XAAR

What goes around, comes around:

Why Xaar's TF Technology ink recirculation is still the best

Adam Strevens | Angus Condie | Mark Crankshaw

TF TECHNOLOGY

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Introduction

External ink tank and printhead manifold recirculation technology had been around for a while before the arrival of Xaar's nozzle level piezo printhead ink recirculation technology which transformed industrial inkjet printing, over a decade ago.

With the launch of the Xaar 1001 printhead in 2007, featuring TF Technology, it was possible for the first time to reliably jet highly-pigmented, viscous inks, opening up exciting new applications – ceramic tile printing, for example – to digital inkjet print.

Since then, printhead ink recirculation has become an essential feature of the industrial inkjet solutions for a significant number of market sectors and applications, such as glass printing with frit inks, high opacity white pigment ink printing for labels, heavily loaded conductive inks for printed electronics, and highly loaded pigment inks for textiles with vibrant colour.[1] Consequently, prospective purchasers of industrial inkjet solutions, from OEMs to end users, are faced with a variety of different approaches to recirculation. Whilst variety and competition are welcome, they make choosing the right printhead more difficult, because each design has its own characteristics, advantages and disadvantages.

This white paper makes arriving at the right choice easier.
It is divided into three parts:

Part 1:

Why ink recirculation is necessary

This section explains the essential characteristics of any printhead ink recirculation system: the common features, and the functions they perform.

Part 2:

Different ink recirculation designs yield different results

Part 2 looks at how different printhead manufacturers incorporate the key features and functions into their recirculation architectures, and describes some of the ways in which different designs impact on system efficacy.[2]

Part 3:

The higher the flow rate, the greater the benefits

Finally, this section refers to a series of controlled experiments that demonstrate how the key characteristics of recirculation – the route and rate of the ink flow through the system – can determine more than how well the printhead handles viscous fluids including those with a high percentage particle loading. In other words the key characteristics of ink recirculation in a printhead also influence aspects of printhead performance such as print reliability, prevention of and recovery from nozzle failures, nozzle latency, printhead priming and ink stability.

Part 1

Why ink recirculation is necessary

The inner workings of early piezoelectric inkjet printheads were relatively simple. The key component was a ceramic actuator material that changed in height and width (became taller and thinner) when a voltage was applied to it. This expansion pushed or bent a membrane pressurising ink in a chamber, and forced a drop of ink out from the nozzle. The actuator chamber had one ink inlet and a straightforward flow of ink from the inlet to the nozzle. All that was required was an appropriate pressure at the meniscus of each nozzle, and sufficient ink flow to meet jetting demand at maximum output.

However, there are limitations to this architecture:

- When the nozzles are not ejecting ink, either because of the particular image being printed (i.e. a lot of unprinted area), or because the whole printhead is idle, the ink not only dwells in the printhead nozzles for what can be a long time, but also for varying times in different chambers and their respective nozzles. During this interval, there may be changes in ink properties such as temperature, viscosity, particle concentration, dissolved oxygen content, and volatile compounds may be lost at an opening to atmosphere – at the nozzle orifice, for example.
- There is also the possibility that debris or air bubbles enter the printhead, particularly in dusty industrial environments, and if the particles are large the probability of them directly blocking nozzles or clogging filters designed to protect the nozzles is high.

With the introduction of the Xaar 1001 printhead in 2007, Xaar resolved these issues. This printhead incorporated Xaar's pioneering and highly innovative ink recirculation method, TF Technology – a world-first for printheads and a key feature in the subsequent Xaar 1002 and latest-generation Xaar 1003, Xaar 501, Xaar 502 and Xaar 2001+ printheads available today. TF Technology continuously recirculates the ink through the complete fluid path, right up to the nozzle inlet and – very importantly (as we will see later) – immediately past the back of the nozzle. This constant movement removes debris and bubbles from the actuator, making jetting more reliable and enabling nozzles to 'self-recover' from blockages. In addition, because ink dwells in any given nozzle for a shorter time, controlling ink temperature, and ink solids and gas content is easier and more uniform across the whole printhead nozzle array.

Figure 1 shows the essential features of any ink recirculation design. Ink passes through the ink inlet into a sub-manifold, where the ink flow is divided via distribution features before ink enters a given actuator pumping chamber. After a droplet is fired, ink which has not been jetted is drawn into a further sub-manifold, from where it returns to the ink delivery system.

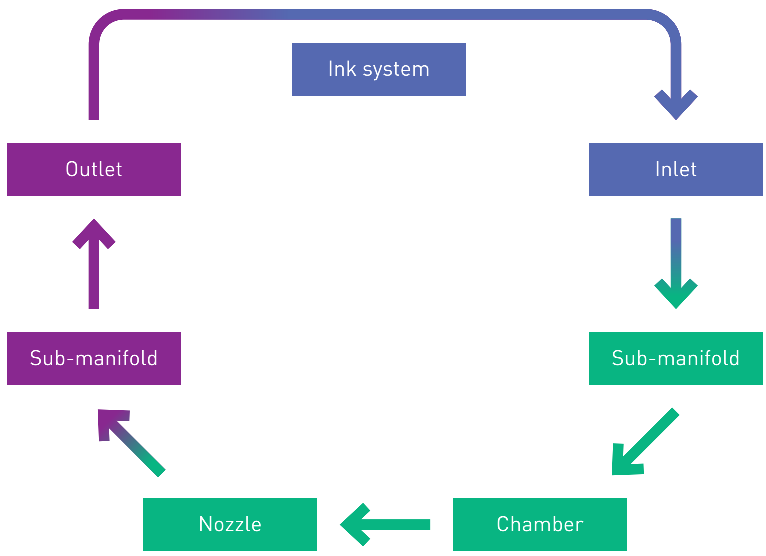

Figure 1:
The essential features of any inkjet printhead ink recirculation design

Part 2

Different ink recirculation designs yield different results

Figure 2 and **Figure 2a** reveal how Xaar engineered the features for ink recirculation into the Xaar 1001 printhead. (This has been developed into the current Xaar 1003 model. The illustration below in **Figure 2** is taken from the original Xaar recirculating ink printhead patent application). There are several features to note. The first is the simple, uncomplicated ink flow. The second is the fact that, as noted above, the ink recirculates directly past the back of the nozzle during drop ejection.

Xaar (WO2001012442, 2001)

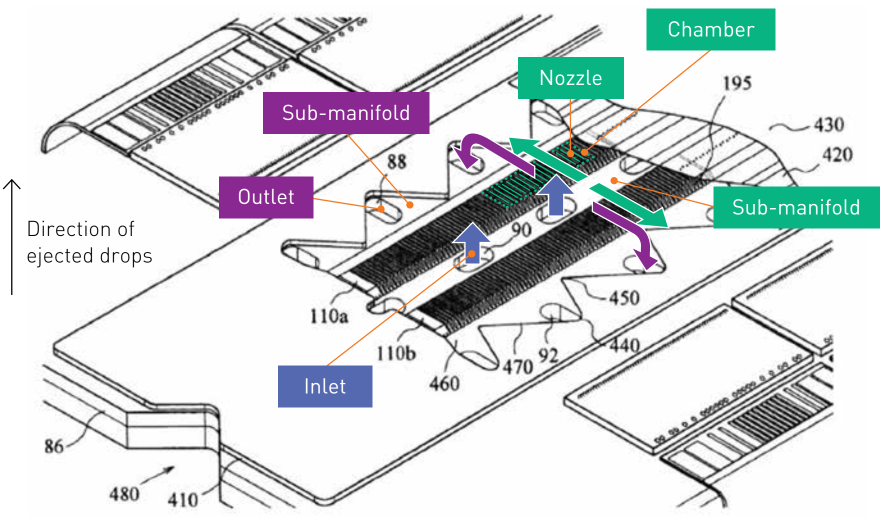

Figure 2:
Xaar original patent on ink recirculating printhead with open architecture for strong recirculating ink flow

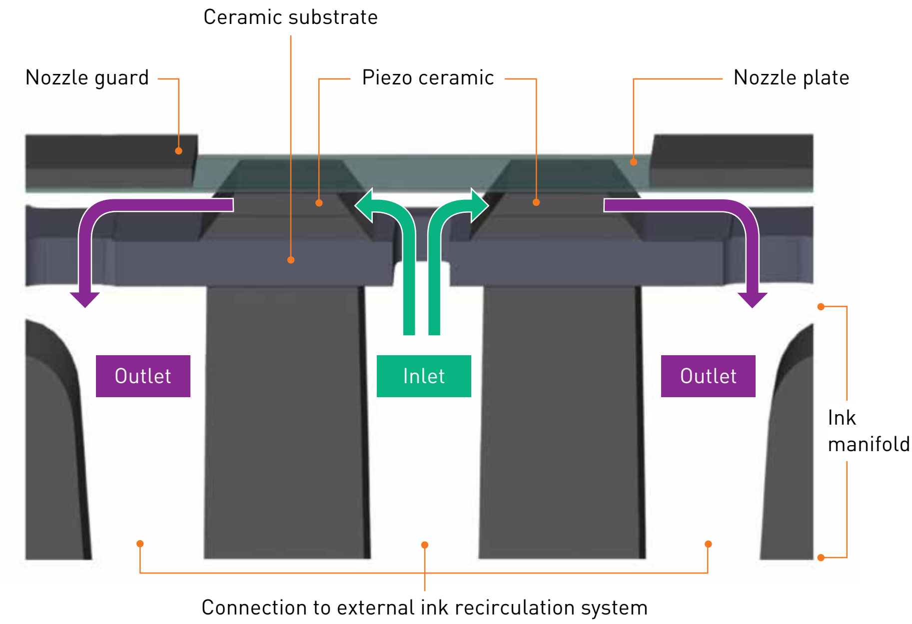

Figure 2a:
Schematic of Xaar TF Technology showing the path of fluid into the piezoceramic channels, directly behind the nozzles, and out again

Compare the Xaar architecture in **Figures 2** and **2a** to that in **Figure 3**, which shows an alternative design. It is immediately clear that the ink path is more convoluted, taking the ink through various ascenders, descenders and recirculation passages as well as through the sub-manifolds. Note also that actuation of the piezoelectric materials takes place on the roof of the chamber, pressing downwards to push the ink down and out through the nozzle. This design – so-called 'roof-mode architecture' – prevents the ink recirculating past the back of the nozzle.

(WO2015147307, 2015)

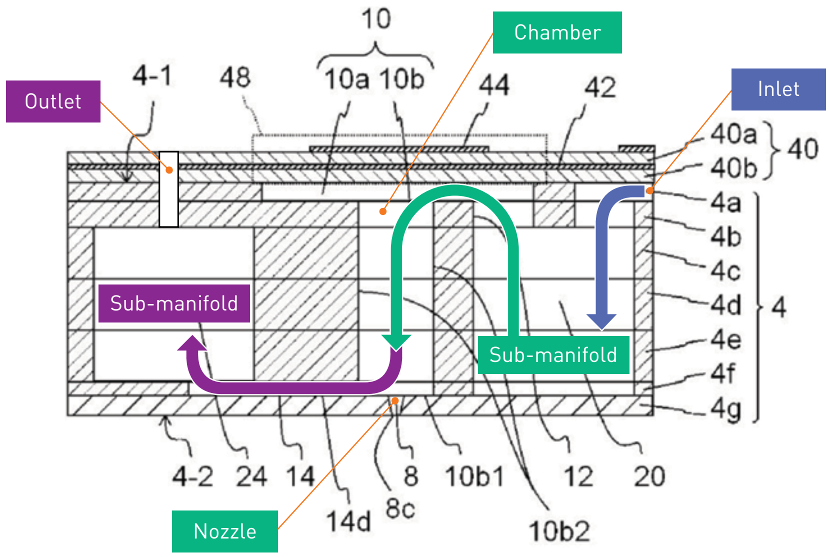

Figure 3:
Alternative roof mode printhead design

Another feature apparent in **Figure 3** is the narrowness of the ink inlets and outlets. There is a reason for this: by limiting pressure loss through the inlets and outlets, energy loss through the nozzle is reduced. However, the disadvantage is that because the overall flow path is restricted, the recirculation flow rate is necessarily much lower.

Look again at **Figure 2**. The sub-manifold channels are much more open, and as a result ink can get immediate access to the channels, enabling the flow rate to be considerably higher than in designs with narrower fluidic features such as in **Figure 2**. There are also pressure chambers both upstream and downstream of the nozzle; this 'double-ended' design prevents pressure loss without resorting to narrow inlets and outlets commonly called restrictors. It also means that more fluid, with more and bigger sub-drops, can be pumped.

For example, recently extremely high drop volume printing modes have been successfully implemented. In the case of a Xaar 1003 GS12 printhead – merged in flight – drop volumes of up to 400 pL are obtained.

Part 3

The higher the flow rate, the greater the benefits

Whilst ink recirculation in printheads is now commonplace (although there are still a few printhead OEMs who have yet to implement printhead ink recirculation), how it is implemented varies according to printhead manufacturer because printhead architecture differs. Some designs deliver inherent advantages when it comes to ink recirculation and other designs are more limited. Consequently, end users will experience greater or fewer benefits of ink recirculation depending on which printhead design they are using. The two main areas where ink recirculation varies by design are: the recirculation flow rate, and how close recirculation is to the rear of the nozzle. When a high flow rate passes immediately behind the nozzles, as in the Xaar 1001/1002 printheads and current Xaar 1003/2001+ models, the result is interaction with the fluid in the nozzle itself. It is this interaction that enhances the printhead productivity, reliability and print quality.

Xaar conducted a series of experiments (see appendix) to establish to what extent these factors improve printhead performance. The experiments looked at three aspects:

- **Nozzle latency and replenishment** – To ascertain if an increased recirculation rate minimised the impact of idle time on start-up print quality. Latency here means the amount of time a nozzle can be left without jetting, after which it stills jets perfectly.
- **Meniscus pressure operating window** – To demonstrate how a high recirculation flow rate reduces the impact of drop ejection fluctuations and widens operating pressure range.
- **Greyscale performance** – To show how the 'open' architecture of TF Technology reduces ink starvation and enables reliable jetting of high volume greyscale sub-drops.

The results of the experiments demonstrate that ink recirculation within inkjet printheads using TF Technology delivers benefits above expectations. Xaar's ink recirculation does more than simply sweep up debris, aid jetting of difficult fluids, and improve ink and actuator temperature control. Under the conditions of high recirculation rate and an ink flow directly past the rear of the nozzles TF Technology promotes an exchange of ink in the nozzle itself. This means that the printhead can be idle for a significant time yet still restart printing quickly and without errors. Static ink drying in a nozzle can become more viscous but this is avoided with the exchange of ink. Furthermore, in such a static case the drying can result in sedimentation of particulate (e.g. pigments for colour) in or around the orifice of the nozzle. This too is avoided with TF Technology.

To summarise, since its introduction in the Xaar 1001, TF Technology has been an essential component of the successive advances Xaar has made in printhead technology, right through to the current Xaar 1003 and Xaar 2001+ families of printheads which set new benchmarks for industrial inkjet printing.[3,4]

In addition, TF Technology has been responsible for significant advances in digital print within a range of applications[5,6] by providing some tangible benefits which ultimately lead to higher production uptime and longer intervals between maintenance cycles.

Reliable printing in dusty environments
Ceramic tile decoration is now almost fully digitised; conversion was only made possible by Xaar's TF Technology ink recirculation which enables printing with ceramic particle inks, often with high pigment loading, in harsh dusty environments. Applications involving printing of corrugated board would similarly benefit from using TF Technology.

High print quality including printing opaque white inks

TF Technology helped to address some of the specific demands of label printing which digital technology had struggled to overcome – such as high print quality, printing skin tones and very small text, as well as printing high-opacity opaque whites[7] (for over-and under-white applications). Titanium dioxide pigments which are used to deliver the required opacity are prone to sedimentation leading to blocked nozzles which is preventable by using the very high ink flow rate of Xaar's TF Technology. Similarly in glass printing applications, TF Technology ensures glass frit-based inks are kept in suspension.

Colour uniformity

Colour uniformity over time and across the print engine in wide single-pass applications such as décor laminates is enabled by the thermal management that TF Technology provides. The continuous fluid flow of TF Technology helps ensure a constant ink temperature and viscosity; this is conducive to preventing colour variations caused by fluctuations in ink viscosity.

Jetting very viscous fluids

This includes printing photopolymer resins for 3D printing,[8,9,10] photoresists for selective patterning of surfaces and solder mask fluids for PCB manufacturing, several of which have viscosities > 20 cP at room temperature.

Xaar 1003

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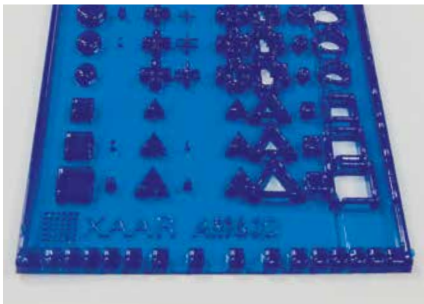
High Laydown TECHNOLOGY

Xaar 2001+

Xaar HL Technology, single pass printed tactile varnish effects[†] with thickness of 80 µm at 25m/min (Xaar 1003 GS12). Up to 130 µm at 25 m/min in single pass is achievable with Xaar 2001 GS12

Ceramic tile gloss effect printed by Scientifica Tiles LLP, India at 60 g/m^2 at 24 m/min with Xaar 2001+ GS12 printheads using Xaar's High Laydown Techology

Decorative Glass printing enabled by scanning a Xaar 2001+ GS12 printhead



2.5D resolution test sample made with photopolymer (40 mPa.s @ 50C) printed using Xaar 1003 GS12 printhead with standard three-cycle jetting

[†]Survey carried out by infotrends indicating that up to 89% premium for tactile or textured effects can be commanded compared to standard CMYK prints. http://whattheythink.com/articles/article.cfm?id=86463

3D printed tensile test bar, produced with BASF photopolymer using a Xaar 1003 GS12 printhead with Xaar's binary jetting High Laydown technology (similar samples were also produced with three-cycle jetting modes also)

Bottle printing station in KHS printer including UV curing lamp and Xaar 1001 (left image) in 'skyscraper' mode; jetting station with white + four colour direct label printing on bottles (above image)

A Xaar jetting test rig with a Stäubli robot arm (at the Iprint Institute for Printing, Switzerland) is shown on the left with the close-up on the right showing a Xaar 1003 printhead mounted on the robot arm for jetting at high levels of acceleration and deceleration[11]

For more information about the Xaar printheads and TF Technology, or to discuss what Xaar can do for your business, contact us: **info@xaar.com** or visit: **www.xaar.com**

Appendix

Experiment #1: Effect of air bubble in a printhead channel

Figure 4 is a simplified schematic of the long axis cross section of a Xaar 1003 jetting channel, showing air bubbles being carried away from behind the nozzle by the flow of the recirculating ink.[12]

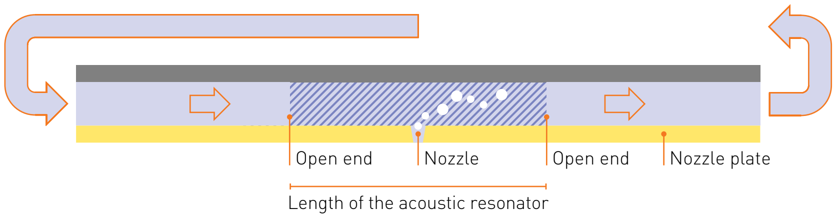
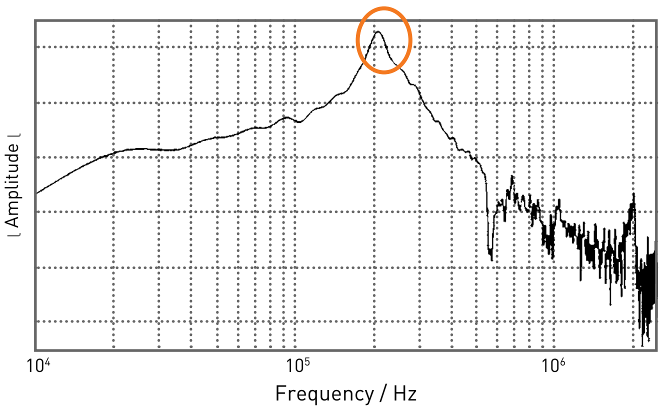


Figure 4:
Schematic showing air bubbles being carried away from behind the nozzle by the recirculating ink flow (indicated by the red arrows)

Figure 5 below shows the amplitude of the acoustic signal in a jetting channel as a function of frequency of the acoustic resonator with no bubble in the channel (left plot) and also with an air bubble in the channel at different distances **a**, **b** and **c** from the centre of the acoustic resonator (right plots).

The data was obtained from experiments carried out at Xaar[13] on a modified Xaar 1001 printhead which enabled controlled introduction and optical monitoring of a 70 μm diameter bubble in a single ink channel. The data clearly shows the acoustic signal shape and peak positions change depending on whether a bubble is present or not and where the bubble is located. Even small bubbles detune the acoustic resonator and can stop drop ejection of a given ink.



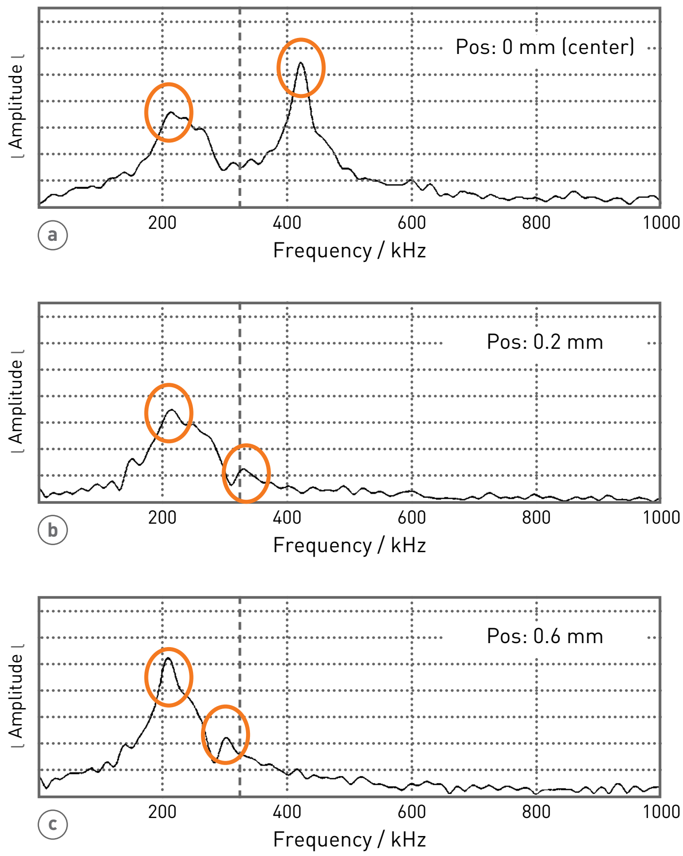


Figure 5:
The plot of acoustic signal amplitude as a function of acoustic resonator frequency (above) shows a single peak for a bubble-free actuator channel. Equivalent plots (right) show the impact on the actuator acoustics for different bubble positions in the actuator channel (**a** = channel centre; **b** = 0.2 mm from centre; **c** = 0.6 mm from centre)

Experiment #2: Nozzle latency and replenishment

When the printhead is idle, the properties of the inkjet nozzles can change, which can impact performance when printing restarts. For solvent or aqueous-based inks in particular, the drop formation changes when a viscous skin layer forms at the meniscus in the nozzle due to partial evaporation of the solvent which can be water. The viscosity of ink around the meniscus is slightly higher than the ink in the main actuator channel or chamber and the rest of the ink circuit. Ink recirculation past the back of the nozzle should promote constant replenishment of the ink in the nozzle and, theoretically, prevent the build-up of a skin layer at the meniscus, thus minimising the impact of idle events on start-up and improving print quality and reliability.

Since it is difficult to monitor the exchange of ink inside the nozzle directly, the experiments[14] adopted an indirect approach, measuring how the drop formation changed depending on (a) how long the printhead was idle before restarting printing and (b) the ink flow rate. Since any viscous layer reduces the drop velocity, this can be evaluated by measuring the dot placement errors.

Using solvent ink, which evaporates, successive bursts of 10 drops were ejected, after different idling times and with different ink flow rates. Dot placement of each of the 10 drops was measured, with the placement of the 10th dot as reference. This was chosen by reasoning that while the viscous skin layer at the meniscus would affect the formation of the first drops in each burst, it would gradually be removed by subsequent drops and would thus not affect the placement of the 10th and last. A Xaar 1001 printhead was operated at different flow rates (30, 60, 125 and 160 ml/min) for five minutes each, without firing (**Figure 6**). In addition, the idling time was varied for various flow rates and the impact on drop placement measured (**Figure 8**).

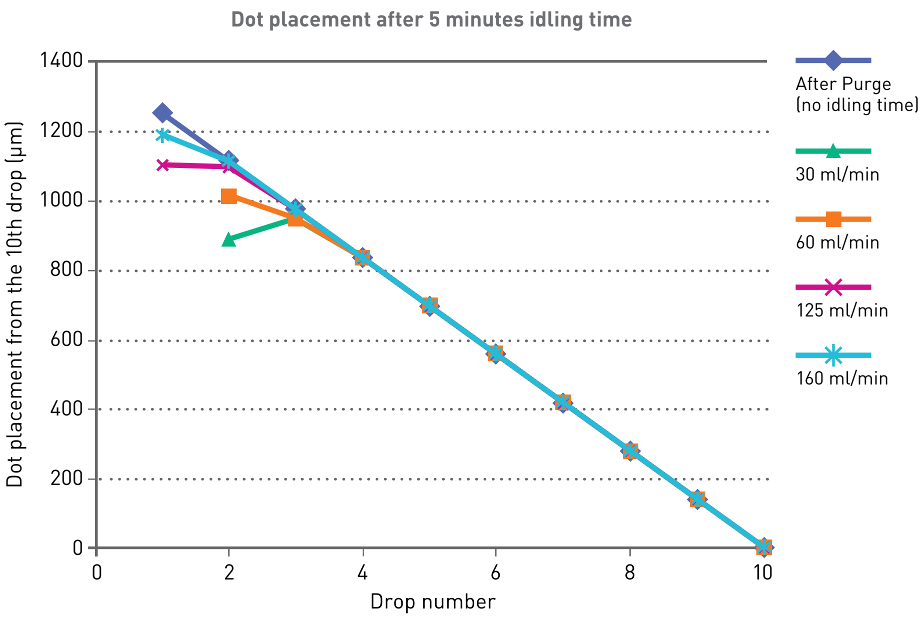


Figure 6: Dot placement after 5 minutes idling time where the position of each dot relative to the position of the dot from the 10th drop in a burst of 10 drops is measured. The test pattern used had a clear pixel between each dot in a burst and 200 clear pixels between bursts

The results are shown in **Figure 6**. As expected, all 10 dots are equally spaced after no idling time (i.e. directly after purging), since there is no time for the viscous skin layer to develop. After 5 minutes idling time when a flow rate of 160 ml/min is used, only the first dot is printed at a reduced distance, assumed to be due to a slightly viscous skin layer. With just a small reduction in the flow rate, from 100 to 125 ml/min, the first dot is considerably misplaced, effectively overlapping with the second drop, which is at nominal jetting velocity. Reduce the flow rate further, to 60 ml/min, and the first drop is missing completely, while the second is considerably reduced in velocity. With further reductions in flow rate, these features become more pronounced, with reduced velocity for both the second and third drops, suggesting the formation of an increasingly viscous skin layer at the meniscus. All flow rates quoted are the rates of ink recirculation in the head measured when it is not jetting. When jetting the total flow rate supplied is comprised of the jetting rate and the recirculation rate unlike alternative printhead designs with more constricted ink recirculation paths. In Xaar 1003 and 2001 printheads the recirculation rate is much larger than the jetting rate.

Figure 7 below shows how dot placement errors reflect the impact of the flow rate in the printhead. For the highest flow rate – 160 ml/min – all placement errors except for the first drop are small. At 60 ml/min, the first drop is missing and the placement of the second is off by 100 µm, and at 30 ml/min by over 200 µm.

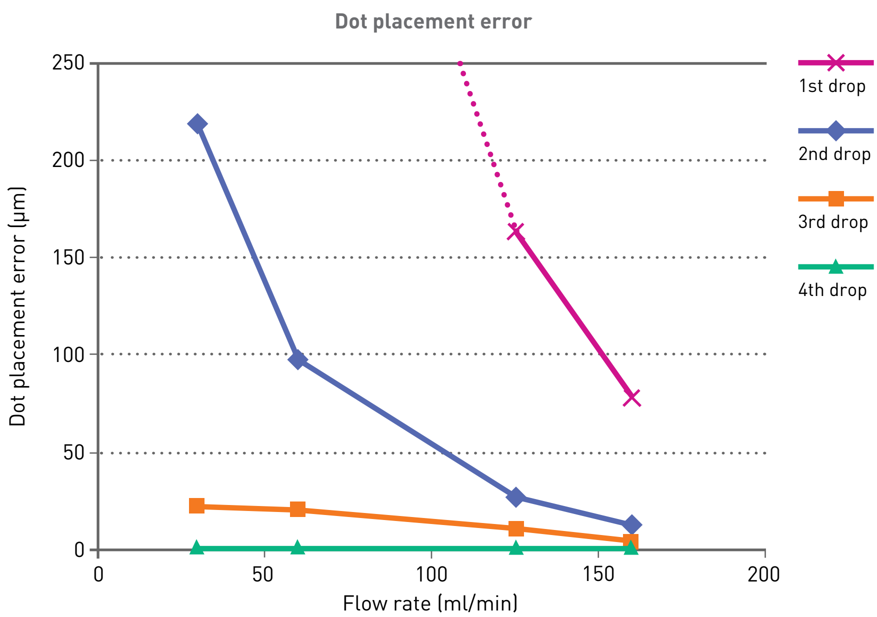


Figure 7:
Dot placement errors for the first 4 dots from the burst of 10 drops as a function of the flow rate (30, 60, 125 and 160 ml/min). Idling time before the burst of 10 drops was 5 minutes in all cases.

Figure 8 shows that, at longer idling times, a flow rate of 125 ml/min prevents the loss of any drop. The first drop is ejected even after an idling time of 24 hours. The dot placement errors of the first drop increase in line with increased idling time, indicating the formation of a more viscous skin, whilst the second and third drops essentially have the nominal velocity.

The conclusion is that a flow rate of 125 ml/min is sufficient to prevent the formation of an increased viscosity skin layer of ink that restricts or even completely blocks any given nozzle.

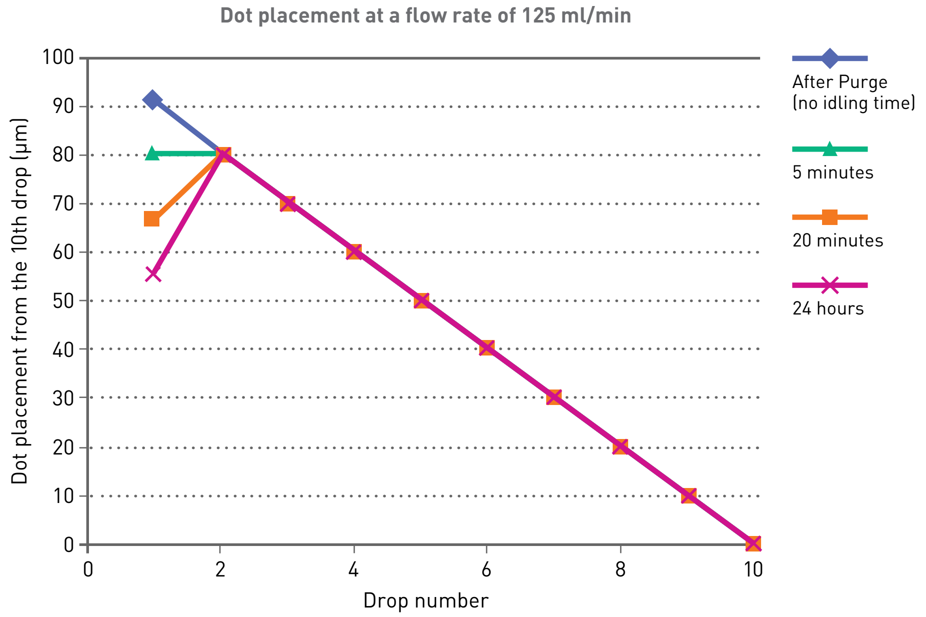


Figure 8:
Dot deviation as a function of flow rate. Flow rate of 125 ml/min prevents formation of a skin layer that can block a nozzle or cause strong deviations from straight jetting

Experiment #3: The impact of idling time on print quality

A third experiment, where the printhead idled with recirculation switched off (i.e. with zero ink flow), recorded the number of subsequent bursts with missing or misplaced drops before quality printing was restored. The results are shown in **Figure 9**. After 30 seconds without any recirculating ink flow, the first two or three bursts display faults, and after five minutes some channels are still not printing after 37 bursts. However, when the recirculating ink flow is restored – even after 10 minutes idling – all channels print correctly with the sole exception of the first burst; this was the case even after intervals of 60 minutes without any recirculating ink flow.

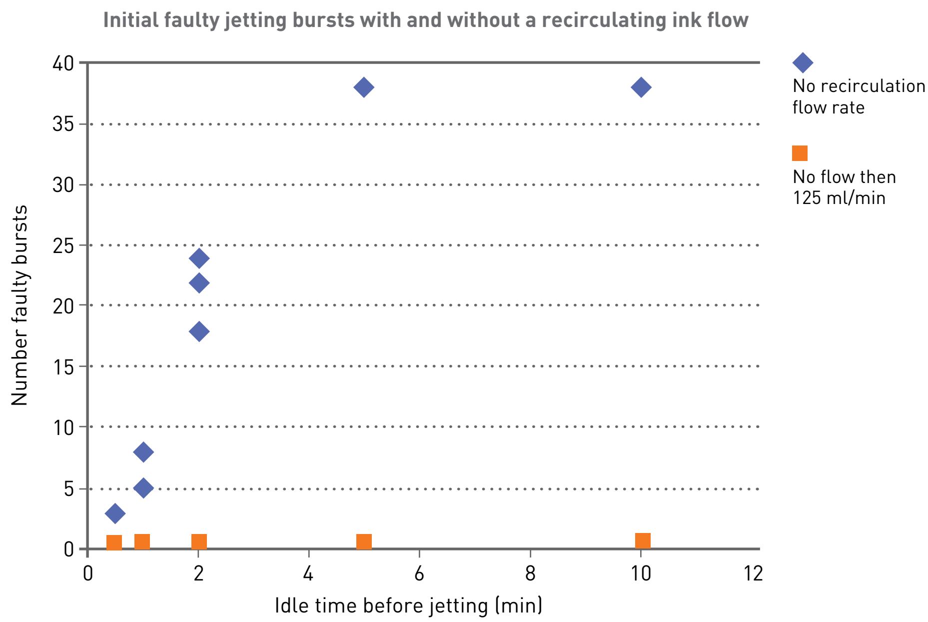


Figure 9:
Initial jetting bursts at zero flow vs nominal. The blue diamonds represent the number of faulty 10-drop bursts before full recovery (i.e. the first burst with no defects)

Meniscus pressure (MP) operating window

Print reliability is always important, but especially in single-pass printing, where any nozzle failures are more likely to affect the final print quality. A prerequisite for reliability is the widest possible operating windows for key parameters, allowing those parameters to vary as much as possible without causing defects or failures.

This experiment was conducted to test the hypothesis that higher flow rates in the recirculation system create larger operating windows for the meniscus pressure (MP) by diluting the impacts of local nozzle effects and ink flow rate, including drop ejection. To do this, it was necessary to measure the range of meniscus pressures at which operation is reliable across a range of recirculation rates.

The MP window was measured by adjusting the ink supply to adjust the MP over a range of values, and independently adjusting the recirculation flow rate by changing the differential pressure (DP) between the inlet and outlet of the printhead. For each combination of MP and DP, the jetting reliability was assessed by visually inspecting the jetting 'curtain' from the head on a jetting rig. **Figure 10** shows examples of good and bad 'curtains'.

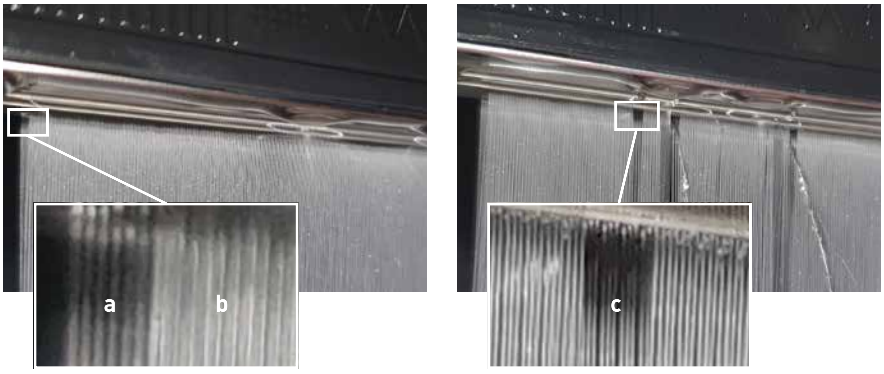


Figure 10:
Above left image with inset from the same showing all nozzles jetting in a double curtain with a row of nozzles corresponding to each curtain. The photo is taken at an angle to the jetting curtains so one can see the start and end of each curtain. The front curtain **a** from the first and closest nozzle row to the camera looks brighter than the second curtain **b** behind it. Above right image with magnified inset shows the non-jetting nozzles in the front curtain of the double curtain **c**

Meniscus pressures are generally set slightly below atmospheric pressure to stop nozzles weeping when not printing. Closer to atmospheric pressure – i.e. at the top of the MP window where pressures are less negative, the MP is unable to hold ink in the nozzle, and ink floods out. At the bottom of the MP window, where pressures are more negative, the meniscus is more prone to break, allowing air to enter the nozzle and cause jetting failure. At each DP (flow rate) set point, the MP was varied to find the least negative pressure at which reliable jetting was possible without flooding, and the most negative pressure before air injection caused nozzle failure. These MP values represent the top and bottom of the MP window at that DP setting.

Figure 11 shows the results for a typical UV-curable ink where the MP window is 20 mbar (-5 to -25 mbar) with a low DP of 40 mbar, but increases to 26 mbar at a DP of 200 mbar.

- Results for a typical UV Ink where differential pressure (DP) across the printhead is essentially a measure of recirculation flow rate strength:
  - Meniscus pressure (MP) window (range) of 20 mbar at 40 mbar DP
  - MP window increases to 26 mbar at 200 mbar DP
- Increasing recirculation rate raises meniscus pressure operating window

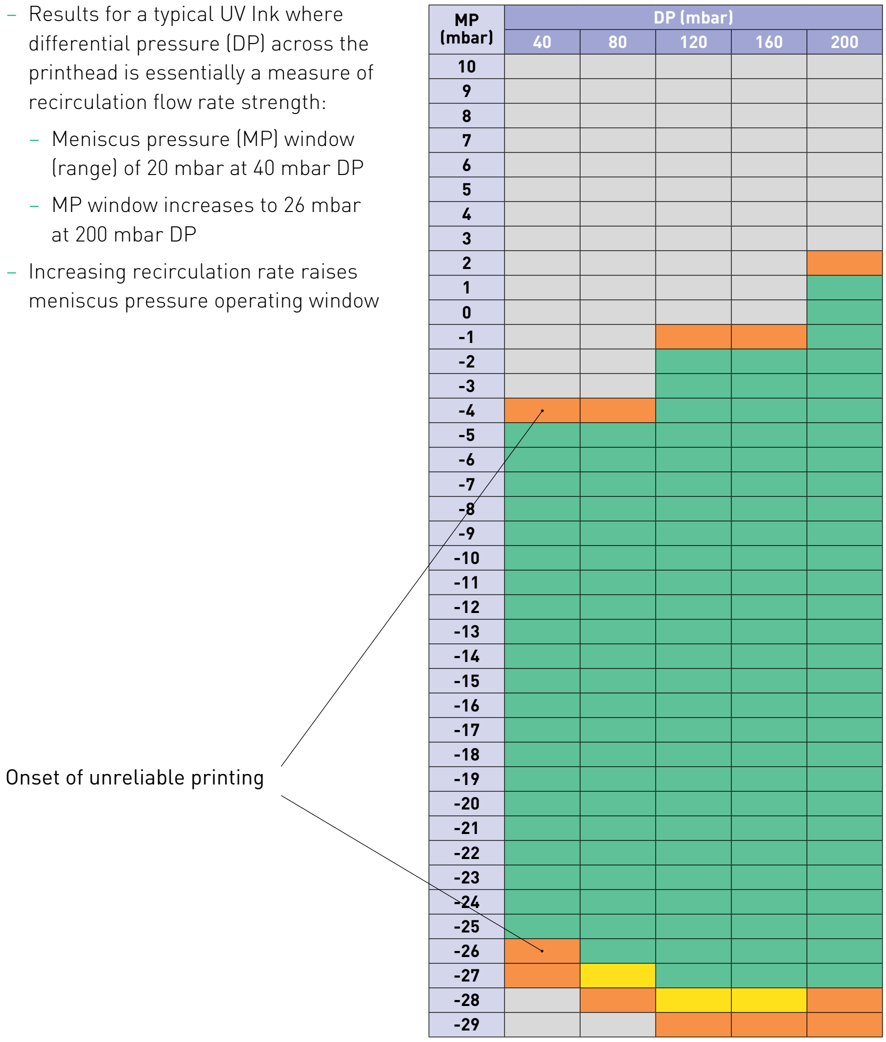


Figure 11:
The green cells represent reliable operation, and the red unreliable (flooding at the top of the range, nozzle failures at the bottom). Yellow indicates borderline/ inconsistent performance.

Greyscale performance

We described earlier how the 'open' architecture of Xaar TF Technology ensures that ink can easily access channels in the printhead. In combination with the 'double-ended' channel architecture, in which two acoustic waves are focused on the nozzle, TF Technology enables the repeated generation of drops without ink starvation. In the case of the Xaar 2001 GS12, the result is maximum printhead productivity for up to 360 µl/s/inch, giving a wide choice of drop size and hence greyscale options for excellent print quality.

Binary performance

It should also be pointed out the higher speed, higher resolution binary printing modes also benefit from Xaar's TF Technology ink recirculation in terms of jetting reliability, in particular with particulate inks. Included in the binary modes is a special low resolution, high drop volume mode called high laydown which was mentioned earlier. In single pass a Xaar 2001+ GS12 U can deposit up to 80 µm UV-cured layer thickness at 50 m/min (dependent on ink and ink system type; with two print bars in series with interstitial UV printing, Braille and warning triangle heights are readily achievable.

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