https://doi.org/10.2352/ISSN.2169-4451.2017.32.207

Ink Recirculation – Xaar TF Technology™: A Study of the Benefits

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Abstract

When Xaar launched the revolutionary 1001 printhead with patented TF Technology® in 2007 it opened up a number of applications to digital print. The ability to handle heavily pigmented inks, avoiding problems such as sedimentation, has been a crucial enabler in areas, for example ceramic tile decoration, glazes, and for white inks.

Since then, recirculation of ink within the printhead has been widely adopted by manufacturers, and a number of printheads offer an ink recirculation capability [1] [2] [3]. Their approaches to recirculation and operational ranges differ. Xaar TF Technology® recirculates the ink through the actuator channels, immediately past the nozzles, and with relatively high flow rates; other printheads recirculate through the ink manifolds, and/or ink flow rates used by different printheads vary significantly.

Besides the challenges of heavily pigmented inks, ink recirculation can have an impact on other aspects of printhead performance. The flow of ink can move debris and bubbles from the ink path, both before they have a chance to impact jetting, and after to recover from a jetting failure. It may even act to maintain the nozzles themselves, but only when the recirculating flow is close to the nozzles.

This publication presents a study on the important factors needed for ink recirculation to offer advantages, and what those advantages are. The study considers aspects such as print reliability, both prevention of and recovery from failures, nozzle latency (decap), and priming. It also considers the interactions between recirculation and stability of inks, in particular high pigment loading inks.

Using the TF Technology™ of the Xaar 1003 printhead, Xaar's latest evolution of the 1001, factors such as the flow rate of the ink and its impact on the above aspects are studied.

The work presented shows that recirculating flow, when it occurs immediately behind the nozzle in a Xaar 1003 printhead, does interact with the fluid in the nozzle itself. This in turn improves nozzle latency such that if recirculation of ink continues when the nozzles are idle, the length of time a nozzle can be left idle for before an adverse effect is seen with some inks can be increased (figure 1). This is in contrast to some previous results with alternative recirculation conditions [4]

Testing also shows that an ink that shows a level of unreliability at a low recirculation flow rate can operate reliably with a higher recirculation rate. Therefore it is not simply having ink recirculation that is important, but the precise operating conditions, and in particular a sufficient flow rate.

Introduction

Until the introduction of the Xaar 1001 printhead, inkjet printheads used ink paths where in operation the nozzles were the only exit for ink which had entered the head at the ink inlet. This is a simple system to implement, where the only main requirements of the ink system are to ensure an appropriate pressure at the meniscus in each nozzle (Meniscus Pressure – MP), and sufficient ink flow capability when jetting at maximum duty.

However, in ink chambers/channels, nozzles, and other internal ink paths the ink might remain stationary if nozzles aren't ejecting ink, whether due to image duty in operation, or the whole head being in an idle state. The length of time ink dwells in the head can therefore be long, and very variable between channels. This in turn can allow ink properties to change, such as temperature, dispersion of particles, degassing, and loss of volatile components of the ink where there is a free surface, notable at the nozzles. In addition, if anything unwanted, such as debris, enters the head, it can only leave through the nozzles, and if too large either blocks nozzles, or clogs filters if present to protect nozzles.

With the introduction of TF Technology® in the Xaar 1001 printhead (and featured in subsequent heads), these drawbacks of 'dead end' ink paths were addressed. The architecture continuously recirculates ink through the whole fluid path, right to the nozzle inlet. This is shown schematically in **Figure 1**. This means that ink at a nozzle when that nozzle is jetted has only dwelled in the head for a short time, so control of temperature, and liquid, solid and gas composition is much easier and more uniform across the array.

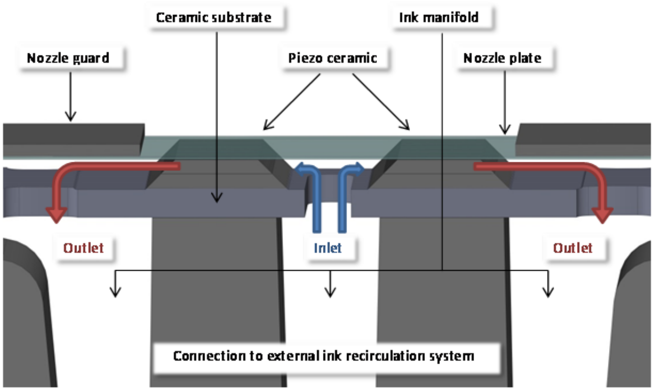

Figure 1 *Schematic of Xaar TF Technology® showing the path of fluid into the piezoceramic channels, directly behind the nozzles, and out again.*

For these reasons, ink recirculation capability has become a common feature in printheads, especially those targeted at applications demanding high print reliability and uniformity, and those using more challenging inks, such as ceramics. But ink recirculation can be implemented in a variety of ways, with advantages and disadvantages to each. This study uses the Xaar TF Technology® architecture, and studies the effect of recirculation immediately behind the nozzle, and with the capability for high flow rates that TF Technology® offers, on operating windows, reliability nozzle latency.

Nozzle Replenishment

One of the particular features of Xaar TF Technology® is that the recirculating flow is through the piezoceramic channels, directly behind the nozzles as shown in **Figure 2**. While other recirculation schemes where the recirculating flow is not close to the nozzles will not result in exchange of fluid in the nozzles themselves, it was still not clear how much exchange of fluid occurs when the flow is directly behind, and the amount of benefit this gives.

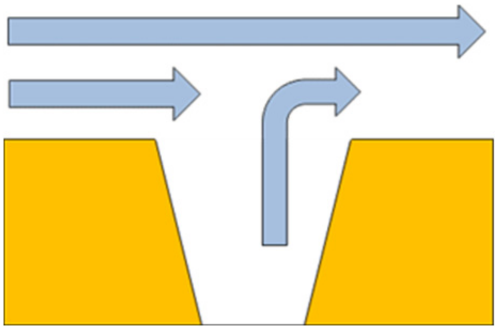

Figure 2*: Schematic of ink replenishment*

Qualitative indications that fluid in the nozzles is exchanged by recirculation behind the nozzle, maintaining print readiness, had already been seen. In an application jetting as part of the process for front side metallisation of solar cells, Xaar 1001 printheads were idling for 5 minutes 1mm above substrates at 180°C, yet would start jetting all nozzles immediately.

Especially for solvent or aqueous based inks the drop formation is changed when a viscous skin layer is formed at the meniscus due to evaporation of the solvent. Constant replenishment of the ink within the nozzle would decrease the tendency of skin formation at the meniscus. We postulate that such replenishment of the ink within the nozzle results from turbulent flow within the nozzle, caused by obstruction of the laminar flow in the adjacent channel in the vicinity of the nozzle inlet. A vortex flow within the channel would cause stirring within the nozzle, partially exchange the fluid within the nozzle, and in effect would prevent the buildup of a skin layer at the meniscus.

Method

Since the exchange of ink inside the nozzle is difficult to monitor directly, an indirect scheme was used. How the drop formation changed as function of the idling time before printing and of the ink flow rate, was used as a quantitative indicator of the ink replenishment. Since any viscous layer reduces the drop velocity, this can be evaluated by measuring the dot placement errors. Therefore the dot placement errors of a burst of 10 drops were measured as function of idling time before printing and as function of the ink flow rate. Dot placement of each of the 10 drops of the burst was measured, with the dot placement of the 10th drop as reference. The reasoning is that while the postulated viscous skin layer at the meniscus would affect the drop formation of the first drops of the burst, this skin layer would be removed by these first drop formations and do not affect the placement of the 10th and last drop of the burst of drops. A Xaar 1001 printhead was operated at different flow rates (30, 60 125 and 160 ml/min) for 5 minutes each, without firing.

In addition, the idling time was varied for various flow rates and the impact on drop placement measured.

It is expected that the drop velocity decreases with increasing idling time, due to evaporation of the ink at the nozzle and resulting in the growth of a viscous skin layer at the meniscus. It is further expected that drop velocity will be positively affected by increasing flow rate due to the postulated replenishment of ink inside the nozzle.

These first two experiments examine the effect of recirculation on maintaining nozzle health. A third experiment was carried out exploring the effect of recirculation on recovery of nozzles by the same process of nozzle replenishment. In this case the printhead was left idling with zero flow rate for periods of time and then looking at recovery of nozzles through the jetting of bursts, either continuing with zero flow, or starting recirculation.

The print pattern of this test run consisted of 37 bursts of 10 drops each (with one clear pixel between each consecutive drop). The interval between the consecutive burst was 200 clear pixels. At time zero the standard flow rate of 125 ml/min was set to zero. After variable time interval Δt with zero flow the print of the test pattern was started, either continuing with zero flow, or restoring recirculation and then after 10 seconds restarting the print test.

Results

Results are shown in **Figure 3** and **Figure 4**. As expected all 10 dots are equally spaced for the case of idling time of 0 min, i.e. directly after purging, since no viscous skin layer could be developed at the meniscus in the nozzle.

At a high flow rate of 160 ml/min only the first dot is printed at reduced distance, indicating a reduced drop velocity of the first drop (**Figure 3**), assumed to be due to a slight viscous skin layer. With only a small reduction to a flow rate of 125 ml/min, the first dot is considerably misplaced, effective overlapping with the second drop, while the second drop is at nominal velocity. At the reduced flow rate of 60 ml/min the first drop is completely missing and the second drop is considerably reduced in velocity. With further reduction in flow rate the first drop is missing and the second, and third drop reduced in velocity. The missing of the first drops and the decreasing drop velocities of the second and third drops with reduction in flow rate hint at an ever more viscous skin layer at the meniscus.

The dot placement errors also show the strong effect of the flow rate in the printhead as depicted in **Figure 4**. For the highest flow rate used, 160 ml/min, all dot placement errors except that for the first drop are small. For a flow rate of 60 ml/min the first drop is missing and the second at a dot placement error of 100 µm. Further reduction in flow rate to 30 ml/min increases the dot placement error of the second drop to beyond 200 µm.

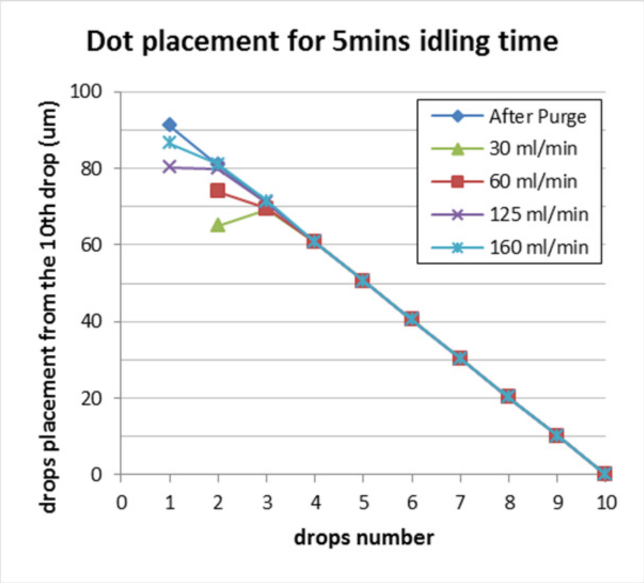

Figure 3 *Dot placement of the 10 dots from a burst in reference to position of the 10th and last dot in the burst. Printing at different flow rates with a constant 5 minutes idling time before firing each test run.*

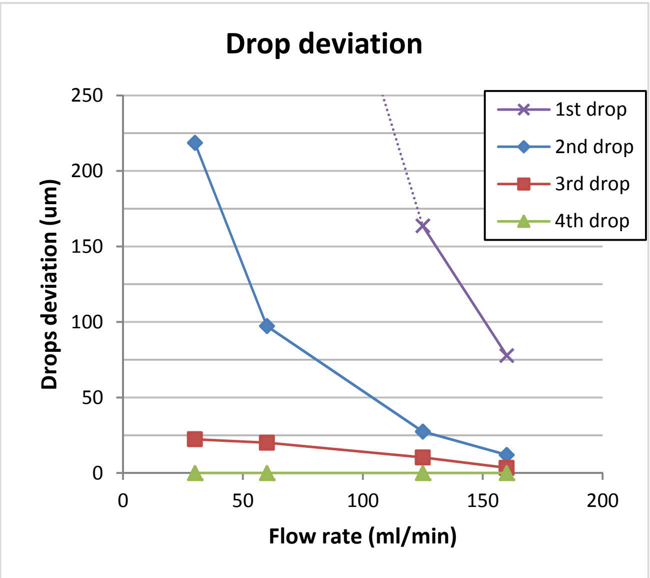

Figure 4 *Dot placement errors for the first 4 dots from the burst of 10 drops as function of the flow rate (30, 60, 125 and 160 ml/min). Idling time before the burst of 10 drops was 5 minutes.*

Looking at longer idling times, as shown in **Figure 5** a flow rate of 125 ml/min prevents the loss of any drop. The first drop of the burst of 10 drops is ejected even after an idling time of 24 hours. The dot placement errors of the first drop increase with increasing idling time, indicating the formation of a more viscous skin. The second and consecutive drops have essentially the nominal velocity.

Conclusion is that the flow rate of 125 ml/min is strong enough to prevent the formation of a skin layer that can contribute to restriction within the nozzle or even to complete blockage of the nozzle.

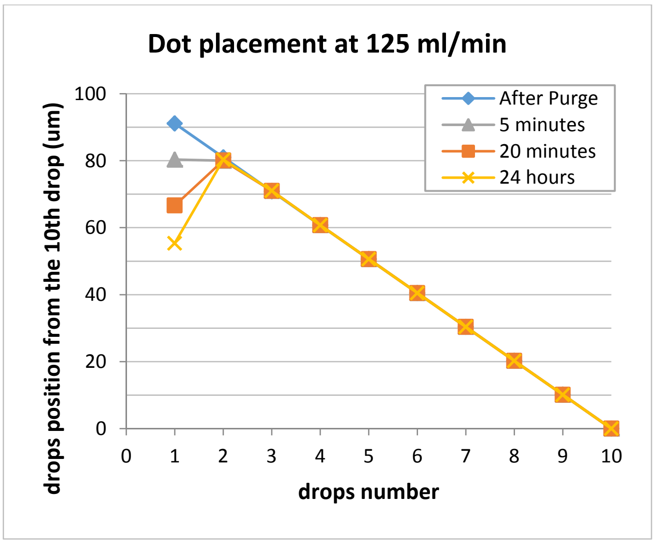

Figure 5 *At standard operation conditions the Xaar 1001 printhead is operated at a flow rate of 125 ml/min. In the present experiment this was achieved at a differential pressure of 100 mbar.*

In the third experiment where the printhead idled with zero flow, the number of subsequent bursts with missing or misplaced drops before good printing was restored was recorded.

Figure 6 shows, as blue diamonds, the number of faulty bursts before full recovery takes place i.e. first burst of drops printed with no defects found. While after $\Delta t=0.5$ minutes at zero flow it took 2 or 3 initial bursts before all channels fired correctly, it took 14 to 18 bursts before correct printing when the zero flow was maintained for $\Delta t=2$ minutes. After $\Delta t=5$ minutes of no flow there were still some channels printing faulty even after the full test pattern of 37 bursts were ejected.

When performing the same test as described above, but switching on the flow directly after the time interval with zero flow, and then – after a further delay of 10 seconds – starting the print of the test pattern, all channels printed correctly except the first burst. This was observed even after time intervals with zero flow of up to $\Delta t=60$ minutes.

We interpret this as further evidence that ink flow directly past the nozzles is very effective to replenish ink in the nozzle, which in effect reduces skin layer formation by exchange of the ink within the nozzle.

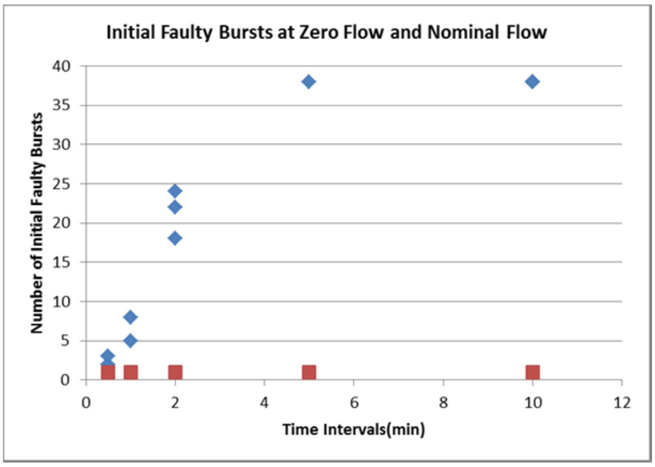

Figure 6 *The number of initial bursts with missing or strongly misplaced drops after different time intervals of zero flow, and 10 seconds after restarting of ink flow directly after the time intervals with zero flow.*

Operating Windows and Reliability

Print reliability is naturally very important in applications, especially for single pass printing where there is less scope for any nozzle failures to not impact the final print quality. This generally has been a strength of ink recirculation in inkjet printheads, and a key part of the success of inkjet in some recent application areas.

A prerequisite for good print reliability is to have operating windows of key parameters to be as wide as possible. This allows those parameters to vary as much as possible without going outside of their operating windows and causing defects or failures. Keeping those parameters as stable as possible is of course desirable, but fluctuations do occur, from the level of control and capability of ink systems, uniformity of media transports etc., through to unavoidable variations such as the effect of variable print data.

The expectation is that higher flow rates for the recirculating flow would give larger operating windows for the Meniscus Pressure (MP) window for example, as the impact of local nozzle effects and flow (including drop ejection) are diluted.

Method

Meniscus Pressure (MP) window was measured by adjusting the ink supply system used (Xaar Hydra) to adjust the MP over a range of values, and independently to adjust the flow rate but changing the Differential Pressure (DP) between the inlet and outlet of the head, which drives the recirculation flow. At each combination of MP and DP, the jetting reliability was assessed by visually assessing the jetting 'curtain' from the head on a jetting rig. An example of what's observed as good and unreliable jetting is shown in **Figure 7**.

Meniscus pressures are generally set slightly below atmospheric, e.g. a gauge pressure of perhaps -15mbar. At the top of the MP window i.e. less negative pressures, closer to atmospheric, the MP becomes insufficient to hold ink in the nozzle and ink floods out. At the bottom of the MP window, i.e. more negative pressures, the meniscus becomes prone to break allowing air to enter the nozzle and cause nozzle failures as shown in the example figure. At each DP (flow rate) set point, MP was varied to find the least negative pressure at which reliable jetting was possible before flooding, and the most negative pressure before air injection caused nozzle failures. These MP values are the top and bottom of the MP window at that DP setting.

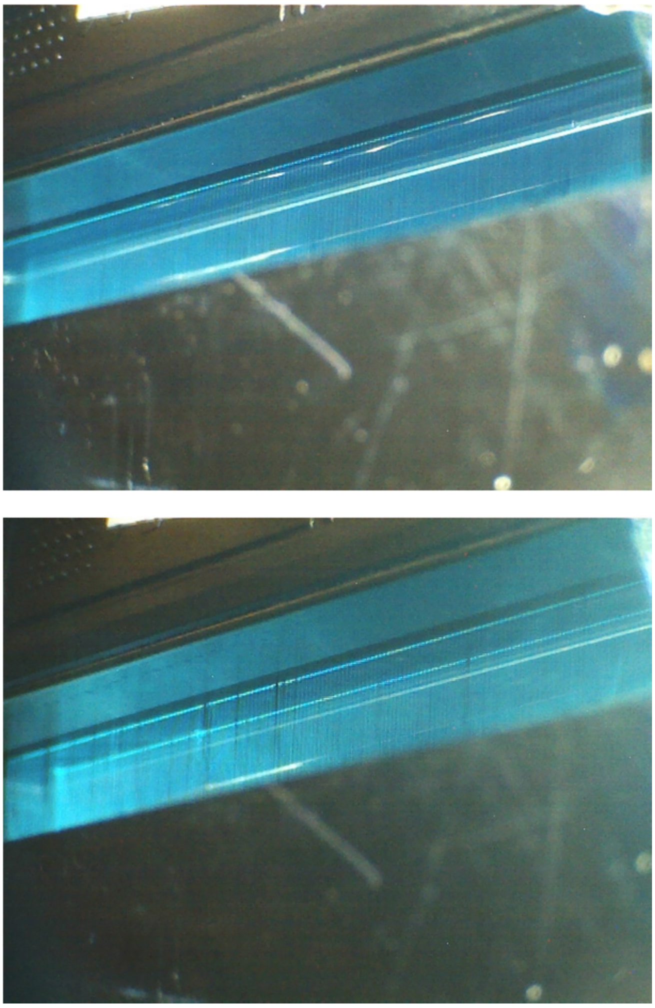

Figure 7 *Showing a good jetting 'curtain' (top) and unreliable, with some missing jets (bottom)*

Results

With a typical UV ink (Sunjet ULX Cyan), the results in **Figure 8** were obtained, where green cells represent reliable operation, red unreliable (flooding at the top of the window, nozzle failures at the bottom of the window), and yellow borderline/inconsistent failure.

These results show that the MP window is 20mbar (-5 to -25mbar) with a low DP of 40mbar, but increases with increasing DP to 26mbar at a DP of 200mbar.

Other inks were also tested. XES is a simple test fluid with a wide MP window, 42mbar at 40mbar DP, but this increased slightly to 44mbar at 200mbarDP. And a ceramic ink (Sunjet brown), being an example of a heavily particle loaded ink typical of ceramic inks, had a MP window of 22mbar at 40mbar DP, but which increased to 25mbar at 200mbar DP.

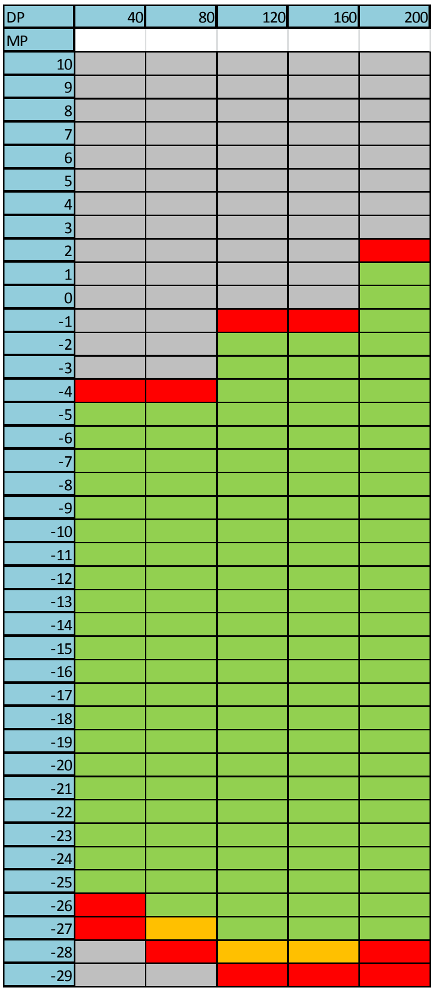

Figure 8 *MP window results for SunJet ULX cyan, showing that the MP window (range of green cells) increases as DP increases.*

Discussion and Conclusions

Ink recirculation within inkjet printheads, as first shown in the Xaar 1001 with TF Technology®, has established advantages for reliability by sweeping away bubbles or debris from channels, for jetting difficult heavily loaded fluids by keeping the fluid in constant motion, and for uniformity by improving ink and actuator temperature control. What in addition this study shows is that because Xaar TF Technology® flows ink directly past the nozzle, there is exchange of ink in the nozzle itself which gives a large reduction in the rate of buildup of, for example, a viscous skin in the nozzle when left idling, and so gives a large increase in the time a head can be left idling and still restart without error. Also, as well as maintaining nozzle health if idling with recirculation, if a head is left idling without recirculation, starting recirculation can quickly reprime nozzles to recover them to restart error-free.

But both parts of this study also show that the beneficial effects of recirculation directly behind the nozzle are further increased as the recirculation flow rate increases. The greatest benefits of recirculation are achieved with the high recirculation flow rates of TF Technology®.

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Author Biography

Mark Crankshaw obtained his B.A.(Hons) in Natural Sciences from the University of Cambridge, and also completed his Ph.D. in Materials Science there. He first joined Xaar in 1999 and as a Development Engineer and Technology Specialist worked on actuator and waveform development, and inkjet applications, before joining Cambridge Display Technology in 2007 as a Principal Engineer. After developing inkjet and other processes for display fabrication at CDT, he returned to Xaar in 2011 as an R&D Manager, and now leads the Printhead Applications group as a Principal Scientist.