FORMULATION, QUALITY, CLEANING AND OTHER ADVANCES IN INKJET PRINTING

A.A. Castrejón-Pita,[1] E.S. Betton,[2] N. Campbell,[3] N. Jackson,[4] J. Morgan,[5] T.R. Tuladhar,[6] D.C. Vadillo,[7] & J.R. Castrejón-Pita[8,*]

[1]*Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK*

[2]*Domino UK Limited, Trafalgar Way, Bar Hill, Cambridge, CB23 8TU, UK*

[3]*Inca Digital Printers Ltd., 515 Coldhams Lane, Cambridge, CB1 3JS, UK*

[4]*Xaar plc., 316 Cambridge Science Park, Cambridge, CB4 0XR, UK*

[5]*Aricode Printing Technology, Millfield, Cottenham, Cambridge, CB24 8RE, UK*

[6]*Trijet Limited, Cambridge, 59 Eland Way, Cambridge, CB1 9XQ, UK*

[7]*3M Corporate Research Analytical Laboratory, Saint Paul, MN, 55144, USA*

[8]*School of Engineering and Materials Science, Queen Mary, University of London, London E1 4NS, UK*

*Address all correspondence to: J.R. Castrejón-Pita, E-mail: castrejon@cantab.net

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This article describes a series of modern developments carried out by the inkjet community in its quest to improve material compatibility, printing quality, and reliability. Recent progresses in rheology have advanced our understanding of liquids at the time scales that are characteristic of inkjet printing processes. As a result, microsecond rheology now permits the formulation of inks with tailored viscosities that vary according to the time-scale of their dynamics, i.e. low effective viscosity during jetting but high at break up and landing. These advances have permitted the community to assess, and often predict, the ink jetting behaviour, at a given printing frequency, based on the linear or non-linear viscoelasticity and other fluid characteristics. *Advances in fluidic systems and in waveform design have now enabled the printing of high viscous inks that were previously impossible to jet on demand. This capability is opening up new markets and opportunities for inkjet, from the printing of glues to the use of heavily loaded ceramic inks. Advances in printhead design, and the assessment of printing patterns using common standards, now allow the verifiable and reliable operation of industrial-scale digital inkjet printing in a wide range of environments. Recent improvements on printhead cleaning protocols, have contributed to an increase in printing speed and operating time by reducing the production of mist and satellite droplets neighbouring the printhead region. Thanks to these improvements, inkjet is displacing traditional technologies, such as offset and screen printing, in large markets including graphics, packaging and labelling.*

KEY WORDS: *inkjet, drop on demand, droplet, printing, ink, formulation*

1. INTRODUCTION

Strictly speaking, inkjet printing covers a broad range of technologies, including thermal, piezoelectric based drop-on-demand printing, valve-jet, and continuous inkjet (CIJ); extensive descriptions of these technologies are found in Basaran (2002) and Castrejón-Pita et al. (2013). However, two technologies dominate the industrial inkjet market: continuous inkjet and drop on demand (DoD). In CIJ, a jet of ink is controllably broken-up into droplets by a pressure perturbation resulting in a train of uniform droplets. In this technology, individual droplets are then steered into the desired location by electrostatic fields. In contrast, in DoD, the liquid meniscus at the nozzle is precisely controlled so that a single pressure pulse produces a single droplet that is timely jetted to produce a print. *The jetting dynamics of the CIJ and DoD processes, in terms of the ink and actuation properties, are theoretically described in Bruce (1976) and in Wijshoff (2010) respectively.* Each of these technologies brings its own rewards and challenges, and these two methods exist to respond to a specific market requirement. For example, the fast printing speeds of continuous inkjet systems are ideal for the printing of expiration dates onto consumer products, while piezoelectric drop-on-demand printing conveys high resolution and colour flexibility for the printing of graphics in packaging, *comprehensive reviews of modern applications of inkjet are found in Hoath (2015) and Zapka (2018).*

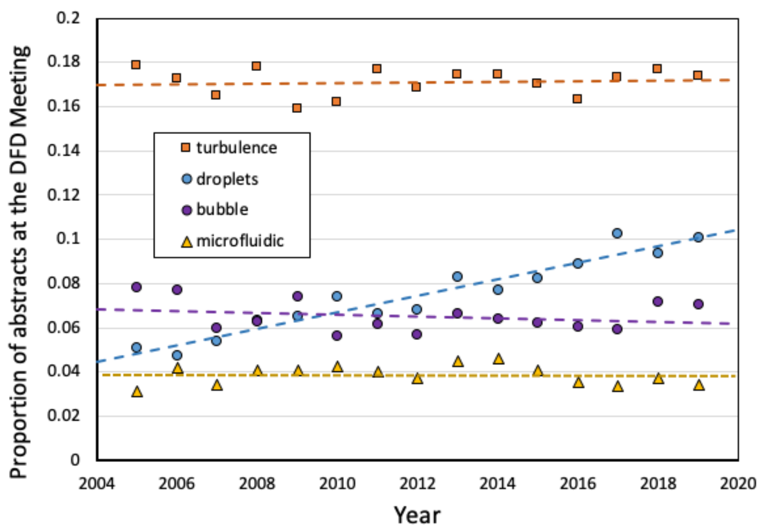

FIG. 1: Ratio of the number of abstracts submitted to the Division of Fluid Dynamics Meeting of the American Physical Society to the total number of submissions per year. As seen, the topics of turbulence and microfluidics are well-established while the popularity of droplets shows a steady increase along the years illustrated. Data is mined from the APS Bulletins (2005 - 2019), e.g. in 2019 there were 328 abstracts with the word "droplet", 111 with"microfluid" and 565 with"turbulence", out of 3,249 abstracts in total.

It has been claimed that three-dimensional (3D) printing is the current driving force behind inkjet research, but labelling and marking are the applications that have made inkjet a very rentable, efficient, and effective technology. Inkjet is a fascinating non-contact technology; it is capable of delivering very small liquid droplets to a substrate in a precise and controllable way in order to produce printed patterns. Predictably, inkjet technologies are expanding on several emerging markets, and this is driven by recent advances in microfluidic design and by ink chemistry formulation. *Some of these advances are driven by an ever-increasing number of novel* *applications; examples of the modern utilisation of inkjet include the inkjet of pharmaceuticals, Boehm et al. (2014), and on the printing of high-quality OLED and QLED displays, Lan et al. (2017) and C et al. (2019).* Due to these qualities, inkjet is gaining momentum in liquid dispensing, dosing, coating, anti-counterfeit printing, drug testing, ceramics and electronics, please see Tuladhar (2017). While the potential of inkjet printing has been demonstrated in these niche areas, some intrinsic limitations are restricting its use and acceptance in a wider range of applications. The main restrictions are that droplet-based technologies are traditionally only compatible with liquids of very specific properties, often exclusively working with low viscosity liquids. These limitations depend on several factors, including the ink properties, the ambient conditions and, critically, on the ink dynamics within the printhead, during jetting and upon deposition. Poor understanding of these factors has hindered the wider use of inkjet in other potential environments. These obstacles have positioned the study of droplets and droplet technologies at the forefront of science. In fact, the science of droplets has been at the foremost of research since the seminal and fundamental works of Savart (1833), Rayleigh (1878), and Worthington & Cole (1987). The formation and deposition of liquid drops are everyday occurrences, and even though droplets have been mentioned in a scientific context for more than 300 years, the fundamental principles are still far from being completely understood. Research on small-scale droplets is an important and wide-ranging topic because many natural, technological and industrial processes involve the transport of drops at micro-scales. The study of drop dynamics has been in continual development right up to current times. The field of liquid droplets offers the perfect platform for theoreticians to study singularities (such as pinch-off and splashing), numerical modellers to study the dynamics of the contact line and coalescence, and experimentalists to understand droplet micro-mechanics at the nano-scale. In fact, the relative importance of the fluid properties (i.e viscosity, elasticity, and surface tension) change according to the length and time scales at which the droplet flow is evolving. Therefore, experimental and theoretical investigations are challenging owing to the need to resolve several spatial and temporal scales. The popularity of the field is now reflected at all of the international conferences, where the field of droplets has overtaken other popular topics in fluid mechanics such as microfluidics and bubbles. In fact, as seen Fig. 1, the number of works on droplets has been steadily increasing in recent years and is looking to compete in popularity with the long-established field of turbulence.

Many of the current studies in droplet dynamics are aiming to improve the existing capabilities of inkjet methods. Applications, such as graphics and packaging, demand fast printing speeds, high print frequency, smaller drop size, and improved colour registration. These demands bring complications and pose significant challenges to the field. For example, as the speed of printing increases, mist, satellite drops and other reliability issues arise to work against the printing resolution. Consequently, the scope under which printheads are expected to perform is constantly shifting. For almost all inkjet technologies there is a drive for increasing web speed, while for different applications print quality is foremost. Additionally, current factory production lines require long print runs where reliability is crucial. Another important current challenge is found in formulation, where research is required to develop inks that can be both consistently mass-produced and fully characterised. It is through ink formulation and characterisation that modern systems have improved print speed, quality and resolution while increasing the range of inks suitable for printing. In addition to these advances on ink formulation, inkjet is benefiting from increasing software and mechanical capabilities, although nozzle plate cleanliness and routine maintenance remain an ubiquitous challenge in inkjet systems.

This paper reports on recent advances in inkjet printing and describes some of the modern challenges faced by these technologies.

2. INK FORMULATION & RHEOLOGY

Inks are produced within very narrow specifications, yet jetting performance often varies between batches. In all inkjet applications, extensive reformulation and jetting optimisation are required for each ink batch to achieve satisfactory printing. This issue is specially complicated for personalised or one-off consignments that often contain non-standard components, such as a high concentration of polymers and binders, colloids or pigments, viscoelastic elements or high (and complex) viscosity carrier fluids. Additionally, formulation varies according to the technique used for dispensing and its application, being notably different for monochrome continuous inkjet and full colour piezo-based digital printing. In particular, ink formulation is much more rigorous in applications bound by regulatory standards of operation. A good example of these is the use of inks for food products, where solvent consumption and use of chemicals outside these regulations can prevent new inks, and even existing inks, from being marketable. With so may different pulls and constraints on ink formulation, it is important to achieve full characterisation and traceability.

Any given commercial ink contains dozens of elements, such as lubricants, solvents, additives (often resins), binders, stabilisers, dyes, and pigments. Variations in the composition result in changes in the ink's physical properties that could place a batch beyond the printing operating window, as described by Derby (2010). In addition, substrate properties, such as wettability and roughness, also play a significant role in the formulation. In fact, this problem is now common, as inkjet technologies are rapidly expanding into applications that go beyond printing on paper or cardboard, with many processes now available for printing on automotive parts, architectural glass, home appliances glass, ceramics, and electronics. Printing onto solid non-absorbing substrates requires the understanding of various phenomena including those related to liquid impact, spreading and even splashing on a substrate, as these issues result in reliability and image definition issues.

The logical first step in the formulation of an ink is to start with this simple question: What are the ideal rheological properties required for an inkjet ink? *The collective wisdom recommends a (static) Newtonian ink viscosity* between* $\eta = 3$ *to 40 mPa s (ideally 10 - 20 mPa s) and a surface tension in the range of* $\sigma = 25$ *- 40 mN/m, see Reis et al. (2005) and Liu & Derby (2019) for relevant examples.* However, even if these relatively narrow ink rheology specifications are met, they might not be sufficient to produce stable printing, the expected footprint, or the desired colour registration. A more integrated question would be, What are the ideal rheological properties required for an ink under the desired operational shear rates? This seemingly small addition to the question is paramount, as it guides both the developer and the user to consider the possibility that inks can display, or are required to show, complex behaviour in shear and/or extensional conditions; this behaviour is often called Non-Newtonian. Consequently, ink formulation is directly determined by the rheological conditions found during the process of inkjet printing. Within the printhead, inks experience shear rates as low as 10^3 s^{-1} in the tank/ink channel, and as high as 10^5 s^{-1} during jetting, Hoath et al. (2015). The high shear rate is seen during actuation, where a fast ($\sim$10 μs or 10^5 Hz) and small (20 - 40 nm) channel compression creates the necessary pressure wave(s) to achieve jetting; this pressure wave is called *waveform* within the inkjet community. In contrast, outside of the nozzle, the in-flight flow is strongly extensional, so droplet formation is the result of a fine balance between capillary and viscous forces. Low or no elasticity in the ink can result in an unwanted satellite formation at high jetting speeds that can otherwise be controlled by elasticity. *In fact, some inks include*

*a liquid viscosity that remains constant at all relevant shear rates *polymer additives to produce a complex rheology. For instance, the shear-thinning properties of poly(3,4-ethylenedioxythiophene): poly(styrene sulphonate) (PEDOT:PSS) model inks have shown clear shear-thinning (e.g. viscosity lowering) during passage through the nozzle, allowing it to be ejected, while recovering it's low-shear viscosity once in flight, Hoath et al. (2015). This is of particular importance in situations in which viscoelastic relaxation times and processing time (time to eject a drop) are commensurable. PEDOT:PSS model inks present viscosity changes of two orders of magnitude within the discussed shear rate domain of inkjet . These large viscosity changes not only make the inks jettable but also affect the droplet formation dynamics thus potentially affecting the quality of printing by influencing the formation of satellite droplets. Ultrafast imaging methods have been devised to measure inks properties (surface tension and viscosity) in flight, in order to be able to understand their in-flight behaviour with the ultimate goal of tuning it's properties to obtain the desired dynamics, Staat et al. (2017). This can lead to improvements in the post ejection dynamics, such as the suppression of subsequent ligament break-up, Bhat et al. (2010). Moreover, the presence of surfactants in the solution can dynamically affect the dynamics upon ejection, and the rheological properties upon ejection, driven by the advection of surfactant and Marangoni flows will be time and length dependent. This is an area of active research as it has been only recently acknowledged that these dynamics effects can lead to dramatic and unexpected results during the formation of drops, Kamat et al. (2020).* However, the addition of polymers, that introduce elasticity, could reduce the droplet velocity to the extreme point where droplets do not detach from the nozzle plate and are pulled back to the nozzle plate. Additionally, too much elasticity can result in the formation of micro-satellite droplets or mist, as found in Tuladhar & Mackley (2008); Tuladhar et al. (2009, 2011). Consequently, an optimum elastic condition exists whereby the liquid filament timely breaks up from the nozzle creating a satellite-free single drop. In rheological terms, both the high frequency linear viscoelasticity (LVE) and the non-linear viscoelasticity (NLVE) shear and extensional behaviours are required in inkjet formulation. In practice, mechanical and capillary rheometers are used to characterise the ink shear rheology while the Piezo Axial Vibrator (PAV) and filament stretching rigs assess the high frequency LVE and extensional rheology, respectively.

2.1 Shear Rheology

In terms of shear viscosity, ink characterisation requires the use of various techniques to reach the process shear rate that is appropriate for inkjet, i.e. the range from 1 to 10^6 s^{-1}. Over this range, Tuladhar & Mackley (2008) demonstrated that most typical inkjet inks exhibit a Newtonian behaviour. However, modern high-particle and high-pigment loaded inks show a Non-Newtonian response at high shear rates. In fact, in these inks, the linear viscoelastic effects of modulus $G'>1$ Pa manifest at frequencies $>$ 100 Hz. These effects are critical for inkjet technologies as they live in the appropriate process shear rates for printing speeds, yet these effects are beyond the range of most conventional rheometers. Such low viscoelastic behaviour is only accessible by the Piezo Axial Vibrator, which is now seen by industry as the only convenient and reliable rheometer capable of reaching such shear rates; further discussions on these topics are found in Mackley et al. (2016); Tuladhar et al. (2009, 2011); Tuladhar (2017); Vadillo et al. (2010). The potential of PAV on the characterisation and differentiation of inks is illustrated in Fig. 2, where a comparison between two ceramic inks from the same supplier is seen at an extended range of shear rates. At low frequency ($<$100 Hz), both inks (i.e. blue and black inks) have similar bulk properties but significant differences appear in the elastic modulus G' and complex viscosity η^* at high frequencies. Additional examples of the use of the PAV in inkjet printing can be

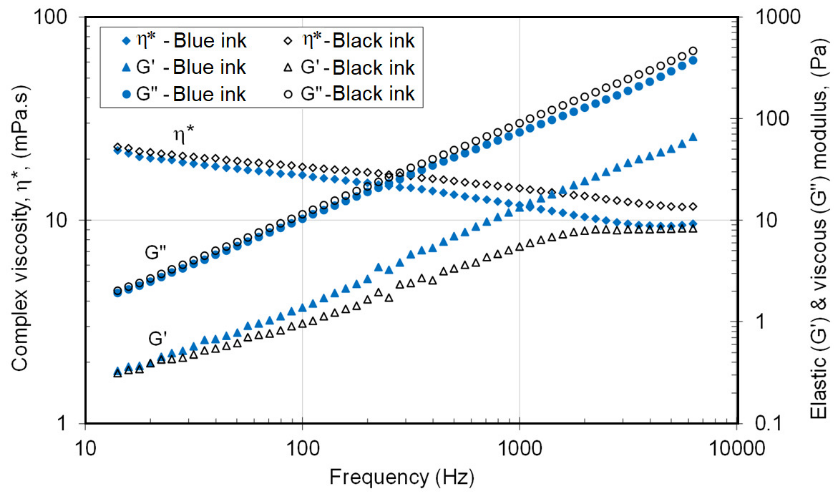

FIG. 2: PAV oscillatory linear viscoelastic data showing subtle differences between two standard ceramic inks (blue and black colour) from the same supplier. It is important to note that these inks present significant differences in the elastic modulus at higher frequencies but otherwise they have similar bulk properties (low frequency), data from Mackley et al. (2016).

found in the literature, e.g. Hoath et al. (2009). Other high-frequency rheological methods, such as the torsion resonator, diffusive wave spectroscopy and micro-rheology, can also access high frequency regimes; these methods are further described in Manson and Weitz (1995); Manson et al. (1997); Schroyen et al. (2019); Vadillo et al. (2010).

2.2 Extensional Rheology

As an ink droplet exits a DoD nozzle of diameter D at a speed u, it undergoes a fast stretching process with extensional deformation rates of the order of 3,000 s^{-1} and shear rates of magnitude $u/D > 10^5$ 1/s, Vadillo et al. (2010). This process jets a high aspect ratio filament (also called a ligature in the inkjet community) that recoils under the capillary forces acting at its surface. As the filament contracts, it might pinch off at one or more locations along its length, creating satellite droplets. Achieving the jetting of a single droplet is done by a careful adjustment of the fluid volume, the jetting velocity, the filament aspect ratio, and the liquid properties. Additionally, filament stretching and break-up, are known to be very sensitive to the extensional rheology at the appropriate time scales of the fluid, McKinley (2005); Tuladhar & Mackley (2008); Vadillo et al. (2010). *Typically, inkjet printing processes are found within the range from 10 to 40* μ*s, Basaran et al. (2013) and Staat et al. (2017).* Several experimental methods have been developed to study the ink behaviour at these time scales. Figure 3 presents examples of three classical thinning behaviours using a filament Capillary Break-up Extensional Rheometer (CaBER). In this method, the extensional viscosity η_{ext} is determined by the thinning rate of a pinching off filament $dD(t)/dt$ by

$$\eta_{ext} \sim \frac{-\sigma}{\frac{dD(t)}{dt}}.$$

An alternative design to the CaBER is the Rayleigh Ohnesorge Jet Extensional Rheometer (ROJER), which is also based on the self-thinning of low viscosity viscoelastic fluids, McKinley (2005). This system operates on an extended range of thinning strain rates and permits a large

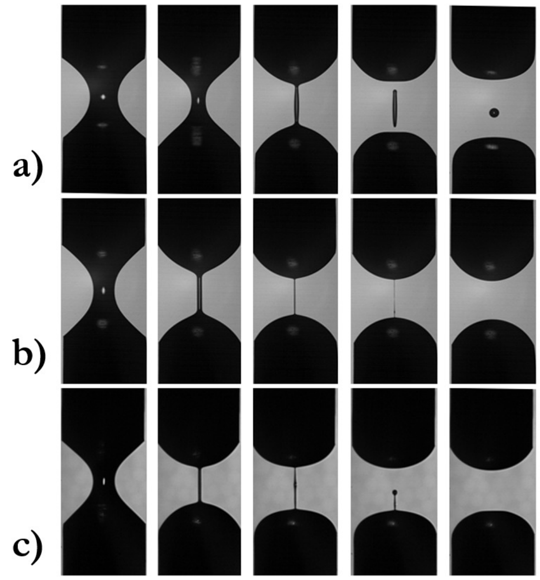

FIG. 3: Sequence of high speed video images showing filament thinning and break-up of model inks after initial stretching in a filament-stretching rig (Trimaster): (a) Newtonian, (b) highly viscoelastic, and (c) optimised viscoelastic, Vadillo et al. (2010).

number of repeats of capillary thinning events in order to reliably access short extensional relaxation times. In a recent work, Wouters et al. (2018) compared the CaBER and ROJER methods concluding that ROJER breakup dynamics is closer to the dynamics observed in an inkjet process, mostly during filament recoil.

The extensional behaviour of the simplest rheological case, a Newtonian solvent, is found in Fig. 3a where the thinning of a liquid filament is followed by the end-pinching that is occurring at both ends of the filament and a single drop is formed at the centre. In contrast, in a highly viscoelastic fluid, Fig. 3b, the thinning dynamics result in a long-lived thin central filament that is reabsorbed into the liquid pinned at the rheometer ends and no central drop is formed. Finally, Fig. 3c presents an optimal viscoelastic behaviour, giving a well-defined stable central filament with short living tails. Extensional rheometry is very useful in the context of inkjet printing, as visible differences in the break-up dynamics are often enough to assess inks in terms of their potential *jettability*; i.e. a quick satellite-free breakup and retraction is better than a long-lived filament that collapses into several droplets. In fact, extensional studies coupled with fast-shear rheology can provide a powerful tool to assess the jettability of an ink. Figure 4 contrasts both the extensional behaviour and the high frequency viscoelastic rheology between two inks: an ink with (good) jetting performance and a non-jetting (bad) ink. In fact, these two UV-curable inks were tested in a Xaar 1001 printhead. The results in Fig. 4 show that the extensional rheometry (CaBER) of the (good) jetting ink displays an ideal thinning behaviour where a well-defined central filament and short lived end tails are formed resulting in the filament recoiling into a single droplet. In contrast, the (bad) non-jetting ink forms a bead-on-string filament that is commonly representative of a highly elastic fluid. These differences are well captured by the high frequency rheological data (graph to the right of Fig. 4), where clear differences are observed between the inks at rates > 50 s^{-1}. During jetting, the bad ink (solid symbols) failed to jet, rapidly flooding the nozzle plate despite adjustments of the waveform shape and the driving amplitude. In contrast, the jetting ink (hollowed symbols) was able to print reliably with a minimal number of

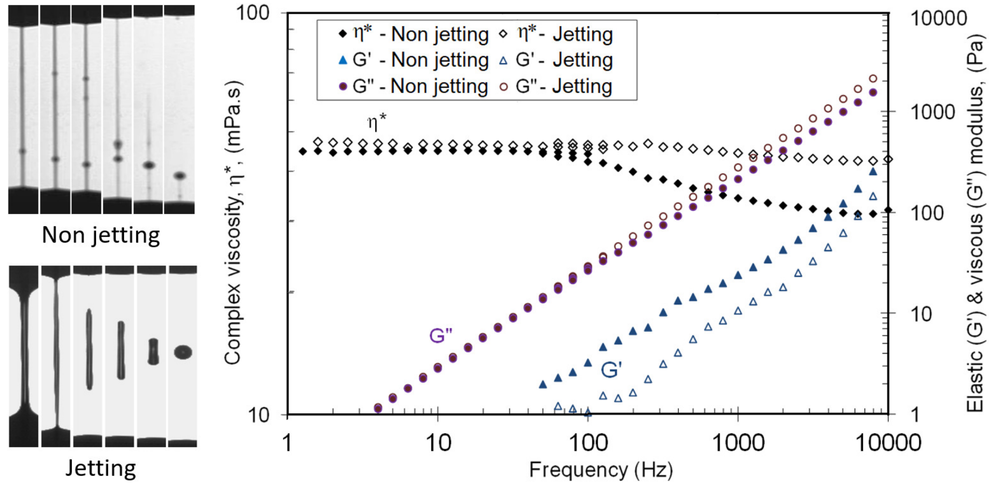

FIG. 4: Extensional behaviour and complex rheology comparison of two UV-curable DoD inks. As seen, these inks have indistinguishable bulk (low frequency) properties, i.e. viscosity and viscous modulus, but their elastic differences at high shear rates prevent one of the inks (solid symbols) from being jetted in a commercial printhead (Xaar 1001), data from Tuladhar (2017).

satellite droplets with a standard waveform.

Accessing the fast-rheology of inks, at the time scales appropriate for drop formation and jetting, enables an efficient ink formulation, and, thus, allows the production of inks with new components, potentially opening new market opportunities. Additionally, ink manufacturers regularly use rheological tools for quality control improving reliability and for extending the length of print runs. Other recent progresses on inkjet systems include the development of novel jetting modes that increase the ink compatibility range of inkjet systems. Some of these advances are detailed in the next section.

3. PRINTING BEYOND THE STANDARD JETTABILITY

As seen in the previous section, the jetting of ink droplets from a printhead is greatly limited by the fluid viscosity. In fact, it has long been established that the breakup of a liquid into droplets can be parametrised by a set of four other variables in addition to viscosity; please see Castrejón-Pita et al. (2013). Therefore, liquid breakup and drop formation are affected by the viscosity, surface tension and density of the ink, a characteristic length (often taken as the droplet diameter D), and the speed of jetting u. In turn, these variables can form a set of dimensionless numbers, e.g. the Ohnesorge number (Oh) defined as the ratio of the viscosity and the kinetic forces arising from surface tension and density (ρ), the Reynolds number, defined as Re$=\rho D u/\eta$, which quantifies the ratio between inertia and viscosity effects, and the Weber number, We $=\rho D u^2/\sigma$, which determines the ratio between inertia and surface tension. *In industry, modern non-invasive optical techniques such as Phase Doppler Interferometry and Holographic Velocimetry have the potential of becoming standard methods for measuring the velocity and size of droplets, which are the critical variables to estimate the Reynolds, Weber and Ohnesorge numbers, Muliadi et al. (2010) and Martin et al. (2015). Moreover, satellite dynamics and post-impact behaviour such as droplet rebound or splashing can also be analyzed with these techniques.* As shown by Derby (2010), these dimensionless numbers result in an upper and lower bound for acceptable

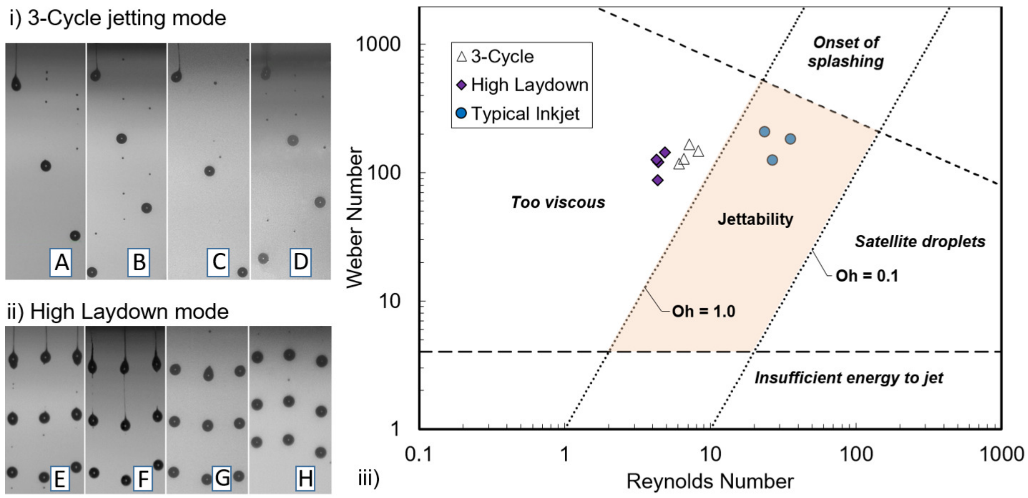

FIG. 5: The jetting of highly viscous inks from a Xaar 1003 printhead. i) 3-Cycle mode at 7 dpd: A, B, C and D show the jetting behaviour of 64.9 mPa s, 60.0 mPa s, 66.1 mPa s and 53.3 mPa s inks, respectively. ii) High Laydown mode at $\sim$ 30 kHz: E, F, G and H exemplify the jetting of 96.8, 95.4, 98.1 and 90.7 mPa s inks, respectively. iii) show the Weber and Reynolds jetting (printability) parametric space as described by Derby (2010). These inks are resin-based and their rheology shows a purely Newtonian behaviour, Jackson et al. (2019).

droplet formation in inkjet printing. The region in which drop formation is acceptable for inkjet, i.e. not too many satellite droplets and droplets at a speeds of $u \approx 5$ m/s, has been called the *jettability* or *printability* region, as illustrated in Fig. 5, and is commonly shown in terms of the Ohnesorge number in a We & Re space. The Oh number is defined as

$$\mathrm{Oh} = \frac{\sqrt{\mathrm{We}}}{\mathrm{Re}} = \frac{\eta}{\sqrt{\rho\sigma D}}.$$

When jetting at Ohnesorge number values greater than 1 (Oh $>$ 1), i.e. viscous forces are greater than kinetic forces, see the flow within the ligature into a droplet impeded, preventing breakup. On the contrary, when the viscosity is low, surface tension high, and kinetic forces dominate, Oh $<$ 0.1, and the ligature breaks up into many smaller droplets; this results in the formation of undesirable satellites.

For typical drop-on-demand inkjet inks in the printability region, the maximum viscosity permitted, before droplet breakup is impeded, is approximately $\eta \approx$25 mPa s. However, recent developments in waveform design and printhead drives have pushed beyond this viscosity limit demonstrating the jetting of inks with viscosities in excess of 50 mPa s. In fact, two modern jetting mechanisms, i.e. the *3-Cycle* and the more efficient *High Laydown* modes, have achieved printing at Oh $>$ 2, see Jackson et al. (2019). These modes are explained below.

3.1 3-Cycle Mode

The conventional method for driving shared-wall piezoelectric drop-on-demand printheads is often referred to as the *3-Cycle mode*, due to the requirement to print the channels in a staggered arrangement of three nozzles. In brief, given that the actuating element is a wall shared between two neighbouring channels, it is impossible to generate a positive (jetting) pressure in two neighbouring channels simultaneously. By synchronously actuating every third nozzle, and then shifting over another set by one nozzle and cycling through the ejection waveform to the next set of every third nozzle, the conflicting pressure requirement is removed.

TABLE 1: Ink properties‡ successfully jetted in the 3-Cycle printing mode.

Ink	Temperature (Celsius)	Viscosity (mPa s)	Density (kg/m^3)	Surface tension (mN/m)	Re	We	Oh
A	70	64.9	1.106	36.4	6.56	128.6	1.73
B	30	60.0	1.121	28.5	7.19	166.5	1.79
C	45	66.1	1.043	37.4	6.07	118.1	1.79
D	35	53.3	1.142	32.9	8.25	147.1	1.47

‡ Here the viscosity is reported at the jetting temperature (second column).

The open, low restriction actuator design, and the continuous high flow recirculation rate of Xaar TF Technology† means that the channels and nozzles are constantly replenished from an actively-driven ink supply system rather than relying on the capillary flow alone; this is increasingly important at high ink viscosities, Crankshaw (2016). Coupling internal recirculation to an optimised acoustic efficiency of the actuator, creates a system capable of jetting Newtonian ink viscosities in excess of $\eta = 50$ mPa s, as demonstrated by the X1003 GS12 printhead shown in Fig. 5 with the viscosity values seen in Table 1. In this mode, jetting and drop formation can be achieved at Ohnesorge values greater than Oh = 1.4, and as much as Oh = 1.8 for inks with a $\eta =$ 60 mPa s viscosity. Good printability behaviour is seen across viscosities that are well beyond the traditional ideal range of $\eta = 10 - 20$ mPa s.

3.2 High Laydown Mode

The High Laydown mode is a modern *single-cycle* firing scheme developed for Xaar shared-wall piezoelectric drop-on-demand printheads that makes much more efficient use of wall movements. Through careful control of the electrode driving potential, and by fully exploiting resonances of the actuator, all nozzles are active at once. This mode jets neighbouring nozzles in the same cycle time, while also increasing the drive voltage efficiency. This means that ejection rates can be achieved up to 5 times higher than the standard 3-Cycle mode. The increased efficiency of this ejection mode implies that the jetting viscosity can be increased further before the actuation voltage limit is reached. As seen in Fig. 5 and in Table 2, this mode permits the jetting of inks with viscosities beyond $\eta = 90$ mPa s. In fact, the good jetting behaviour of high viscosity inks can be achieved at room temperature, e.g. ink F, as well as at elevated temperatures, e.g. ink E, and for a wide range of surface tensions. In terms of dimensionless numbers, results indicate that it is possible to jet fluids with Ohnesorge number values that are greater than Oh = 1.7, and as high as Oh = 2.6; a significant increase above the limit of Oh = 1.0, which was established by Derby (2010).

The evidence demonstrates that ink jetting can be achieved beyond the limit of printability (as conventionally defined). This is a significant result for industry, as inkjet technologies aim to move into other markets that are traditionally dominated by other methods, e.g. screen printing, and that are capable of printing high-viscous inks. The full capabilities of the 3-cycle and High

† The TF Technology is a registered trademark of Xaar plc in the US and other countries

TABLE 2: Ink properties successfully jetted in High Laydown printing mode.

Ink	Temperature (Celsius)	Viscosity (mPa s)	Density (kg/m^3)	Surface tension (mN/m)	Re	We	Oh
E	60	96.8	1.100	52.2	4.35	87.6	2.15
F	25	95.4	1.078	36.7	4.27	125.6	2.62
G	33	98.1	1.089	36.4	6.56	128.5	1.73
H	27	90.7	1.148	28.5	7.19	166.5	1.79

Laydown jetting modes are not yet completely understood, and further research is required to determine their maximum printing viscosity or speed. Great advances have been done in piezoelectric acoustics and in the design of inkjet systems but it is clear that these improvements alone are not responsible for the jetting at the maximum viscosities seen in Table 2. According to Bruce (1976), the pressure gradient ΔP causing the flow of a Newtonian fluid through a cylindrical nozzle is given by

$$\Delta P = \frac{\rho u^2}{2} + 32\frac{\eta u l_{nozzle}}{d_{nozzle}^2} + 2\frac{\sigma}{d_{nozzle}}, \tag{1}$$

where l_{nozzle} and d_{nozzle} are the nozzle length and diameter, correspondingly (additional terms are required for conical nozzles but the following analysis stands correct). Evaluating Eqn. 1 at conditions typically found in inkjet systems, e.g. $u = 5$ m/s, $d_{nozzle} = 50$ μm, and $l_{nozzle} = 50$ μm, clearly indicate that the pressure contribution to viscosity losses are *about* 20 times greater than that to inertia or surface tension. Therefore, in an inkjet system, most of the piezoelectric actuation is viscously dissipated, and, thus, the upper limit on the jetting viscosity appears to be restricted, as commonly assumed, by the driving voltage of the printhead. The viscosity losses vary linearly with the ink viscosity; consequently, jetting a fluid with a $\eta = 100$ mPa s practically requires actuations that are 5 times stronger than that for a $\eta = 20$ mPa s ink. Although considerable improvements have been made in piezoelectric acoustics and power, the community speculates that *high viscous printing is the result of a complex interplay of forces during jetting and breakup. Indeed, the breakup of viscous fluids has recently been in the spotlight due to the interplay of inertial, viscous and capillary forces, all playing a role at different time and length scales. Depending on the fluid properties, and the initial conditions upon jetting, the route to breakup and drop formation can transition through a series of different regimes mandated by different scaling laws in turn controlled by the flow within the thinning neck, Castrejón-Pita et al. (2015). Moreover, it has been theorised that the local dynamics at the pinch-off may be further affected by secondary action of the piezoelectric elements such as harmonics, nonlinear acoustical effects, and the recirculation of ink within the printhead, effectively permitting drop formation beyond what is theoretically possible. The consensus of industry is that further research is required in this field.*

Apart from the liquid properties, the expansion of inkjet methods into other fields has been limited by a variety of other practical issues. In the following section, the challenges for monochrome continuous inkjet and colour digital drop on demand printing on the quality of printing are explored.

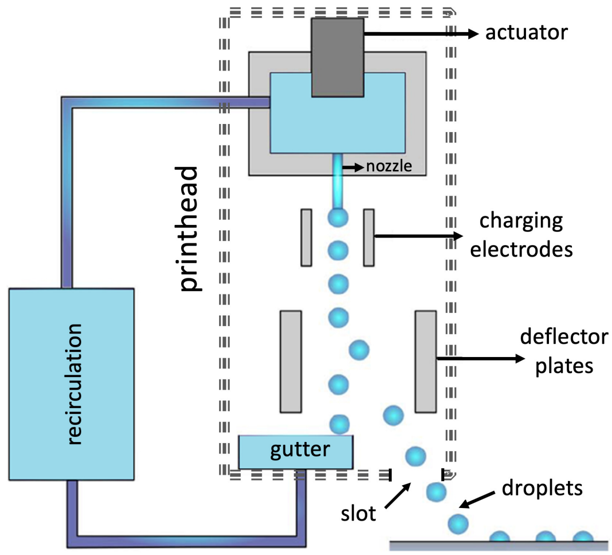

FIG. 6: Schematic diagram of a continuous inkjet printing system.

4. PRINTING QUALITY

With more than 45 years of use, continuous inkjet printing is a mature technology ubiquitous in day to day products. In this long history, CIJ has mostly been used alongside production lines for the fast-marking of merchandise and packaging. As technology has moved forward so has the speed of production lines leading to ever increasing printing speeds. For continuous inkjet printing, this translates into an increase in drop frequency. To achieve this, while maintaining satellite free breakup conditions, the drops are physically closer together, smaller in diameter, and carry larger electrical charges to achieve the same deflection heights as for low frequency printheads. These requirements often have a negative effect on the printing quality. Increasing user demand for print quality implies that drops need to be placed closer together on the substrate, e.g. the printing of QR codes requires high-placement control of the printed droplets to obtain a good grade.

In continuous inkjet printing, charging electrodes apply a charge, *of approximately* 6×10^{-15} *Coulombs,* to a drop as it breaks away from the jet. The drop is then electrically attracted to a deflection plate and then deflected through the printhead until it hits the substrate. *Uncharged drops travel straight through the printhead, between the electrodes, hitting a gutter where all the non-printed droplets are recirculated and reused*; this is illustrated in Fig. 6. The extent to which a drop is deflected is dependent on the charge applied by the charging electrode and the velocity of the jet, which, in turn, is dependent on the pressure at the printhead. Importantly, the pressure of the ink, at the nozzle, controls the distance between drops, but instabilities within the printhead can degrade the breakup of the jet introducing satellite droplets.

Looking only in the direction of deflection, print quality is determined by the factors listed in Fig. 7. In fact, these factors are not isolated from each other but many of them are coupled in their effects on the printing quality. For example, drop size affects the jetting speed, or more precisely, the deceleration of the droplet by air drag as it travels though the printhead. The longer the throw distance is (distance from the printhead to the substrate), the more the drop decelerates before impacting the substrate. Drop deceleration is undesired in the printing of small

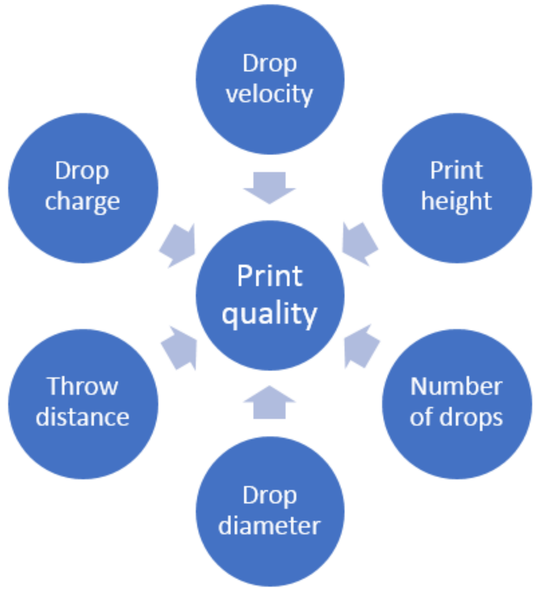

FIG. 7: Factors influencing print quality in a continuous inkjet printer

droplets as the surrounding airflow can interfere with their trajectories and, consequently, with the printing quality, Rodriguez-Rivero et al. (2015). Another important factor is the number of jetted drops, i.e. the printing frequency, as this determines the physical spacing between the drops in flight. A higher printing frequency brings the drops closer to each other, which, in turn, increases the repulsion forces between them. *Drop velocity, diameter and proximity to the substrate all contribute to the aerodynamic interactions between the drops and to the quality of printing, Rodriguez-Rivero et al. (2015) and Hsiao et al. (2012). Therefore, as a drop passes through the gap between the printhead and the substrate, it disturbs the air behind causing the following drops to change speed or flight path. These effects are coupled and depend on the separation of the droplets (printing frequency) and their speed.*

Maximising print quality in a CIJ involves a balance between the printhead design and the control provided by the electric charge applied to each drop. The drop charge controls not only the deflection produced by the charging electrode but also the repulsion between drops. In addition, the throw distance and some of the aerodynamics within the head are dictated by the printhead design and geometry. Getting the balance by maximising the drop placement accuracy via adjusting these variables is essential.

Print quality encompasses more than just drop placement. The quality of each printed dot on the substrate is affected both by the ink and the substrate properties. The printed shape (circularity), colour, density, adhesion and size all dictate the print quality. Perfectly placed droplets would not be acceptable in an application if the ink rubs off the substrate or if it is too faint to be read. This is particularly important with the rapid increase in use of QR codes. In these prints, the drop size and density can make the difference between a pass and fail read. With a move towards smaller, high resolution QR codes, printed by CIJ, the print quality is being pushed to its limits.

Print quality in full colour digital (drop on demand) printing is dictated by a number of other factors. In fact, in this technology, distinguishing between different features of print quality and

FIG. 8: Examples of dot size, bleed, line quality and mottle for a full colour sample.

deciphering whether they qualify as a pass or fail is a significant challenge. This is, because many aspects of print quality are subjective, and different viewers/users can have contrasting opinions of what is an acceptable printing quality. However, the consensus among industry is that the main aspects contributing to print quality, in a full colour digital print, can be divided into three categories: i) mechanical, ii) ink effects and iii) workflow and colour management.

Both the printhead design and the ink formulation determine the print quality but the first challenge during development is to decouple the two. Mechanical performance can be assessed by printing a well-designed print target or pattern. Colour registration, inoperable nozzles, misfiring nozzles and encoder accuracy can all be detected by image processing methods that identify present, or missing, features in the correct location of a target print. Another aspect considered in the print quality is the waveform that is driving the jetting, as this determines the amount of ink put down on the substrate, the speed on impact, and the gradient of each colour. In general, each ink is run with a particular waveform tailored to maximise the colour gamut whilst delivering the correct droplet size while keeping satellite free conditions. Assessing the size and quality of the printed drop is a good assessment of waveform performance.

Ink properties are assessed in terms of their interaction with the substrate and with other inks. Here, the inter-colour bleed is a key consideration on the image sharpness, but the dot size, bleed and mottle all affect the printing quality. Inter-colour bleed is controlled by the interflow of ink between two colours, and can result in the blurring of its boundary or an increase in line width for single-colour prints. In fact, line quality is often quantified through the measurement of the line width. The raggedness of a printed line gives an indication of the effective ink flow on the substrate and is measured as the deviation of the edge of a line from its ideal position. Mottle is the change in density of a region of solid colour, and an inappropriate control makes a printed surface appear uneven and blotchy. On a smaller scale, graininess shows the same effect, giving a speckled appearance. Understandably, both mottle and graininess are symptoms of defective substrate interactions. Generally speaking, these effects are amplified on rough surfaces.

The colour gamut is often measured accurately using a reference standard, such as the Fogra wedge, where the gradient of a colour is assessed as it transitions from zero to a 100% ink density. Mottle, image sharpness and banding can also be improved using a screening process, while printing decreasing sized text can identify the minimum size readability achieved. Quality targets for each application may vary, i.e. for large scale printing sharpness and line raggedness are less important as a reader might not perceive these effects from viewing them at a greater distance. However, for small scale packaging these become the priority, with the readability of minute text being essential.

The final stage during quality assessment is to quantify the impact of the workflow and colour management for the digital press. This generally includes ripping an image, screening it and applying other validation work, such as calculating ink limits to prevent too much or too little ink being put down. Workflow and colour management are used to optimise a digital image, and the printer settings, in order to give the best possible printed image quality. This includes ripping, screening and setting ink limits. This is a very complex process which determines the droplet placement, timing and size, and is highly dependent on the waveform used to generate the drops. This can control the colour gamut, density and even alter the appearance of the image. Other printing quality controls include the assessment of ink adhesion and material compatibility, and some of these points are discussed in the next section.

5. CURING, DRYING & ADHESION

Ink designers are continuing to push the boundaries of ink functionality to meet the needs of the packaging industry. One trend is focused on the need for better traceability and codes that provide tracking and security information. Often a key driver is legislation, such as the Falsified Medicines Directive of the European Union, or its equivalent in other regions, where traceability and unique identifiers are required on packaging. In fact, the need for more information in printed codes and labels has seen some replacement of coding equipment from continuous inkjet and laser to thermal inkjet (TIJ), as it provides a higher resolution.

In TIJ printing, droplets are ejected on demand upon the generation and expansion of vapour bubbles by the action of fast-acting heating elements located near the nozzle, Kobayashi et al. (1981). Thermal inkjet (also known as bubble-jet in the 80s) was the first DoD method to be successfully commercialised as a low-cost inkjet printer and it has dominated the colour home-printing market for decades. One of the main limitations of this technology is, due to the working principle, its ink chemistry as most inks are aqueous- or water-based inks which may be seen as an obstacle for novel functional inks, Le (1998). TIJ technology provides good quality codes at high resolution but is not ideally suited to coding and marking because it has a relatively low speed when compared to competing technologies. As in DoD, TIJ operates with an open nozzle technology, that often needs capping and wiping to prevent ink from drying in the nozzles. Such strategies are undesirable in an industrial application because they reduce system availability. The inkjet industry has developed solutions to avoid the partial drying, evaporation or curing of inks at the printhead. Small office and home office (SOHO) market inkjet technologies tend to be designed solely for the printing onto absorbent substrates, i.e. paper, and are frequently water based, in which the long drying time helps with the so-called *decap time*[‡].

Industrial inkjet companies have developed a range of solvent based TIJ inks aimed at reducing drying time, and are improving adhesion on non-absorbent substrates, whilst maintaining a reasonably long drying time, as discussed by Brown et al. (2011); Cross et al. (2014); Selmeczy et al. (2016). All of the various formulations use a combination of fast and slow drying solvents to extend *decap* times as well as the addition of a surfactant. The mechanism for prolonging the *decap* time appears to centre on keeping the nozzle wetted at all times. In this solution, the fast solvent evaporates, while the slow drying one keeps the nozzle wet and unblocked; the surfactant spreads the ink over the nozzle improving wettability.

Food packaging has seen the widespread adoption of low surface energy materials incorporated into multi-layer thin films. A typical high barrier thin film can incorporate up to 11 layers containing food-grade polymer (e.g. polypropylene) for safe food contact, a metal foil (e.g. aluminium) to provide a barrier against oxygen, light, microorganisms, odour and taint, an abrasion

[‡] *Decap* time is the time that a cartridge can remain uncovered and yet produce a high-quality print without the need for a wipe or clean to refresh the nozzles

resistant layer (e.g. nylon) for strength and an extra layer that provides both toughness and the printing surface (e.g. polyethylene). Package print layers are often coated with a thin layer of polymer or varnish to give a bright high-gloss finish to enhance the brand information. An additional final layer is often added to give a low energy surface in order to prevent the accumulation of dirt and dust on the package. Whilst the use of multi-layer thin films has a positive impact on product weight and packaged product shelf-life, it presents a challenge for manufacturers of coding and marking equipment. The low energy substrates intrinsically prevent good adhesion from a wide variety of inks. The glossy print has also led to more widespread use of pigmented inks in inkjet in order to increase the contrast between the printed code and the packaging. Various approaches have been taken to improve adhesion, covering a very wide range of polymer architectures. One approach has been to develop novel polymers which attempt to produce morphologies that can key into low energy surfaces, such as the use of non-covalent bonding interactions and self- assembling molecules or hyper branched GRAFT copolymers, Hart et al. (2015) & Canning et al. (2017). Multi-layer films pose another problem even for well adhered inks: these are inherently flexible, which requires a degree of flexibility from the coding ink, e.g. polymers of vinylidene chloride are commonly used as flexible wrapping films in the food industry. Ink formulations have also been used to address this issue and also resist processes commonly found in food processing such as steam sterilisation or freezing, De Saint-Romain (2014).

Chemists and formulators have also provided inks with useful functionalities such as a time-temperature indicator, Bourdin and Morgan (2016). A time temperature-indicating ink, is developed to match the degradation of foodstuffs. This way, the ink changes colour depending on its exposure to different temperatures for different lengths of time, so that it changes colour quickly if the temperature is high, and slowly if kept cold, similar to the behaviour of fresh foods. The time-temperature indicator is printed and then activated by exposing it to uv light, causing the dye to undergo a reversible molecular transition, causing the colour change. The rate of the reverse reaction depends on temperature, but also on the dye suspension in its polymer matrix, which allows the ink chemist to control the rate of colour change by choosing a suitable polymer or blend of polymers to match a specific food product.

Inkjet inks have also been formulated to undergo chemical changes, e.g. inks have been formulated to indicate the presence of oxygen. In these inks, a chemical reaction occurs between the dye and the oxygen, for example, to show that a food package has leaked, Hurme and Sipilaeinen-Malm (2009), or that it is undergoing degradation. Such inks are suited to drop on demand systems, where the ink can be isolated from the atmospheric oxygen. A further ink formulation is used for printing on wet bottles, Harries et al. (2017). In this application, the ink contains a pigment for a high contrast against the brown or green glass commonly used for beverages. Additionally, the ink contains reactive polymers that allow the ink to adhere well to the glass bottle even if it is wet, as a result of washing or condensation.

The last ten years have seen a resurgence in ink development, where formulation goes beyond the remit of jettability. As discussed in the introduction, this interest coincidentally follows the resurgence in academic scientific studies of inkjet technologies that started 15 years ago. It is clear that a good grasp of the physical parameters, which allow good jetting and surface wetting, has allowed ink development chemists to be more adventurous in their use of polymer architectures, morphologies and reactive chemistries to provide industrially useful results. *In fact, surface wettability is a very active area of inkjet research as the substrate characteristics are of crucial importance in the post-impact dynamics of an ink drop. This will not only determine the final footprint but also whether (partial or complete) rebound is observed as it would be the*

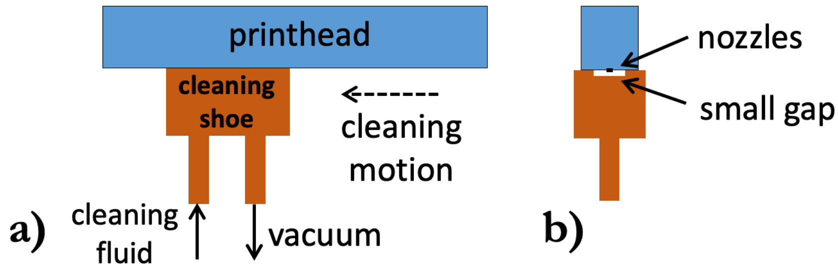

FIG. 9: Schematic view of a non-contact printhead cleaning method: a) shows the front view and b) the side view from the length of the nozzle plate

case if the substrate is superhydrophobic, Josserand & Thoroddsen (2016) - or repellent. There exists a collection of empirical, semi-empirical and theoretical works aiming at predicting the droplet maximum spreading diameter as a function of their impact speed, size, fluid properties and contact angles, Josserand & Thoroddsen (2016).

6. RELIABILITY & CLEANING

In a commercial environment, a printer is expected to be ready to print whenever it is required and is expected to carry on printing for as long as necessary to complete an order. Business profitability depends upon achieving their target utilisation. Compared with analogue printing methods, inkjet printing is a hugely complicated and delicate process, with the printheads being probably the most delicate and critical components in the system. Most of the other components in an inkjet printer can be selected from mature technologies, and a reasonable choice can be made between cost and reliability. The machine architecture can also be designed with appropriate levels of robustness and redundancy. Printheads, unfortunately, are at what is sometimes referred to as the *bleeding edge* of technology and require careful treatment. A key to achieving good machine reliability is to keep the printheads clean and undamaged. In fact, cleaning and maintenance must be designed into an inkjet printer from the outset and not added as an afterthought.

Physical damage to printheads may occur if they are struck by the substrate: measures are normally put in place to reduce the likelihood of this happening. Typically, devices are installed to detect any approaching raised piece of substrate so that the substrate transport system can be stopped or the printheads rapidly raised to avoid the danger. A less obvious threat to the printheads is the ink itself. A well-formulated ink should pose little risk, but a bad batch of ink, or an incompatible ink (different colour, different manufacturer), may result in the formation of large clumps of pigment particles, which can block the printheads. Radio frequency identification and traceability of ink are now implemented in industrial printing systems to validate the ink before an inlet valve opens to admit the ink into the system. In addition, filtration of the ink, as it circulates through the ink system, can help prevent blockages in the printheads: a filter is easier and cheaper to replace than is a set of printheads.

Over time, ink mist, dust, paper fibres and partially-dried or partially-cured ink will accumulate on the nozzle plate of a printhead and make the jetting unreliable. The aim of cleaning is to prevent this from happening, or to restore the heads to a clean state. For industrial inkjet printing machines, the scale of cleaning is large and the consequences of human error greater. For this reason, most industrial inkjet printers have one or more automatic cleaning systems for the printheads. These provide more consistent and reliable cleaning than a human operator, but

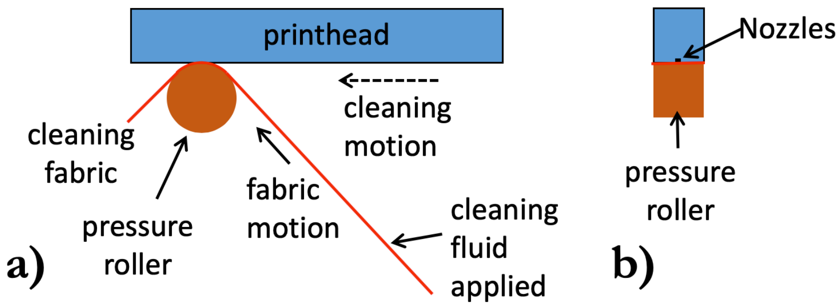

FIG. 10: Schematic view of a contact printhead cleaning method: a) shows the front view and b) the side view from the length of the nozzle plate; please note that the fabric is in direct contact to the nozzle plate.

are themselves not without issues. To paraphrase Juvenal: "But who will clean the cleaning station?" Normally, this task is given to a skilled machine operator, who has the necessary level of training to ensure that the cleaning system is adequately maintained.

There are two common cleaning methods for printheads, i.e. contact and non-contact. Non-contact cleaning is typically achieved by a *cleaning shoe* where vacuum is applied to the printhead to draw ink through the nozzles and to draw contaminants from the nozzle plate, Fig. 9. The technology is considered to be non-contact as a small gap exists between the printhead nozzle plate and the shoe in the vicinity of the nozzles, as illustrated in Fig. 9b. In an elaboration of this method, a cleaning fluid can be injected so that contaminants are washed from the nozzle plate. An advantage of non-contact cleaning is its gentleness as it is unlikely to damage the nozzle plate. However, it is also a disadvantage as it may not be able to remove partially-dried or partially-cured ink. A direct contact cleaning system is often used for more thorough cleaning. A direct contact cleaner typically uses a roll of fabric which is wiped along the nozzle plate, illustrated in Fig. 10. As the wiping progresses along the printhead, the fabric advances to maintain a supply of clean fabric in contact with the printhead. Optionally, a cleaning fluid may also be applied to the fabric. *Typical cleaning fluids are normally designed to dissolve partially dried or partially cured inks of the type being used. For pigment-based inks, the cleaning fluid should be compatible with the inks in the sense that it does not destabilise the pigment dispersion and cause the pigment particles to agglomerate; an example of such fluids is the trihydroxysilane-based solution found in Fassler et al. (2001). Cleaning fluids must also not cause damage to the printheads, so are normally tested for compatibility with all printhead materials into which they are likely to come into contact.* Although most cleaning actions are automated, there will still be occasions where human intervention is required.

A common feature of droplet formation in inkjet printing is the generation of small satellite droplets. Some of these may make their way onto the substrate, but others do not and can accumulate on adjacent printheads, possibly causing contamination of pure colours. Satellite droplets can also land on other parts of the printer where they can produce a range of problems including damaging the surrounding electronics, flooding the nozzle plate, being re-ingested partially-cured into the nozzle and intensifying aerodynamic effects around the print gap. For low-throughput printers, the rate of the generation of satellite mist may be so sufficiently small that any stray ink build-up can be cleaned up during routine maintenance. However, in high throughput industrial inkjet printers, the capture of satellite mist by means of a vacuum extraction system is preferred. A typical mist/satellite extraction system comprises a collecting nozzle close to, and downstream of, the printhead(s), a mist filter and a fan, illustrated in Fig. 11. After

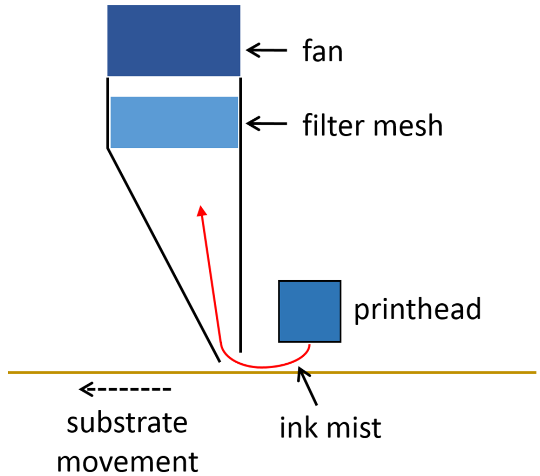

FIG. 11: Schematic view of a typical extraction system used in inkjet systems to collect satellite mist; the fan produces the vacuum required for the extraction.

some period of continuous operation, the filter on the extraction system needs to be removed and replaced periodically.

Effective cleaning is paramount to the continuous operation of inkjet systems. As described, the technologies used to achieve this are basic, but essential, and must be incorporated into the printer at an early stage of the design. It is desirable to automate as much of the cleaning as possible, although human intervention will always be needed.

7. CONCLUSIONS

In this manuscript, a series of factors currently affecting the reliability, compatibility and quality of inkjet processes have been described and discussed. The continuous reliable operation of printheads and printers depend on a large variety of aspects, including ink formulation, the actuator and architectural designs, material compatibility and cleanliness. In fact, there is a trade-off between these factors, the quality of print and the throughput of an inkjet printing machine. Most industrial inkjet processes normally operate at the lowest printing quality acceptable in order to maximise the throughput of a printer. By doing so, the total output of the machine, and, hence, profitability can be maximised. The customer also benefits by receiving prints of an acceptable quality at the lowest cost. However, the quality of printing is constantly being driven forward and the need for smaller, faster, higher quality images must be met by printer manufacturers. Understanding the system properties, which control and limit print quality and reliability, are essential for designing and optimising printers to give the best possible results. Consequently, controlling and characterising these factors have become critical in the inkjet world.

In general, the quality and throughput of a machine are selected during its design by the choice of the native nozzle and drop sizes, the number of printheads used, and the way in which the substrate and printheads move and travel relative to each other. The droplet size must be reduced to improve printing quality but reducing the droplet has the effect of reducing the printing speed as a reduction in drop volume results on a much bigger reduction in the printed surface area. Therefore, an increase in the printing frequency is required to keep up the printer's throughput. However, smaller and close together droplets exacerbate aerodynamic (and electrostatic) interactions. *In an industrial environment, aerodynamic effects are mitigated by adjusting the speed of the substrate, the throw distance, the layout arrangement of the printheads and by the raster. In fact, aerodynamic effects on inkjet are active areas of industrial research, motivated not only by the desire to print onto non-flat, shaped and rugged substrates but also by the need to achieve longer throw distances, Bayona et al. (2015), Rodriguez-Rivero et al. (2015) and Hsiao et al. (2012). However, a solution that takes into account all these factors and optimises the overall process, speed and quality of printing has yet to be developed and used at industrial scale.*

The effect of the transitional behaviour seen in thinning liquid filaments prior breakup on the formation of inkjet droplets is a topic of great interest for printhead manufacturers. This interest exists because the inner dynamics of jetted filaments could be theoretically controlled to induce an inertial, inertial-viscous or inviscid breakup, without the need to introduce complex rheology. Further research is also required in the development of instruments to characterise inks at the time scales relevant to current and future applications of inkjet. PAV and extensional rheometers have recently gained access to rheological data at the few microsecond scale, but conventional tensiometers are still limited to report the dynamic surface tension at surface lifetimes in the tens of milliseconds range, Hoath et al. (2015). In fact, similar restrictions exist in inkjet-based tensiometer methods where the surface information is accessible at the hundreds of microsecond range from the analysis of droplet oscillations. These approaches are still far from the time scales relevant to inkjet (< 1 μs). Consequently, the inkjet community would benefit from the further development of these kinds of instruments.

Finally, reliable long printing runs are accomplished by cleaning and servicing. In fact, reliability directly influences the cost of prints for a given substrate. Additionally, the cost of print is determined by the costs of consumables (mainly ink), the costs of the power needed to run the machine (electricity, gas, compressed air), and the depreciation cost of the machine. By maintaining a high utilisation of the printer, the depreciation cost can be amortised over more prints, thus reducing the cost per print.

In conclusion, the current emphasis in the literature on drop formation is helping the field of inkjet to optimise existing technologies. However, the industry is also looking for a solution that breaks the paradigm: jetting satellite-free drops at a faster rate than previously possible.

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