Influence of Printhead Geometry, Print Conditions and Fluid Dynamic Properties on the Jetting Behaviour

Tri Tuladhar, John Tatum and Paul Drury; Xaar plc, Cambridge, UK

Abstract

This paper investigates key dynamic properties of the ink, at the timescale relevant to the inkjet printing, that can differentiate between good and bad inks which otherwise looked identical. An "Ink fluid map" is created for specific printhead which take account of the printhead geometry, jetting conditions and ink's bulk and key dynamic properties. This paper presents case studies whereby the "ink fluid map" is utilised to (i) identify optimum printhead geometry and print conditions (velocity, print frequency and temperature) for a given ink; (ii) formulate/recommend ink that meets both bulk and dynamic properties for reduced misting, satellite formation and improved reliability.

Introduction

Recent advances in inkjet technology and ink chemistry, have imposed stricter requirements on both existing and new applications with (i) increased drop velocity, (ii) high print frequency, (iii) controlled drop size, and (iv) improved directionality and (v) be able to jet exotic fluids. However, increased misting/satellites and reliability issues (temporary or permanent line drop out, flooding, drop directionality and velocity fluctuation, etc) work against achieving these requirements. The effect can be mitigated to some extent by optimising the drive mechanism (waveform and drive amplitude) in drop on demand (DoD) devices and fluid modifications (composition and properties) within the window of printhead operation. In extreme cases and for novel applications, printhead redesign and modification of drive electronics may be required.

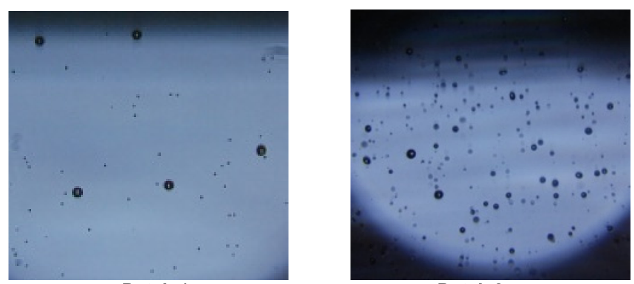
Ink's conventional physical properties alone are an insufficient guide to ink performance. The fluid is subjected to high frequency pressure fluctuations in the channel during actuation, high shear at the nozzle wall and large extension in-flight. Small variations in ink dynamic properties influence the upstream flow dynamics and jet break-up mechanism downstream. A fundamental understanding of ink chemistry and the influence of individual components, as well as the ink as-a-whole, on dynamic flow behaviour in-channel, through the nozzle, in-flight and on-substrate during printing is vital. This understanding will help tailor specialized inkjet fluids for new applications in existing and future printheads.

It is important to look at the combined influence of all four components (i) printhead, (ii) drive profile, (iii) ink and (iv) substrate and process condition to achieve targeted drop size, reduced satellite/mist formation, high print speed, frequency and print reliability.

Ink formulation and jetting behaviour

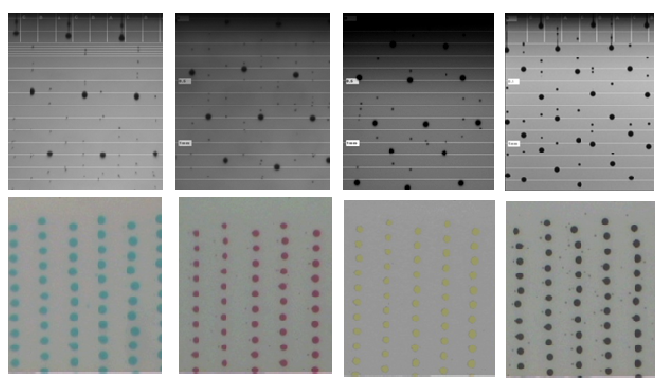
One of the key challenges in ink formulation is to develop inks that are consistent. Ink formulations are maintained to keep key parameters within specifications, yet it is often noticed that there are marked differences in the jetting performance between batches or between colours of apparently identical inks.

Though ink carrier components (solvent, oil, varnish, water) of the ink are mainly Newtonian, introduction of pigments to the carrier fluid produces considerable deviations from the Newtonian behaviour. This is due to particle association (by chemical bonds and/or physical interaction) during flow. The size and concentration of the pigment particles affect ink's bulk properties. Dispersants are added to stabilise the pigments. Additives such as resins are often present to bind other components of the ink and contribute to the properties of the ink once on the substrate (e.g. gloss, resistance to heat, chemicals and water). Any subtle variations in any of these additives can influence the viscosity of the fluid and also it's elasticity due to their polymeric nature which could result in marked differences in the jetting behavior. Ink formulators will find it very difficult to adjust these properties.



Batch 1 ***Batch 2***

Figure1. *High speed in-flight jetting photographs between two batches of identical inks. Images obtained from Xaar 1001 PH using Spark Flash Rig*



Cyan Magenta Yellow Black

Figure2. *Differences in the jetting behavior between colours of a commercial UV ink sets: Top row (In-flight) and bottom row (on-paper) Images.*

Figures 1 and 2 show such examples where the jetting characteristic varied between batches and colours. In both cases, the ink was jetted using the same printhead (Xaar 1001) with the same jetting condition (drive profile and drive volt) to achieve 6 m/s drop velocity. As a consequence extensive and time consuming ink reformulation and validation (optimization and/or separate waveform development) are carried out for each batch or between colours to achieve satisfactory jetting. This issue is further complicated when developing inks for niche applications which could contain special (i) pigments/particles with high loading concentration and density, (ii) polymers/binders of high molecular weight, (iii) carrier fluid with different physical and chemical properties. Any variations in the composition could change fluid physical properties (such as density, surface tension, viscoelasticity, speed of sound) beyond the existing printhead operating windows.

Bulk and dynamic properties

In any inkjet system, the ink goes through various physical and geometrical constraints which influence the flow dynamics and finally the jetting characteristics. Most print heads have a narrow operating range in terms drop of velocity, print frequency and fluid properties.

Inkjet ink is carefully formulated to achieve ink stability and bulk properties that meet jetting, substrate and process/environment requirements while also ensuring it is chemically compatible with printhead material.

Bulk properties such as surface tension and viscosity play a key role in the jetting of the inkjet ink. Their roles are varied depending whether they are in the upstream or downstream. As the jet emerges from the nozzle, the viscosity and elastic stresses resist the necking motion of the liquid filament, whereas surface tension and inertia influence the resulting shape and form of the emerging drop. The optimum values of the surface tension and viscoelasticity becomes a compromise of what is required upstream (in the channel) and downstream (in-flight). Ink's combined bulk properties have to be matched to operate efficiently at jetting temperature.

Controlling droplet formation and in particular, the break up and corresponding tail or ligament is highly dependent on the combined influence of these bulk properties and the rheology of ink as it flows through the nozzle.

In the case of DoD, apart from physical properties of the ink, the dynamic properties (viscoelasticity, intermittent pigment stability, dynamic surface tension) also play an important role in the ejection of the ink and subsequent drop formation as the ink is a cocktail of many components and is subjected to different flow regimes during jetting.

For piezo-electric inkjet devices, high frequency voltage pulses (waveform) are applied to a piezo-electric element. This causes an ink-filled channel to deform, thereby creating a fluctuating pressure profile. Through fluid acoustics two or more consecutive waves are super-positioned which guide the pressure pulses towards the nozzle [1]. The required super-position is achieved via adjustments to the electrical signals driving the piezoelectric actuator i.e. waveform frequency, voltage amplitude and pulse duration [1]. As a result, a strong acceleration of fluid occurs inside the nozzle which overcomes the viscous dissipation and the energy associated with forming a new surface so that fluid is jetted at high speed. The propagation and reflection of acoustic pressure waves are function of fluid properties, printhead design and constituent materials. The amplitude of the applied voltage pulse modifies the fluid acceleration in the channel and hence velocity of the jet ejected from the printhead.

Ink fluid map

The inkjet printhead operates in microsecond timescale and small differences in printhead geometry, print conditions and dynamic fluid properties in microsecond timescale also influence the jetting characteristics. It is therefore very important to characterise ink properties in the timescale relevant to the jetting conditions.

Unlike bulk properties, it is not easy to quantify the dynamic properties of the inkjet ink at the print conditions (very high frequencies, shear rates and velocity) using conventional measuring tools. Recently some prototypes have been developed [2-5], which have a capability to measure some of the dynamic parameters at conditions similar to those encountered during jetting. The quantitative measurements from this have given deeper insight into the link between the fluid dynamic properties and jetting characteristics. [2-6] have used such tools to look at the influence of ink dynamic properties on the on the jetting behavior.

Over the last few years, fundamental background studies have been carried out to establish a link between fluid bulk and dynamic properties and jetting. Key dynamic properties have been identified at the timescale relevant to the inkjet printing to identify key features within good and bad inks which otherwise looked identical. These features can be utilised to distinguish subtle differences between batches or colour, thus generating "ink physical fingerprint". One of the many feature incorporated in ink physical finger print is elasticity as reported earlier [3-6]. The optimum elasticity value is printhead and jetting condition specific. High elasticity influences jetting velocity and could forms a thin ligature which breaks up at multiple points resulting in many satellites (or mist). In extreme cases, the jet does not detach from the nozzle and is either pulled back into the nozzle or floods the nozzle. Low or no elasticity results in satellite formation at high jetting speed. The presence of some optimum elasticity is required whereby the liquid filament connecting the main drop is instantly pulled into the main droplet after breaking from the nozzle giving a satellite free drop.

Xaar exploits complex rheological techniques to analyse ink and generate a fluid map to determine the suitability of the ink. The fluid map also takes into account the combined influence of bulk properties, jetting conditions (print frequency, drop speed and size) and ink physical finger print. The fluid map is tailored to specific printhead and gives us a good indication of the degree of misting, satellite and reliability.

Figure 3 shows examples of the Xaar fluid map. The Xaar's fluid map uses 5 criteria (labelled as **A-E**) to establish the ink's suitability for the given jetting condition and predict its jetting characteristic. For commercial reason, the detailed of the Xaar criteria are not disclosed in this paper. These 5 criteria include printhead geometry, jetting conditions, bulk static properties and dynamic properties of the fluid at conditions similar to that experienced in the printhead. Each criterion can be associated with misting, satellite and reliability. Some criteria represent more than one failures mode depending on where it is on the scale. Ideally, an ink should satisfy all the criteria and fall within the preferred recommended zone ("80-100") to give optimum jetting characteristics. The severity of failure depends on (i) number of failed criteria and (ii) how far-off (below or above) the recommended range. We have encountered very few commercial inks that meet all the criteria.

Case studies

The "ink fluid map" is a powerful tool to differentiate between inks and can be used to prescreen inks, recommend jetting conditions and aid ink reformulation.

I. Differentiate between inks

Figure 1a shows the fluid map comparisons between colours (Brown, yellow and pink) of a commercial ceramic inks. Though all three inks had similar bulk properties and speed of sound, the fluid map indicates that the jetting behaviour will be marked different. The pink meets criteria **A**-**C** and close to the recommended range for criterion **D** where as brown colour met only one criterion. This would indicate that pink is a better ink and should give better jetting characteristic than brown it met only one criteria. Jetting tests showed pink to be most reliable and gave fewer satellites and misting in agreement with the fluid map.

II. Influence of temperature

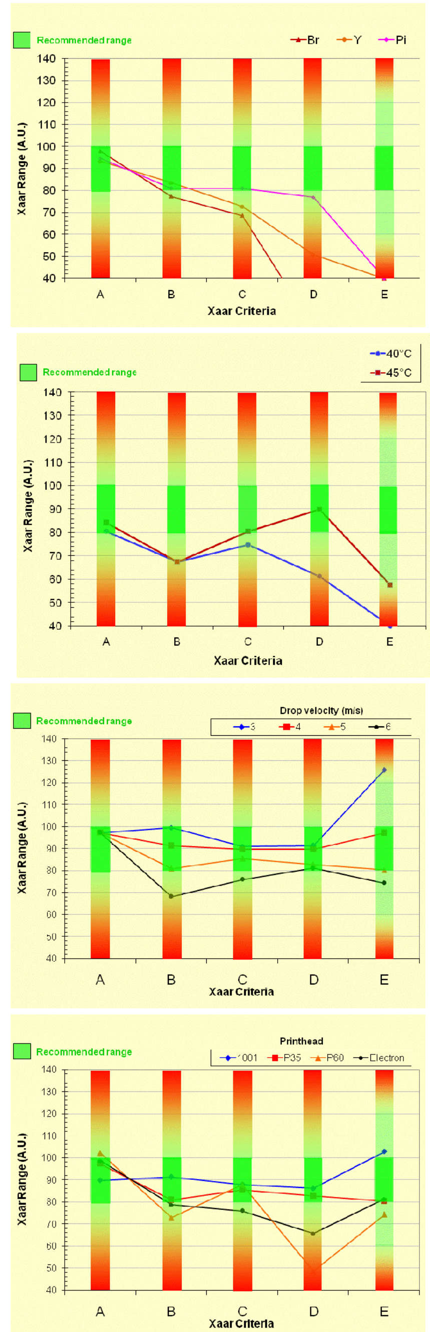
Jetting characteristic of the ink is sensitive to temperature due to changes in the bulk properties. The effect is noticeable for 10-20°C variation in temperatures. In some cases, the ink shows drastic jetting behaviour changes for small differences (±1-5°C). This drastic behaviour can not be linked to bulk properties alone. In such fluid, we found some of the dynamic properties change significantly over few degrees centigrade. Figure 3b shows an example of such ink whose criteria **D** and **E** deteriorated when the temperature dropped from 45 to 40°C. Jetting observations also showed that this ink performance improved significantly when jetted at 45°C as opposed to 40°C. It is for this reason, the ink usually come with recommended jetting temperature and have to be strictly adhered to such sensitive inks. If possible, it is usually recommended to avoid such sensitive inks.

III. Print conditions

Jetting conditions play an important role. It influences many of the fluid map criteria and thus the jetting characteristic. Figure 3c shows an example of the ink whose fluid map criteria varied as a function of final drop velocity. In this instance, the ink should give the best results at 4-5 m/s.

IV. Printhead type

Physical geometry, size and shapes of printhead channels, nozzles and the drive profile are different for each printhead type. It is for this reason, inks are usually tailored to operate for specific printhead which has narrow operating windows and can handle ink of set properties. Figure 4d shows a suitability of a commercial ink in four Xaar printhead. The fluid map incorporates printhead geometry to determine the suitability of the ink. Based on the fluid map, this particular ink is ideally suitable for Proton 35 (P35) and to some extent in 1001. It is very likely that this ink will perform badly in Proton 60 (P60) and Electron heads.



(a)

(b)

(c)

(d)

Figure 3. *Xaar fluid map showing differences between (a) colours; (b) temperature; (c) jetting conditions and (d) printhead type.*

V. Ink reformulation

The detailed understanding of the inks dynamic properties, printhead operating windows and drive profile can be exploited to expand the ink envelope that gives good jetting characteristic (lower satellite/misting and good reliability) and also show insensitivity to temperature fluctuation and drive profile.

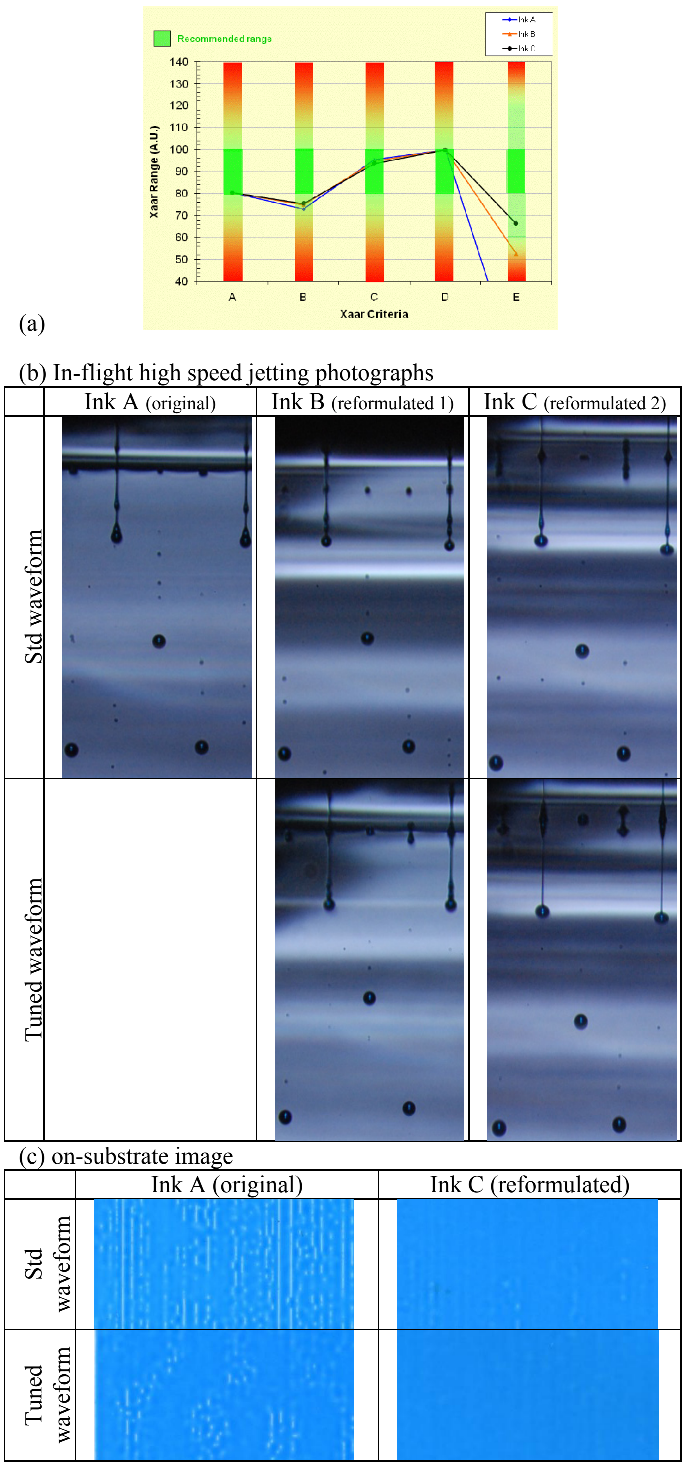


Figure 4. *Fluid characterization of commercial and reformulated inks for 1001at 6 m/s drop velocity: (a) Xaar fluid map; (b) in-flight images (c) substrate images after printing continuously for 300 metres.*

Figure 4 provide such example where the performance of a commercial UV ink (Ink A) is significantly improved. The fluid map (Figure 4a) shows that the ink A meets most criteria but lacked criterion **E**. The ink was then reformulated with special additives to improve criterion **E** while still maintaining the bulk properties and other dynamic criteria similar to original ink. The fluid map shows that both reformulated ink B and C should jet better than the original ink A. The ink C would be the best candidate as it was closer to the recommended range in criterion **E**.

Ink B and C gave fewer satellites as compared to original ink A for the same jetting condition as shown in-flight photographs (Fig 4b). Further tuning of the drive profile further reduced the satellite. The overall reliability of the ink was also found to be significantly improved with the reformulated ink. The figure 4c shows the images on substrate after continuously printing 300 metres from a commercial label printer utilising 1001 printheads. The modified ink C had much fewer print defects than original ink A. The performance of the ink C varied little with different drive profile indicating it to be less sensitivity to drive profile. Furthermore, the print performance of ink C did not change over 10°C (±5°C of the recommended value) where as the print defect increased outside the recommended temperature for original ink A.

This example demonstrate that complex rheological knowledge can be used to formulate/recommend ink that meets both bulk and dynamic properties for reduced misting, satellite formation and improved reliability for the given printhead and jetting condition.

Conclusions

The subtle changes in the ink properties during printing are important as far as the jetting of the fluids are concerned. Novel rheological techniques to quantify fluid properties close to printing conditions can provide quantitative correlations between jetting and rheological properties. These techniques have proved useful as a prescreening tool to rank inks by detecting subtle changes in ink properties between batches and colours. They can also be exploited during formulations by being able to quantify, control and match dynamic properties (higher frequency viscoelasticity and extensional properties) of the ink. Further techniques capable of quantifying fluid rheology at printhead system resonance frequency, dynamic surface tension in microsecond time domain, meniscus and pressure profile during jetting, and mists at the print condition have to be explored to obtain more detailed insight into fluid properties and jetting.

Acknowledgements

We would like to thank all our industrial and academic partners with whom we have worked closely over the years.

References

[1] Drury et al. NIP25, 95-8 (2009)
[2] TR Tuladhar, MR Mackley, J. Non-Newtonian Fluid Mech., 148, 97-108 (2008).
[3] TR Tuladhar et al. NIP25, 423-426 (2009)
[4] D C Vadillo et al. NIP25, 736-739 (2009)
[5] D C Vadillo, et al., J. Rheol, (2010).
[6] S Hoath et al., J. Image Sci. Tech, 53(4), 041208(2009).

Author Biography

Tri Tuladhar received his PhD in Chemical Engineering from the University of Cambridge (2001). He has over 10 years experience in R&D in academia and industry. Recently, he has focused on rheology of inkjet printing ink and developed measurement techniques to link fluid rheology to jetting behaviour. Currently, he heads Xaar's development in the rheological characterisation of inks in the inkjet environment.