Dynamics of Impaction and Post-Impaction Behavior of Drop-On-Demand (DOD) Inkjet Drops on Textiles

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Abstract

In order to better understand the drop impaction and post-impaction dynamics of digital textile printing, various numbers of drop-on-demand inkjet drops were deposited on textiles, and the process was visualized using a high speed camera. As a comparison, experiments were also conducted on a high quality inkjet paper under the same conditions. Dynamics of DOD drops accumulation and spreading on the substrates and final state ink distribution show drastic differences between digital printing on textiles and paper. The effect of yarn hairiness on ink deposition was also demonstrated.

Introduction

Textile digital printing, with inkjet printing as the mode of application, has become an accepted technology; however, the broad utilization of this flexible method faces a number of barriers. Technical hurdles to inkjet application of colorants to textile materials exist in two forms. The first is in the dynamics of drop formation and surface motions of solids-laden inks. The second is the role of the surface morphology and surface chemistry encountered in textile materials. In the study reported here, the spreading of DOD drops jetted onto textiles, the final ink distribution on the textile surfaces and the effect of yarn hairiness on digital textile printing were investigated.

Experimental

The equipment used for this work consisted of the following:

- a piezo-electric inkjet head with thirty-two 45-μm diameter nozzles and actuating signal source;
- a high resolution digital camera and lens (1.2 μm/pixel, 10.7× magnification);
- copper solid-state laser for delivering pulsed laser light of 25-ns duration;
- a one-dimensional translational stage with programmable traveling speed and scheme; and
- a system to delay the camera and laser pulse amplitude for imaging and to control the translational stage for positioning and housing the inkjet drop.

As shown in Figure 1, the camera was arranged to have a 45 degree observation angle to the plane of the substrate. A laser light was projected at almost the same angle and reflected from the substrate to the CCD camera. The images of DOD drop impacting and spreading in this study were taken using this setup. Other images were taken with Leica DMRXA microscope and SEM. Properties of the three liquids (water and two water-based pigmented inks) used in this study are listed in Table 1.

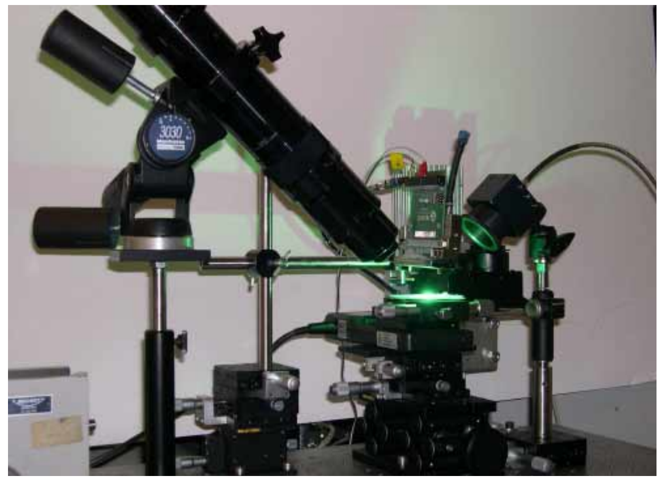

***Figure 1**. High speed imaging system*

Table 1: Ink Properties

Ink	Surface tension, mN/m	Viscosity, cPs	wt% of pigment	Dispersion mechanism
1	73	1.0	0	N/A
2	33	4.5	5	electrosteric
3	34	5.8	1.5	electrostatic

A flash photography technique developed previously [1] was used for visualizing the drop formation process. An example of the drop formation process is shown in Figure 2. The clock was started at the point of the emergence of ink from the nozzle. The process of drop formation was highly reproducible for the first 130 μs. For longer times, reproducibility of the formation of satellites decreases due to the long length of the liquid ligament after the secondary breakup (at which the primary drop and the liquid ligament was separated as shown in Figure 2 at 75 μs). As a result, the number, sizes and velocities of satellites were different for each actuating signal. At 160 μs in Figure 2, six random chosen scenarios of the contracting liquid ligament show the irreproducibility of the formation of satellites at high actuating voltage. However, the size and speed of the primary drop were highly reproducible.

In order to visualize the impaction and spreading dynamics of DOD drops on the substrates and to have sufficient space for the laser light to be reflected to the camera (Figure 1), the distance

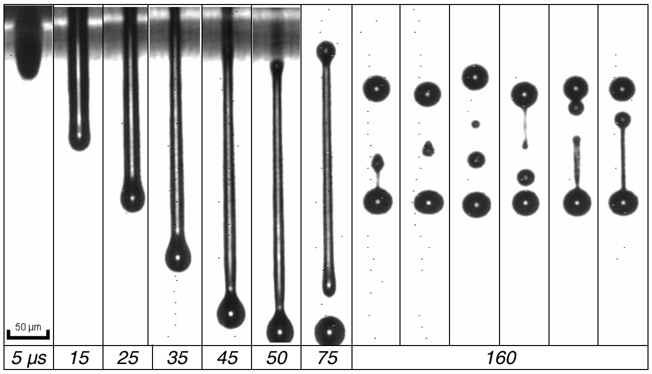

Figure 2. Drop formation process at actuating voltage of 27 V. The liquid was the base solution (without pigment) of Ink 3

from the nozzle to the substrate was set to be 6.0 cm, which is much higher than the conventional operation distance. The larger separation distance affected the impact position of the satellites, but not that of the primary drops which had a much higher speed (6.1 versus less than 3.2 m/s of satellites). Thus the satellites did not interfere with the observation of impact of primary drops, as illustrated in Figure 3. In this study, we visualized only impaction dynamics of the primary drops. For studying the final distribution of ink on the surface of the fabric for varied amount of drops, the printing distance from the nozzle to the substrate was maintained at 0.3 cm. At this printing distance, the satellites and the primary drops had the same trajectory, and impacted at the same position on the substrate.

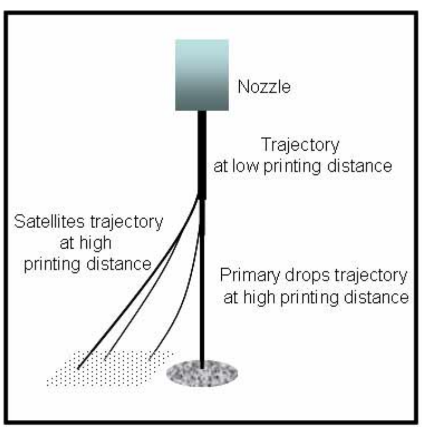

Figure 3. Illustration of trajectories of primary drops and satellites

A train of actuating signals was designed using a computer-programmed waveform generator and sent to a single piezo-electrical nozzle. The number of actuating signals was varied, which corresponds to a varying number of primary drops impacting on the substrates. We found that for the printhead used in this study, the drop formation process was independent of the frequency up to about 7 kHz. At higher frequency, the time interval, Δt, between two consecutive actuating signals was not long enough for sufficient acoustic damping in the nozzle chamber, resulting in interaction between two consecutive actuating signals. In this study, Δt, was varied, but chosen to be no less than 150 µs (frequency no higher than 6.7 kHz). By using this strategy, reproducibility of primary drop formation was achieved.

The two fabrics used in this study were bleached, mercerized combed cotton broadcloth and filament polyester oxford weave. Both were obtained from Testfabrics, Inc. For comparison, Epson high quality inkjet paper was also used. For the cotton fabric, yarn size in both warp and filling directions was 40's c.c., and the thread count was 133×72, which means that in the warp direction, there were 133 yarns/inch, and in the filling direction, there were 72 yarns/inch. For the polyester fabric, the yarn size was 250 denier in both warp and filling directions, and the thread count was 56×40. The SEM pictures for both samples are shown in Figure 4. Due to the short length of the cotton fibers, fibers protrude from the surface of the cotton yarns, creating a "hairy" fabric.

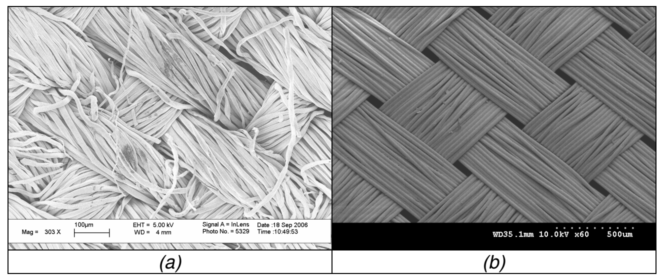

Figure 4. SEM pictures for: a) bleached, mercerized combed cotton broadcloth; and b) filament polyester oxford weave

Dynamics of DOD Drops Impacting on Inkjet Paper and Textiles

A series of 40 primary drops made of Ink 3 (see Table 1) were impacted on inkjet paper, cotton fabric and polyester fabric. The total ink deposited in each case was 1.1 nanoliters. The drops (diameter of 37 µm and speed of 6.1 m/s) were jetted at a frequency of 6.7 kHz, so the time, Δt, between two consecutive actuating signals was 150 µs. The digital camera frame rate and the shutter time were 1000 fps and 500 µs, respectively.

Images taken at a series of times for the accumulation of all 40 drops is shown in Figure 5. Time was measured starting at the last frame prior to the first impaction on the substrate. Due to the uncertainty of when the first drop hits the substrate, the first frame with drops may contain one to seven drops. When time reaches 6 ms, all 40 drops will have impacted the substrate.

For all three substrates, as drops accumulated, the diameter of liquid mass increased and the edges were confined by the local surface morphology. The main liquid mass on inkjet paper (Figure 5, (a)) appears oval for all 6 images. Note that the camera was arranged to have a 45 degree observation angle to the plane of the substrate. Thus the actual vertical dimension is $\sqrt{2}$ larger than appears in the photograph. When the vertical dimension is increased by this factor, the liquid mass resembles an irregular circle. For the cotton fabric (Figure 5, (b)), the drops were deposited on a warp yarn (running in the vertical direction of the images). The fibers acted as barriers for spreading. Due to the fibers' orientation in the vertical direction, the liquid mass spread more in that direction. For the polyester fabric (Figure 5, (c)), the drops were deposited on a weft yarn (running in the horizontal direction of the images) with a position very close to the intersection between a warp yarn and a weft yarn. As shown in Figure 5 at 2 ms, the accumulated liquid spread to the fibers in the warp yarn, but further spreading in that direction was inhibited by the vertically oriented warp fibers which acted as barriers. As a result, the deposited drops spread more to the left direction in the images where there were no such barriers.

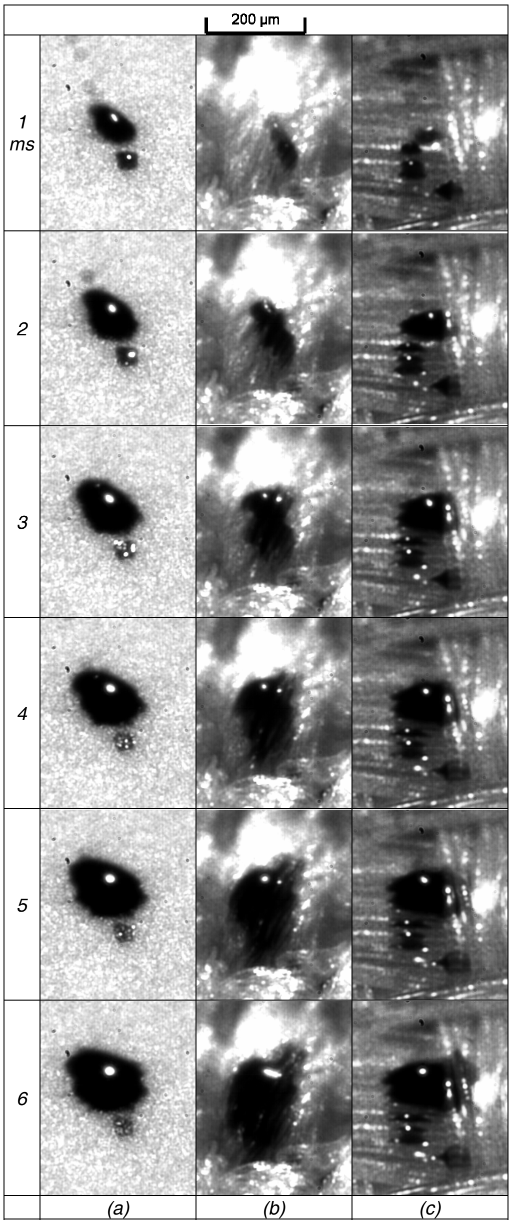

***Figure 5**. First 6 ms of accumulation of a series of 40 primary drops on: a) high quality inkjet paper, b) cotton fabric and c) polyester fabric, respectively*

When time reached 6 ms, all 40 drops have impacted the substrate and the impact process driven by inertia was over. Liquid movement was then driven by capillary forces until the ink reached to its final position. Images of the substrate surface at various times are shown in Figure 6. The area colored by the ink increased with time for all substrates, but reached the final value much quicker for the inkjet paper.

For inkjet paper, ink spread over the surface in all directions and wicked into the substrate. The fabrics had a much higher mean surface roughness with individual fibers tending to run in the directions of the warp and weft yarns which affected the direction of capillary flow and the pigment distribution (as shown in Figure 6, 121 ms). For both fabrics, the ink on the warp yarn flowed in the vertical direction while the ink on weft yarn flowed in the horizontal direction. For polyester fabric (as shown in Figure 6, part (c)), at 6 ms, much of the liquid mass was positioned on a weft yarn (on left) which intersected with a warp yarn (on right). A small amount of the liquid was on a few fibers in the warp yarn. When time reached 121 ms, however, more liquid mass was distributed on the warp yarn.

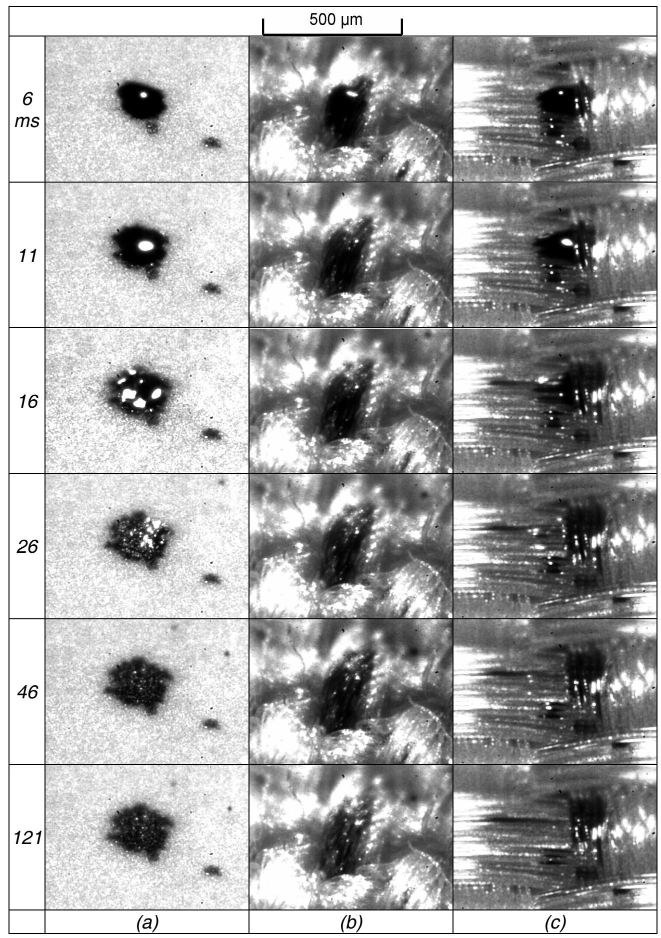

***Figure 6**. Further spreading of the 40 primary drops to the final position on: a) high quality inkjet paper, b) cotton fabric and c) polyester fabric, respectively*

Final Ink Distribution on Inkjet Paper and Textiles

Figure 7 shows a SEM picture of a 43-µm (41.6 picoliter, no satellite, Ink 2) single DOD drop deposited on inkjet paper and on cotton fabric. The circles in the middle of the pictures indicate the size of the DOD drop. The ink distributions on inkjet paper resembled an irregular circle with diameter approximately doubled that of the impacting drop. The ink distribution for the cotton fiber is not circular. The cotton fiber size is about 20 ± 10 μm and the yarn size is about 200 μm. Consequently, the size of the DOD drop is about the size of 2 to 3 fibers, including the gap between neighboring fibers, and the yarn size is about 4.7 times bigger than the ink drop. The distribution of the pigment on the surface of the fibers gives a hint for the direction of spreading process. The impacting ink drops spread further along the fiber direction than in the transverse direction. The fibers acted as a barrier for transverse spreading. This observation agrees well with the phenomena discussed below for the cases of multi-drop impaction on fabrics.

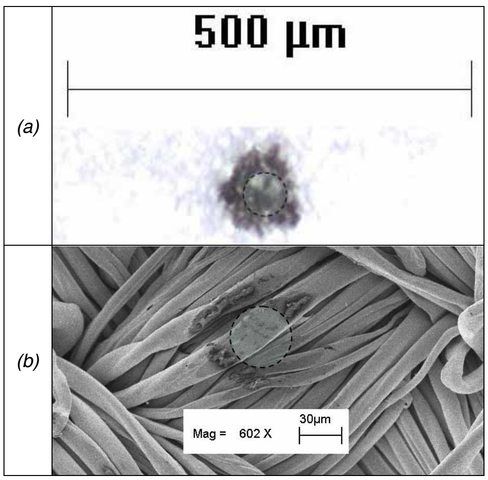

***Figure 7**. Optical microscope picture (a) and SEM picture (b) of a single DOD drop of 43-μm diameter deposited on high quality inkjet paper (top) and cotton fabric (bottom). The dashed circles represent the size of a single drop*

Final ink distribution was studied varying the amount of Ink 3 deposited on cotton fabric and inkjet paper. The printing distance between the nozzle and the substrate was 0.3 cm so that primary drops and satellites were deposited on the same position. Figure 8 shows the dried pattern of 20, 40, 60, 80, and 100 drops (approximately 1.1, 2.2, 3.3, 4.4, 5.5 nanoliters, including satellites) deposited on the inkjet paper and Figure 9 shows 20, 60, 100 drops (approximately 1.1, 3.3, 5.5 nanoliters, including satellites) deposited on the cotton fabric. The jetting frequency was 1 kHz.

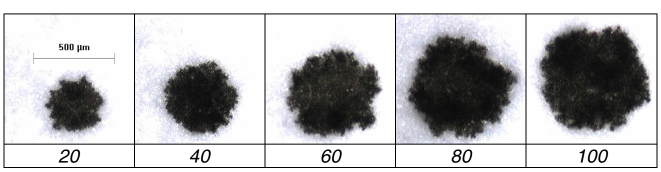

***Figure 8**. Varied amount of ink deposited on high quality inkjet paper. The number of drops deposited is shown below the image*

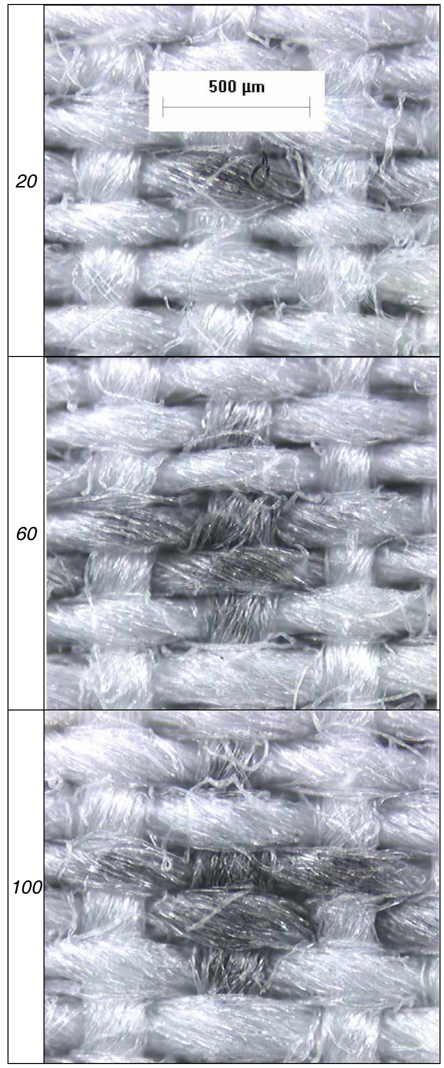

***Figure 9**. Varied amount of DOD drops deposited on the cotton fabric. The number of drops deposited is shown next to the image*

The final ink distributions on inkjet paper resembled irregular circles, with their size increasing as the number of drops increased. The final ink distribution on the cotton fabric was greatly affected by the fabric structure, that is, the yarn direction and intersections. The ink tended to stay on one yarn as drops accumulated until excess ink moved to neighboring yarns. As the number of drops increased, the change in the ink distribution on the cotton fabric was mainly the increasing distance over which the ink spread along the yarns.

Figure 10 shows three randomly chosen pictures of 100 drops deposited onto the cotton fabric after drying. The distribution of ink depended on the impaction location on the fabric, and the patterns on the three fabrics were different. While the patterns were different, in all three cases, the movement of liquid was along yarns. Sometimes when yarns intersected, some of the ink moving along the yarn changed directions and moved along the intersecting yarn.

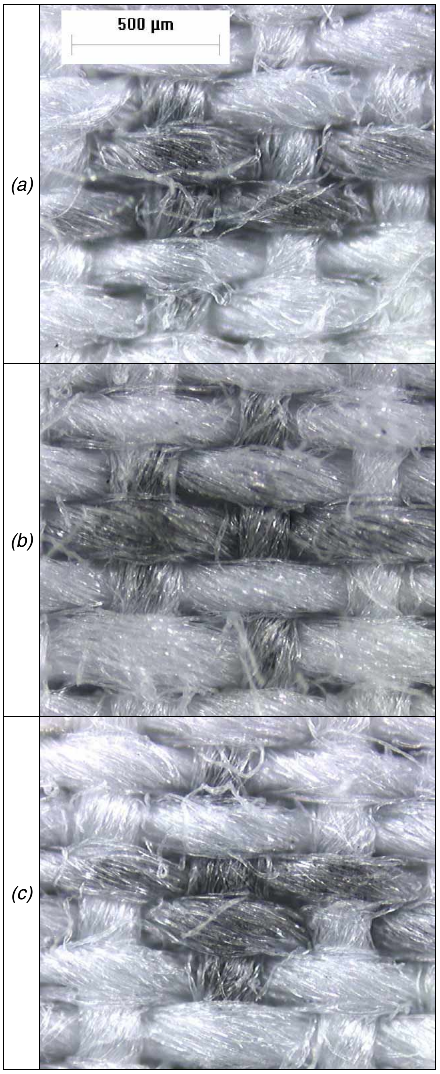

Figure 10. *Three random chosen cases of 100 drops (including satellites) depositing on cotton fabric*

Role of Yarn Hairiness on Digital Printing on Textiles

As mentioned earlier, due to the short length of the cotton fibers, fibers protrude from the surface of the cotton yarns, creating a "hairy" fabric. These fibers can affect the final ink distribution. Figure 11 shows inkjet printed water drops (Ink 1) captured by a surface fiber. In case 1, the captured water had a clam-shell shape [2], and remained on the fiber. In some instances, the accumulated water fell from the fiber onto the fabric, as illustrated by case 2 in Figure 11.

In both cases shown in Figure 11, ink distribution was affected by a surface fiber. In case 1, ink remained on the fiber and did not reach the intended location. While for case 2, depending on the orientation, length and stiffness of the fiber, the final location of the accumulated ink would be random. Figure 12 gives several examples for the two cases observed in inkjetting Ink 2 onto cotton fabric. All the pictures were taken after the ink was dry. For images (a) and (c), 4 and 6 drops, respectively, were captured and remained on surface fibers. As a result, the fibers were coated with pigment. For image (e), it appears that only part of the captured drops remained on the fiber and the rest fell down to the fabric. The portion left on the fiber dried and formed a barrel-shape [2] pigment body, and the part that fell can be seen as a grey region on the fabric. As a comparison, images (b), (d), and (f) show final ink distribution when the drops were deposited directly to the fabric.

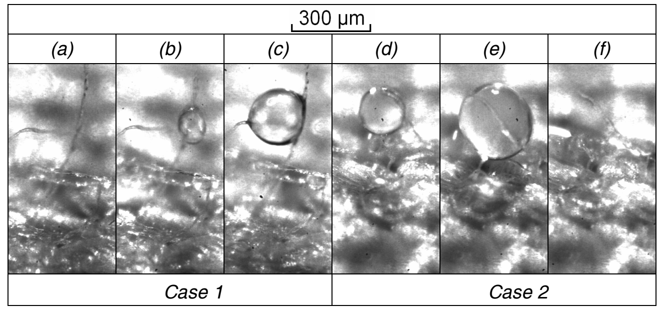

Figure 11. *DOD drops captured by surface fiber on the cotton fabric. Case 1: images (a), (b) and (c) show before, intermediate and after the accumulation of captured drops on a fiber, respectively. Case 2: images (d), (e) and (f) show intermediate, state of maximized captured drop volume, and state after captured drop fallen down onto the cotton fabric, respectively*

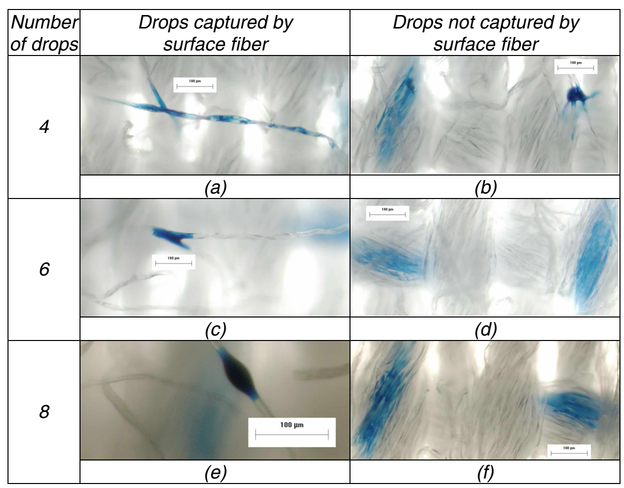

Figure 12. *Effect of surface fiber on final ink distribution on cotton fabric. All the scale bars shown in the images represent 100 μm*

Conclusions and Discussion

Various numbers of drop-on-demand inkjet drops were deposited on textile fabrics, and the process was visualized. As a comparison, experiments were also conducted on a high quality inkjet paper under the same conditions. Dynamics of DOD drops accumulation and spreading on the substrates and final ink distribution show drastic differences between digital printing on textiles and paper. The final ink distributions on inkjet paper resembled irregular circles, with their size increasing as the number of drops increased. The final ink distribution on fabric was greatly affected by the fabric structure, that is, the yarn direction and intersections. The ink tended to stay on one yarn as drops accumulated until excess ink moved to neighboring yarns. As the number of drops increased, the primary change in the ink distribution on the cotton fabric was the increasing distance over which the ink spread along the yarns. Fibers protrude from the surface of the cotton yarns, creating a "hairy" fabric. These fibers can affect the distribution of ink on the fabric.

Acknowledgements

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Author Biography

Xi Wang received his bachelor degree in knitting engineering from the University of Qingdao, China (2002), and he has been a graduate student in the School of Polymer, Textile and Fiber Engineering at Georgia Institute of Technology since 2004. His research interests includes digital printing of textiles, DOD drop formation and impaction on patterned rough surfaces, rheology of DOD inkjet inks, and thermal sciences in industrial fiber and carpet/textile processes (heating, drying, curing).