Aerodynamic Effects in Ink-Jet Printing on a Moving Web

Wen-Kai Hsiao, Stephen D Hoath, Graham D Martin and Ian M Hutchings
Inkjet Research Centre, Institute for Manufacturing, Department of Engineering, University of Cambridge, Cambridge, UK

Abstract

The airflow between the fast-moving substrate and stationary print heads in a web print press may cause print quality issues in high-speed, roll-to-roll printing applications. We have studied the interactions between ink drops and the airflow in the gap between the printhead and substrate, by using an experimental flow channel and high-speed imaging. The results show: 1) the gap airflow is well approximated by a standard Couette flow profile; 2) the effect of gap airflow on the flight paths of main drops and satellites is negligible; and 3) the interaction between the gap airflow and the wakes from the printed ink drops should be investigated as the primary source of aerodynamically-related print quality issues.

Introduction

The scope of commercial ink-jet printing has extended significantly in recent years. For new applications such as single-pass graphical printing or even mass-production of printed electronics, there is a common trend towards greatly increased printing throughput achieved by printing on a continuously moving web substrate. To achieve this, both the number of print heads used, and hence the number of available nozzles, as well as the speed of the moving substrate are increased. While there is some practical evidence of print quality issues related to higher print speed, the effect of the substrate motion-induced airflow on the dynamics of the printed drops has not been thoroughly investigated.

The air flow between a moving substrate and a stationary wall is typically approximated by classic plane-Couette flow. While Couette-type flows have been extensively studied [1-2], few studies have been conducted specifically to investigate their implications for ink-jet printing. In their study of the effect of airflow on ink drop motion in wide-format printers, Link et al. [3] empirically and numerically confirmed that the airflow between a print head and a moving substrate conforms closely to the profile of a standard Couette flow. Their results also suggested a modest to strong intensity of turbulence near the substrate at substrate speeds up to 2 m/s. However, as they could not obtain reliable PIV measurements within 600 µm of the moving substrate, there is still uncertainty in the validity of this conclusion. Additionally, their simulation predicted that the deviation of a 20 µm ink drop subjected to such cross-flow would be negligible in term of its effect on drop placement precision. While this prediction broadly agrees with our preliminary results on the effect of gap airflow on drop and satellite trajectories, the experiences of industrial users seem to contradict our observations. One possible explanation is that the flow dynamics in the print gap during printing is more complex than previously assumed. For example, the interaction between the wakes of the jetted drops and the gap airflow needs to be investigated as a potential cause.

Experimental setup

A model was constructed to investigate in real-time the simplest scenario: the interaction between a continuously moving substrate and a single printing nozzle. The belt-drive of the print head motion stage from a HP ink-jet printer was adapted to form the moving substrate. A section of the 4 mm-wide drive belt was enclosed within a PMMA channel. Two precision ball-bearings were used to support the belt as it passed through the channel to minimize belt oscillation and deflection. A 56 mm-long fixed carriage was mounted over the drive belt in the channel, maintaining a gap of 2 mm above the moving belt. At approximately 30 mm downstream from the leading edge of the carriage, a single-nozzle print head (MJ-AB-01-80, MicroFab Technologies USA) was used to eject drops of ethylene glycol (EG) as a model ink across the gap and on to the moving belt. A schematic diagram and an image of the flow visualization channel are shown in Figure 1.

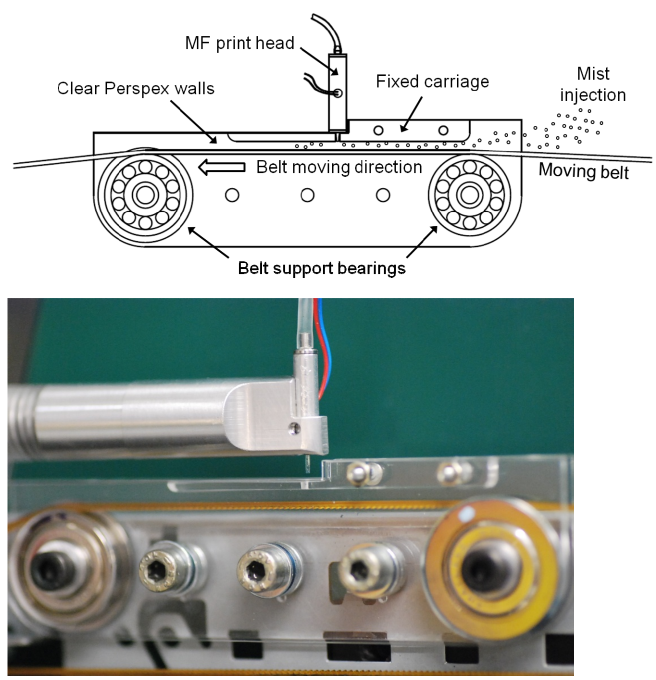

Figure 1 *Schematic diagram and image of the moving-belt and airflow visualization channel. The MicroFab printhead is raised above the fixed carriage for clarity.*

To visualize the airflow within the print gap, a mist of small water droplets 1 to 5 µm in diameter was injected approximately 60 mm upstream from the carriage and transported into the gap by the air current above the moving belt. The imaging arrangement was similar to the set-up described in our previous communication [4].

With illumination from a high-power, long-duration flash (SI-AD500, Specialised Imaging UK), an ultra high-speed video camera (HPV-1, Shimadzu Japan) was used to capture the motion of the mist droplets in the print gap at 125k fps. Image analysis with an ImageJ-based routine was then used to track the trajectories of the mist droplets in order to analyze the air flow pattern [5, 6]. The deviation of the flight paths of the drops and satellites within the print gap was also evaluated by using a stroboscopic imaging technique [7] in which a 20 ns duration spark flash (MiniStrobokin 40, HSPS Germany) and a CCD camera (EC1020, Prosilica USA) were used to capture high-resolution still frames showing jetted drops, ligaments and satellites for image analysis.

Results

Airflow profile in the print gap

One of the primary aims of the investigation was to study the airflow in the print gap in its entirety, i.e. from the surface of the moving belt to the lower surface of the carriage. Figure 2a shows a typical frame (grayscale inverted for particle tracking analysis) from the high-speed videos with the flight paths of mist droplets identified by the ImageJ routine. Initial observations indicated that the mist droplets are effective as tracers for air flow, as their trajectories follow the belt motion closely as they move across the field of view. In addition, the droplets are shown to move at similar velocities at the same height above the moving belt. As the depth of focus of our imaging system is greater than the nozzle diameter, this suggests that the air flow is relatively uniform across the width of the belt around the nozzle. Therefore, our experimental setup reasonably approximates a 2-D flow field between two boundaries with infinite depth, i.e. the effect of the boundary layers at the PMMA walls on the airflow around the nozzle is negligible. As expected, the gap airflow conforms to the standard, linear Couette flow profile over the belt speed range investigated. Figure 2b shows the velocity profile for a belt velocity of 1 m/s. Although Link et al. [3] hypothesized that turbulent flow may occur close to the moving substrate, no evident of significant turbulence or the existence of vortices was observed on or near the moving belt in our experiments.

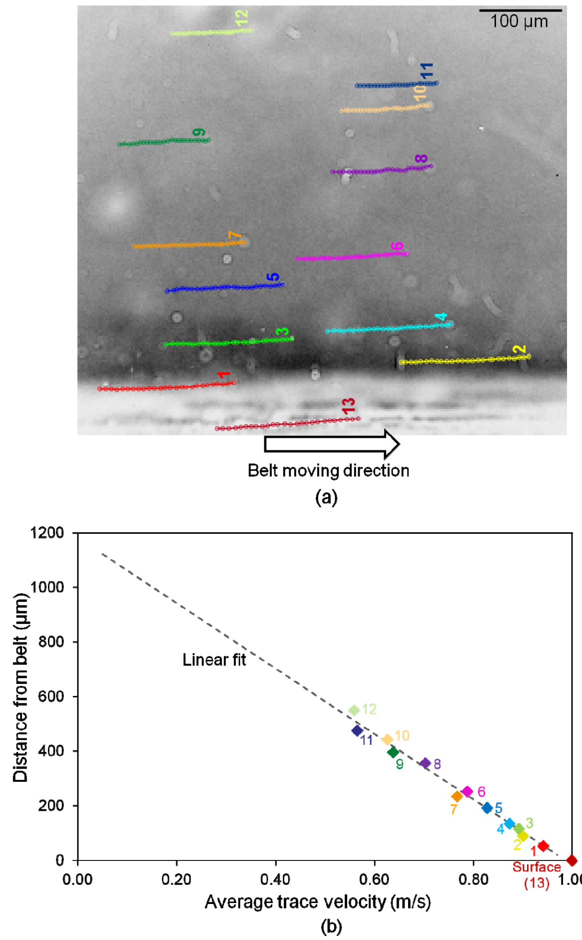

Figure 2 *a) Inverted shadowgraph image of mist traces above a belt moving at 1 m/s, with vectors showing the motion of individual mist droplets, and b) velocity profile of the mist droplets.*

Jetted drop and ligament deflection

Figure 3 shows single-flash images of ethylene glycol drops with attached ligaments just before impact on the moving belt travelling at speeds range from 0 to 2 m/s. The main drops are approximately 80 µm in diameter, with an average velocity of 6 m/s. Reference lines are added to the images to indicate the center axis of the drop and ligament when the belt is stationary. As the belt speed increases, the main drops and their trailing satellites shift in the direction of the belt motion. The ligaments become bowed and appear to elongate slightly. Using a custom image analysis code, the center positions of the main drop, ligament, and individual satellites can be determined as functions of belt speed. Averaged over more than 10 images for each value of belt speed, these results indicate a linear increase in the magnitude of deflection as the belt speed increases, as shown in Figure 4.

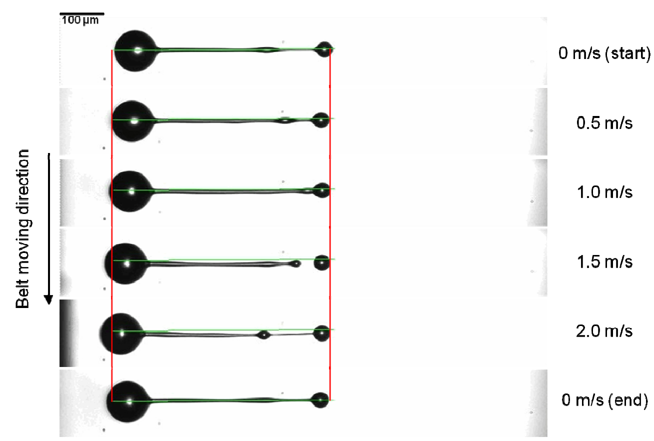

Figure 3 *Jetted ethylene glycol drops, ligaments, and satellites moving from right to left across the print gap at belt (substrate) speeds from 0 to 2 m/s.*

Although the print gap airflow has been shown to have an effect on the jetted drops and satellites trajectories, the effects observed are generally minimal. For example, for substrate speeds up to 2 m/s the average sideways deflection of the trailing satellite is less than the diameter of the satellite itself. This observation is in general agreement with the simulation results of Link et al. [3], who estimate the shift in the trajectory of a 20 µm-diameter drop to be around 13 µm at a substrate speed of 1 m/s (the trailing satellites in our experiments are typically around 25-30 µm in diameter). In addition, the average magnitudes of deflections observed are significantly less than the final spreading radius of the deposited main drop (approximately 80-100 µm). As the ligaments and satellites generally reach the substrate within tens of µs after the main drops, they normally fall within the splats formed by the deposited main drops, and hence have minimal impact on print quality.

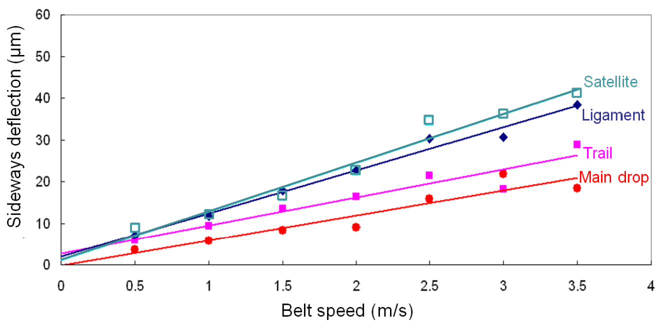

***Figure 4** Deflections of the main drops, ligaments, and satellites as a function of substrate speed.*

Interaction between gap airflow and wakes of the jetted drops and satellites

By jetting drops and satellites on to the moving belt while monitoring the gap airflow with the mist droplets, the interaction between the gap airflow and the wakes trailing behind the jetted drops can be visualized. Figure 5 consists of snapshots from the high-speed videos showing how the airflow in the gap is disturbed by the passage of the large main drop, as indicated by the mist droplet traces. It can be clearly seen that the mist droplets in or near the path of the main drops are deflected from their original trajectories and shifted toward the moving substrate.

At low substrate speed (around 0.5 m/s), the disturbance caused by the passing drop is fairly localized, as shown in Figure 5a. In addition, the wake of the drop, indicated by the region in which the trajectories of the mist droplets are significantly disturbed, is nearly symmetrical above the trail of the passing main drop. This suggests minimal interaction between the drop wake and the gap airflow. As the substrate speed increases, the wake of the passing drop becomes increasingly asymmetric, i.e. most of the mist droplet deflections begin downstream from the main drop trail, as shown in Figures 5c and 5d. The implication is that the disturbances caused by the passing drop are being carried further downstream by the gap air flow at higher substrate speed, potentially changing the air flow pattern and affecting drops jetted from the neighboring nozzles.

Discussion and summary

Preliminary results of an experimental study of the print gap airflow dynamics during ink-jet printing are presented. Visualizing the gap airflow by using mist droplets and high-speed video imaging technique, we have confirmed that the airflow pattern between a fixed wall (print head) and a moving substrate resembles the standard laminar Couette flow profile as reported elsewhere. However, our observation of airflow dynamics extremely close to the moving substrate reveals a lack of turbulence and vortices, contrary to previously reported simulation results.

Our experiments also show that even at high substrate speeds (greater than 3 m/s) the deflections of the drop and satellites trajectories caused by the air flow are relatively minor. Our observations are in general agreement with the suggestion that there is insufficient kinetic energy in the gap airflow to affect the flight paths of the main drops or large satellites [3]. However, as the model ink (ethylene glycol) and drive waveform used in our study produced well-behaved jets and drops, with a minimal number of relatively large satellites trailing a short distance behind the main drop, our results may not be representative of situations when more complex and problematic inks are printed. For example, printing under less ideal condition on an industrial scale may produce a large number of µm and sub-µm sized micro-satellites.

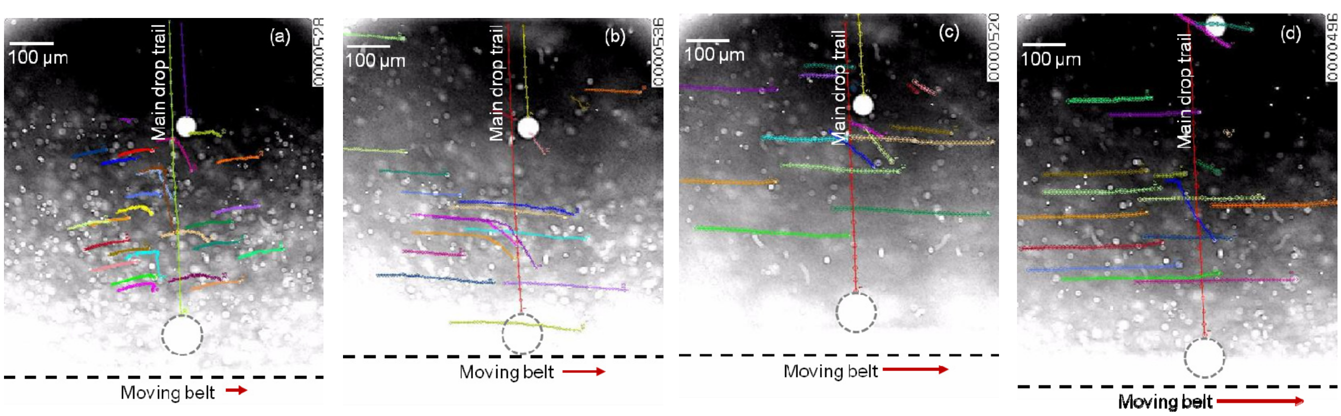

***Figure 5** Disturbance of the gap air flow caused by the passage of a large jetted drop (approximately 80 µm in diameter, travelling at ~3.3 m/s) with substrate speeds of a) 0.5 m/s, b) 1.0 m/s, c) 1.5 m/s, and d) 2 m/s.*

These might be expected to behave in a similar manner to the water mist droplets used to visualize the airflow in this study which were 1 to 5 µm in diameter. Such micro-satellites can be easily disturbed by the gap airflow even at relatively slow substrate speeds and thus cause print quality issues. Further work is needed to study the dynamics of micro-satellites in the gap airflow. In addition, when satellites are produced late in the droplet ejection process, these will trail further behind the main drops in flight and therefore may not be shielded by the wakes produced by the main drops. Under such conditions, it is possible that these late satellites may be significantly disturbed by the gap airflow.

Finally, we have studied the disturbances in the gap airflow caused by the wake of the passing drop. The extent to which these disturbances are carried downstream from the printed drop is shown to be dependent to the substrate speed. At substrate speeds greater than 1 m/s, the trajectories of the deflected mist droplets indicate that the disturbances may extend up to millimeters downstream from the printed drop, potentially altering the airflow pattern around adjacent nozzles and drops. In addition, while the Reynolds number for the gap airflow investigated here is within the reported laminar regime for Couette flow ($Re < 480$), it is well within the turbulence transition regime for a disturbed Couette flow ($Re = 280\text{-}360$) [2]. As injecting a printed drop into the gap can be considered as introducing a disturbance, it is possible that a specific jetting frequency might trigger the onset of turbulence. Further investigation, including monitoring of the airflow further downstream over a longer period of time after drop injection, needs to be considered to extend our understanding of this possibility.

Acknowledgements
We thank the Engineering and Physical Sciences Research Council (EPSRC, UK) for financial support through Programme Grant number EP/H018913/1 ‘Innovation in Industrial Inkjet Technology’ and the EPSRC equipment loan pool for the use of the Shimadzu high-speed camera and light source.

References
[1] Aydin, E.M. and Leutheusser, H.J., Plane-Couette flow between smooth and rough walls, Exp. Fluids (1991), 11, 302-312.
[2] Tillmark, N. and Alfredsson, P.H., Experiments on transition in plane Couette flow, J. Fluid Mech. (1992), 235, 89-102.
[3] Link, N., Lampert, S., Gurka, R., Liberzon, A., Hetsroni, G., and Semiat, R., Ink drop motion in wide-format printers II. Airflow investigation, Chem. Eng. Process. (2009), 48, 84-91.
[4] Castrejón-Pita, J.R., Hoath, S.D., Castrejón-Pita, A.A., Morrison, N.F., Hsiao, W.-K., Hutchings, I.M., “Ultra-High Speed Particle Image Velocimetry on Drop-on-Demand Jetting”, Proc 27th Int. Conf. on Digital Printing Technologies, NIP27, Minneapolis, MN, USA, (2011), 93-96
[5] Abramoff, M.D., Magalhaes, P.J., Ram, S.J. Image Processing with ImageJ, Biophotonics International (2004), 11(7), 36-42.
[6] Meijering, E., Dzyubachyk, O., and Smal, I., Methods for Cell and Particle Tracking, Methods Enzymol. (2012), 504(9), 183-200.
[7] I.M. Hutchings, G.D. Martin & S.D. Hoath, “High speed imaging and analysis of jet and drop formation”, J. Imaging Sci. Technol. (2007), 51, 438-444.

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.