Evidence of Print Gap Airflow Affecting Web Printing Quality

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Abstract

The current study extends our earlier investigation on the real-time dynamics of print gap airflow around a single jetted drop over a moving substrate. In the present work, simulated web press printing was performed using a stationary grey-scale commercial inkjet print head to print full-width block of solid colour images onto a paper substrate with extended print gaps. The resultant printed images exhibit patterns or 'wood-graining' effects which become more prevalent as the relevant Reynolds number (Re) increases. The high-resolution scans of the printed images revealed that the patterns are created by oscillation and coalescence of neighboring printed tracks across the web. The phenomenon could be a result of drop stream perturbations caused by unsteady print gap airflow of the type similar to that observed in the previous study.

Introduction

The current study extends our earlier investigation on the real-time dynamics of the print gap airflow around a single jetted drop over a moving substrate [1]. We have previously reported that while the gap airflow between a moving substrate and a stationary print head appears to conform to a laminar Couette flow profile, there are significant interactions between the wakes trailing the jetted drops and the gap air flow. These interactions have been shown to create local flow disturbances around the trajectories of the jetted drops in our previously reported results. Additionally, and perhaps more importantly, we have shown that these induced flow disturbances can be carried downstream by the gap airflow and may potentially affect the trajectories, hence the deposition accuracy of the jetted drops from adjacent nozzles. Considering that a typical industrial inkjet print head often has nozzles arranged in densely-packed arrays, it is conceivable that such disturbance can rapidly and significantly grow in magnitude and complexity under certain printing conditions.

In a typical high-speed inkjet web press, images are printed onto a continuous web of substrate (paper, polymer film, etc.) as it is passed at constant speed under a stationary print head. While a real commercial print press will consist of many print heads arranges in several print bars, each responsible for printing down a single colour in the final images, the fundamental aerodynamic interaction of the system may be understood by consider the simpler case of a single multiple-nozzle print head printing ink droplets onto a moving substrate. Schematics depicting the aerodynamic condition between the print head and the substrate investigated in this study are shown in Figure 1. It is important to note that the print head used (Xaar XJ1001) is a developmental unit and the experiments were carried out with printing parameters, especially print gap height, significantly outside the specified range.

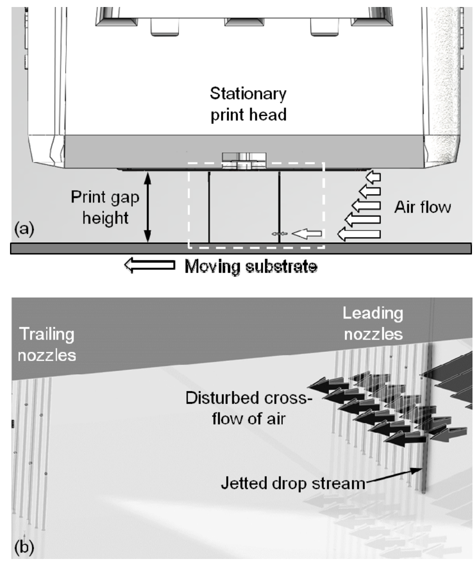


Figure 1 *Schematics of (a) print gap air flow condition and (b) air flow across jetted drop streams modeled as vertical columns.*

Also note that while the air flow is clearly disturbed by the jetted drops, as demonstrated in our earlier study, the relevant Reynolds number (Re) is not defined by the jetted drop diameter as the resultant value (less than 5) is much lower than the typical range of 10-20 indicating the onset of unsteady flow trailing a sphere [2].

Experiments

Simulated web press printing was performed using a custom print rig, as shown in Figure 2. A stationary (0° tilt angle) grey-scale XJ1001 inkjet print head was used to print full-width (70.5mm) blocks of solid colour images onto moving paper substrates using a black UV-curable ink. The substrate movement was programmed with sufficient lead-in and lead-out distances to ensure not only a constant speed during printing, but also to minimize any aerodynamic disturbance from the edges of the stage platform and paper. In addition to substrate speed, the system also allows for variations of print gap size (throw distance), printing frequency, printed spot size (drops per dot or dpd) as well as row and nozzle group printing orders. While the simplest way to alter the print gap air flow is varying the substrate speed, to reproduce the same image at a different substrate speed requires a matching change of printing frequency. Re for the print gap air flow is defined as:

$$\mathrm{Re} = \frac{y_p U_s}{\upsilon}$$

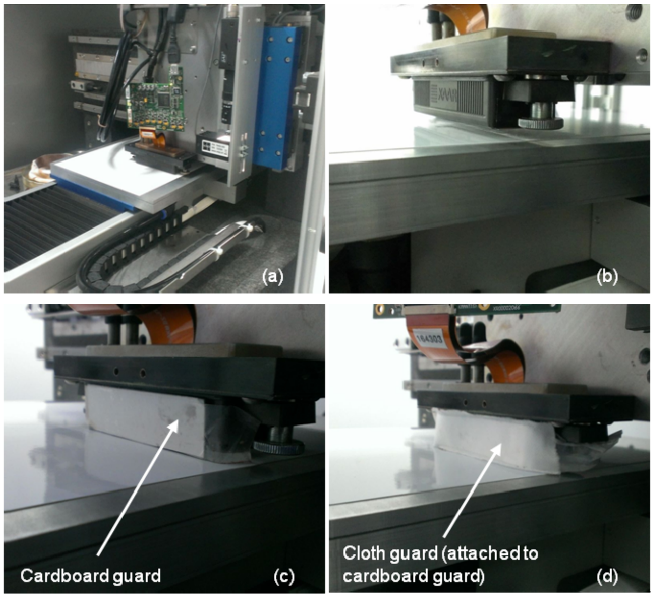


Figure 2 *(a) Image of the printing rig with close-ups of (b) print head without air guard,(c) with hard guard only and (d) with both hard and soft guards .*

where y_p is the print gap height, U_s and υ are the substrate velocity and kinematic viscosity of air, respectively. Changing print gap height can therefore be used to simulate the effect of varying substrate velocity. To further test the effect of changing gap air flow on the printing results, a temporary air guard, consists of a hard cardboard shield extended to 0.5 mm above the substrate and a "soft" anti-static cloth shield covering the remaining gap, was attached to the leading edge of the print head. The print samples were studied by scanning the printed images with a high resolution scanner (Epson V750 Pro) at resolutions up to 12800 dpi. A MATLAB program was written to find the printed tracks in the scanned images and produce quantitative analysis of the printing dynamics.

Results

Effect of print gap height

Figure 3 shows the block images printed with 12 pl ink drops jetted at 6 kHz with 4.7 m/s towards a moving substrate (423 mm/s) with print gap height varies from 2 to 5 mm. It should be noted that the straight white lines or lighter strips along the print direction are caused by missing nozzles or deviated jets from defective nozzles, therefore are unrelated to the aerodynamic effect discussed below. In addition, as the print head consists of two rows of nozzles, the adjacent printed tracks are therefore produced by drops jetted from nozzles in different rows and at different times. The spacing between each nozzle row is 4.2 mm.

It can be seen clearly that unsteady patterns have developed at the print gap height greater than 3 mm. The patterns are roughly symmetrical about the middle of the images and all have a characteristic "developing zone" at the leading edge of the print, therefore strongly suggesting that their cause is aerodynamic in nature.

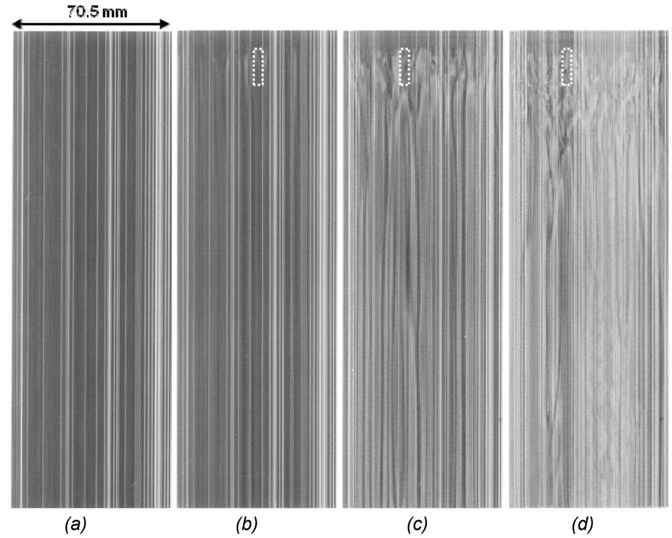


Figure 3 *Printed sample with print gap height varies from (a) 2 mm (Re=70), (b) 3 mm (Re=105), (c) 4 mm (Re=140) to (d) 5 mm (Re=175). Rectangles indicate where the close-up, high-resolution scans were taken for Figure 4.*

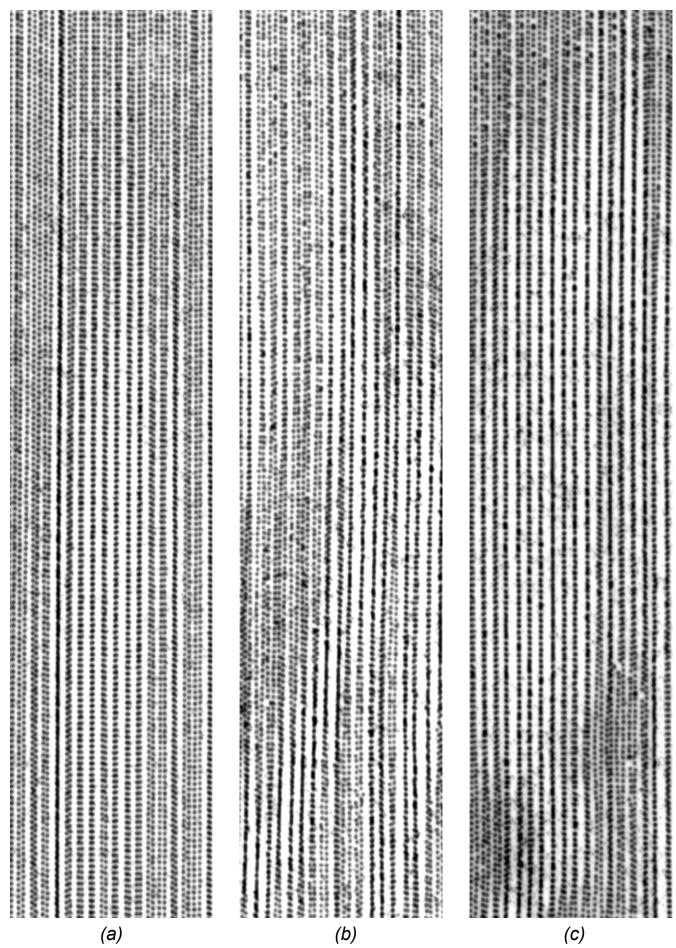


Figure 4 *Close-up scans at 12800 dpi of the transition regions (areas indicated in Figure 3) for print gaps of (a) 3 mm, (b) 4 mm and (c) 5 mm.*

While the mild patterning in the 3 mm sample eventually fades out visually, the initial vortex-like patterns in the 4 and 5 mm samples smooth out and morphed into ‘wood-grain’ patterns further down the images.

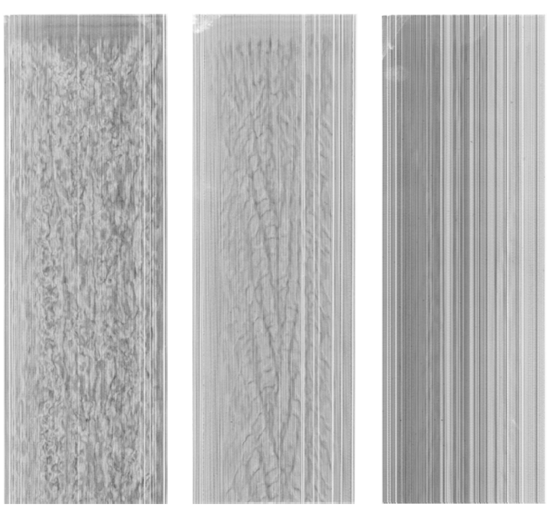
Figure 4 shows the close-up scans of the transition regimes as indicated in Figure 3. The unsteady patterns are shown to be caused by oscillation and coalescence of neighboring printed tracks along the printing direction. Such phenomenon appears to occur over a region affecting several pairs instead of acting in isolation among individual pairs of printed tracks.

As the tracks merge the ink coverage over an area reduces and the contrast lightens locally. In the case of printing with a 3 mm print gap (Figure 4a), pairs of the printed tracks consolidate and separate but still remain reasonably parallel to the printing direction. In contrast, in the samples printed with 4 and 5 mm print gaps (Figure 4b and 4c) the printed tracks are shown to not only consolidate but also waver along the printing direction, hence indicating a significant deterioration of drop stream stability.

Finally, although satellite deposits are evident in the printed samples it is important to note that the unsteady patterns observed are not created solely by misplaced satellites. Therefore, such print quality issue cannot be addressed by the normal route of optimizing the jetting parameters to minimize satellite generation.

Effect of air guard

As the unsteady patterns are assumed to be related to the print gap air flow, modifying the air flow should result in a direct change of the characteristics of the patterns. The combination of the hard and soft shields attached to the leading edge of the print head was intended to reduce the air flow in the 5 mm print gap. However, the samples printed with the air guard installed, as shown in Figure 5, demonstrate an opposite effect. The printed sample with air guard in place (Figure 5a) exhibits a significant increase of apparent complexity in the unsteady patterns which does not smooth out as in the case of printing without guard (Figure 3d).



(a) (b) (c)

Figure 5 *Printed samples with air guard installed with (a) both rows of nozzles, (b) only trailing row of nozzles, and (c) only leading row of nozzles firing.*

To isolate the cause of this effect, printing was repeated but with only one row of nozzles firing at a time. While the sample printed with only the trailing row nozzles (further away from the air guard) still exhibited unsteady patterns with vortex-like patterns (Figure 5b), printing with only the leading row nozzles (just behind the air guard) resulted in minimal visible patterns (Figure 5c).

The results suggested that the air guard did not eliminate air flow completely in the print gap. Instead, it is likely that the angular momentum gained as air was re-directed around the guard edges has led to significant unsteady flows and vortices in the area around the trailing row of nozzles. In contrast the leading row of nozzles, situated closely behind the guard, would be in a shielded region where the air flow remained relatively undisturbed.

Image analysis

A custom image processing routine has been written in MATLAB to provide quantitative analysis of the printed samples. A region of the print sample has been scanned in 16 bit grayscale at 3200 dpi resolution. To locate the individual printed tracks, the scanned region were divided into sections 30 pixel in length (in y- or printing direction) and the lengthwise pixel grayscale levels were summed up across the region width (in x- or nozzle row direction).

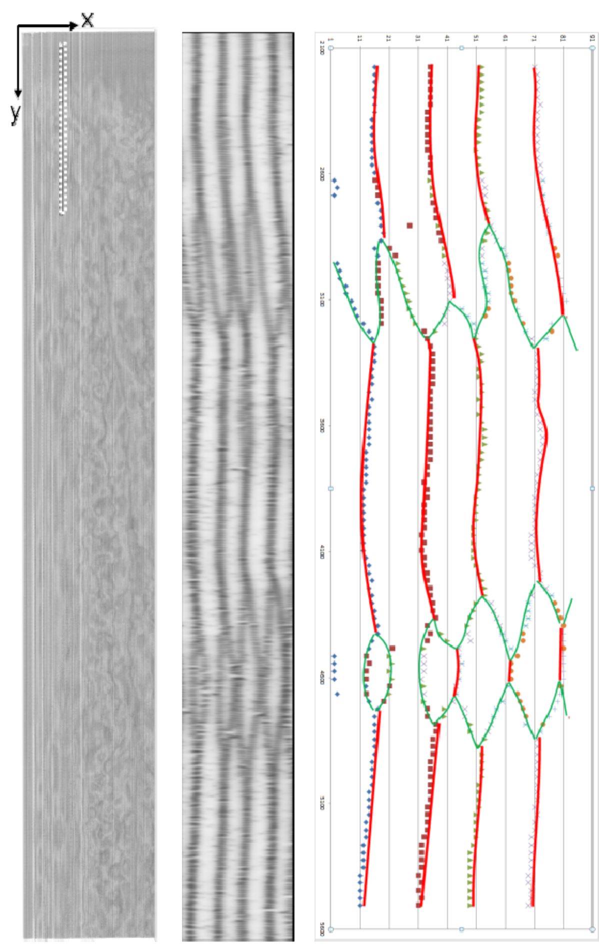


Figure 6 *An example of data extracted from the scanned image showing the consolidation dynamics of a group of printed tracks.*

The minimal gray values would then indicate the positions of printed tracks.

Analysis of a small area of the scan is shown in Figure 6 where initially 8 adjacent drop streams from both rows over-printed each other and produced 4 consolidated printed tracks. However, later, external disturbances caused almost simultaneous shifts of all 8 streams. In the first instance, all 8 drop streams were disturbed and 4 streams from the same row appear to shift by nearly a native pitch of the print head (1/2 of the nozzle pitch in a row) to the right. The result was a 'switching' of the consolidating drop streams pairs. Although 4 consolidated printed tracks remained after the disturbance at roughly the same x-positions, they were produced by different pairs of drop streams. A second instance of disturbance briefly separated the drop streams but not enough to restore the original pairing order. As the positions of the consolidated tracks are mostly constant, a possible conclusion is that the external disturbances predominantly affect drop stream stability from one row over the other; a theory supported by the alternative row printing results with air guard installed. Further refinement of the image processing routine will allow identification of the row origins of individual printed tracks which can be used to validate this hypothesis.

Discussion

The qualitative assessment and quantitative analysis of the printed samples have shown that the unsteady patterns were created by local consolidations of printed tracks produced by unsteady movements of drop streams. There are several possible causes of such drop stream movements. First, we can probably rule out nozzle defects or other intermittent faults of the print head and its associated sub-systems. Nozzle defects typically result in fixed deviations of drop streams. Amplified by the increase of print gap height, they manifest as white streaks in the printed images. As the print head studied was a well-used test unit, there are many such streaks visible in our printed samples. However, the streaks caused by nozzle defects are clearly identifiable as they remain straight, in contrast to the transient and often turbulent appearance of the unsteady patterns of interest. The close correlation of the unsteady patterns to the changing air flow condition (e.g. air guard installation) also renders it unlikely that intermittent system faults are responsible.

If the unsteady patterns observed are not caused by nozzle defects or system faults then they may be induced aerodynamically. We now discuss two possible aerodynamic contributions. The Couette flow in the print gap has been comprehensively identified by previous studies [1, 3]. While the flow itself and its interaction with the drop wakes have been shown to have minimal effect on the trajectories of the main drops, their influence on the drop motion perpendicular to the flow direction has not been adequately investigated and may contribute to the disturbance. Alternatively, in the study of nozzle plate ink flow by Beulen *et al*., vertical air flow induced by a continuous drop stream has been identified and quantified [4]. For a continuous stream of 30 pl ink drops the induced air flow velocity has been estimated to be about 60% of that of the jetted drops (drop speed in our experiments was 4.7 m/s). Estimating the extent of drop stream induced air flow by the growth of the boundary layer around a liquid jet emerging from a nozzle, interactions between flows from both rows are possible at print gap greater than 5 mm [5]. Such interactions may explain the apparent increase in pattern complexity when both rows were printing compared to printing with just the trailing row (with air guard in place). It is of course possible that the unsteady patterns are influenced by the combined effect of both gap cross-flow and drop stream induced air flows. Analyzing such dynamics may be beyond the reach of the current investigative method and would require sophisticated 3-D numerical modeling.

Summary

An empirical study has been conducted to investigate the effect of aerodynamic condition in print gap on web press printing quality. The occurrence of unsteady patterns in the printed samples has been correlated to systematic variations of the print gap air flow characteristics by altering the gap height and incorporating an air guard on the print head. A custom image processing routine was used to analyze the high-resolution scans of the samples to extract quantitative data and determine the origins of the unsteady patterns. The initial results suggested that a combination of cross-flow in the print gap and the induced air flows around the jetted drop streams may be responsible for the print quality issue investigated.

Acknowledgements

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Author Biography

Wen-Kai Hsiao received his BS from the University of California, Santa Barbara and his MS and PhD from Massachusetts Institute of Technology, all in Mechanical Engineering. He joined the Cambridge, UK, Inkjet Research Centre in 2007 with research interests in drop deposition behavior of Newtonian, non-Newtonian, and functional colloidal fluids. In addition, he is also active in developing novel ink-jet based manufacturing processes for electronic, optical, and biological applications.