amounts of ink. We also defined several mathematical parameters of image quality to judge essential properties of the ink-substrate interaction. We showed that the lack of homogeneity of printed dots is not crucial and therefore those parameters are not relevant. The roundness parameter, however, was found to be of high importance.

Conclusions

We have developed an analytical method – using drop formation, imaging and data processing – that proved to be able to predict the results of printing on given substrate before mass production. Very small amount of ink (less than 1 ml) is needed. With respect to drop formation, on each of eight substrates belonging to three different groups, the results of the simulated printing were very similar to those of printing on an industrial machine. With respect to data processing, the roundness parameter seems to be highly significant regarding ink behavior on the surface.

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