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Predicting the jetting performance of an ink and issues associated with translating a printable ink in the lab to large-scale industrial manufacturing

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Abstract

Inkjet technology is advancing to allow for more printable materials (e.g. higher viscosity inks can now be jetted). However, there is an issue of materials that can be printed in the research lab becoming unprintable when scaled up to the industrial scale. In this review, the differences between inkjet printers that are used in academic research and those that are used in industry are discussed. In academia, there is a focus on exploring new applications where inkjet can provide an advantage, which requires the use of simple inks (e.g. a solvent). In industry, the focus is on productivity, which results in inks containing a range of additives that ensure regular, reliable printing over long cycle times. Therefore, the principal question is, how does one gain confidence in an ink's printability regardless of the printer or scale of work employed? Inkjet research uses small-scale printers whereas industry uses large-scale printers. The scale of work leads to printing conditions specific to the machine used that can change the printability of an ink (as it translates from academia to industry). This difference in printing conditions is creating a gap between academic inkjet research and industrial inkjet development. To understand how to traverse this gap, all the factors that affect the printability of an ink need to be evaluated and understood. Printability is determined by fluid properties, rheology, and printing conditions. Thus, this review investigates printability. By understanding all the factors that affect printability, and how research-lab inkjet and industrial inkjet differ, an improvement in the transfer of newly researched inkjet systems into the industrial markets can be achieved.

Keywords: Ink formulation, inkjet printability, rheology, additive manufacturing, jet-ability performance

1. Introduction

The inkjet printing industry has grown rapidly; from its start in the 1970's to today when most offices and many homes have inkjet printers (Le, 1998). Equally, inkjet has become dominant in graphics production, with examples including newspapers, product labels and billboard posters. Inkjet printers are also used for industrial expiration date labelling, security features and identification numbers unique to their host. This illustrates one of inkjet's strongest properties: its capacity for real-time customisation and variable data printing that allows incremental changes needed for batch marking (Martin et al. 2008). Thus, industrial inkjet printing has become integral to modern manufacturing.

One of the most appealing advantages of inkjet printing is its ability to create features without the need for stencils, templates, original masters or moulds. This advantage eliminates several production steps (e.g. the long process of making moulds) and turns inkjet printing into a highly efficient means of actualising a design. This efficiency is highly desired for many applications. Thus, much research has been done to understand what makes a material printable and to expand inkjet technology into printing new materials. As inkjet is researched, new printers and inks are constantly being developed, allowing for the industry to expand by printing polymer resins, nanoparticles, patterns on textiles, live cells and ceramics, to name some examples (Basaran et al. 2013; Calvert 2001). Additionally, when using specially formulated inks, inkjet printing is not restricted to 2D images. Layers composed of a repeating image, or a new image, can be placed on top of one another, to create 3D objects, which enables inkjet technology to be employed in a wider variety of applications.

As inkjet research continues to expand inkjet applications there is more demand to use inkjet technology for large scale production. However, upscaling new inkjet discoveries has proven to be difficult. Some inks become unprintable when upscaled to industrial production, despite working perfectly in small-scale research labs. This issue is slowing the growth of inkjet technology as a whole and limiting the transfer of new discoveries to large-scale production.

2. Inkjet printing technology

Inkjet printing is an additive manufacturing technique that selectively controls the deposition of liquid droplets onto a substrate. Although there are now many different types of inkjet printing all can be divided between two classifications: Continuous inkjet, where there is a continuous stream of ink, and Drop on Demand (DoD) inkjet, where droplets are produced only when needed (Hoath, 2016; Magdassi 2010). These two major classifications can be further divided into subcategories based on the printhead type (Shah et al. 2021). However, the most common digital inkjet printer type in the market today is the piezoelectric DoD printhead (Sohn 2023).

Piezoelectric DoD printheads operate via the expansion and contraction of a piezoelectric element that can be inside or next to the ejection chamber of the printhead to eject droplets. The expansion and contraction is controlled by an applied voltage, thereby allowing for complete control over the ejected droplet placement, volume, and speed (Shin and Korvink 2012; Liu et al. 2013). Piezoelectric DoD printers are also compatible with a wide variety of printable materials, such as live cells, pharmaceuticals, nanoparticles, organic light-emitting diodes, polymers and more (Kim et al. 2016; Boehm et al. 2014; Beedasy and Smith 2020; Calvert 2001). Since piezoelectric DoD printers do not use heat, unlike thermal DoD, to eject droplets this allows for more freedom in ink formulations. Due to the high degree of droplet control and high degree of ink freedom piezoelectric DoD printers have become the fastest growing inkjet division on the market. Which is one of the reasons the over $100 billion inkjet industry is expected to double within the next 10 years (Straits Research 2024).

3. Ink formulations and printability

While piezoelectric printheads are compatible with many materials, it still takes a long time to formulate these materials into printable inks. An ink is classified as printable when it can repeatedly produce droplets of the desired volume and speed, without satellite droplets. Satellite droplets are very small uncontrolled droplets. In the past, developing a printable ink was a long process of practical trial-and-error. Inks were formulated, tested in the printer, analysed and reformulated until the desired performance was achieved. Potentially, taking over a hundred reformulations to get an ink that is correct. This trial-and-error process, which is still employed although not exclusively, is extremely time-consuming, can damage the printer and is costly; especially when a test ink clogs a printhead and it needs to be replaced (industrial print heads can cost in the region of thousands of dollars). Therefore, significant savings could be gained by predicting if an ink is printable before it is loaded into the printer. By analysing the properties of printable inks, a formulation chemist can reduce the number of times a trial ink needs to be loaded into the printer.

It is widely recognised, in the inkjet community, that a fluid's physical properties affect its printability. The main properties are surface tension (σ), viscosity (μ) and density (ρ). Surface tension is a measure of a liquid's resistance to an externally applied force, which in inkjet printing is the force that determines the shape of the droplet, as well as the droplet's break-off behaviour. Viscosity is the property that determines the fluid's resistance to flow. The higher the viscosity the harder it is to get the fluid to flow through the nozzle. Using these properties, along with nozzle diameter (d) and drop velocity (v), one can calculate dimensionless numbers, such as the Capillary number (Ca) [Equation 1], the Reynolds number (Re) [Equation 2], and the Weber number (We) [Equation 3] that can be used in understanding printability (Hoath 2016). However, the most common dimensionless number used for evaluating printability is the Z number, which employs the Weber and Reynolds numbers. The Weber number is a ratio of internal forces to surface tension, and the Reynolds number is the ratio of internal forces to viscosity. By combining these two numbers into the Z number [Equation 4] one gets the ratio of internal and surface tension forces to viscosity. As this creates a single number that contains the main fluid properties that influence printability it has become a popular means of evaluating printability. The second method is the Ohnesorge number (Oh) [Equation 51], which is simply the inverse of the Z number.

$$\mathrm{Ca} = \frac{\mu v}{\sigma} \qquad [1]$$

$$\mathrm{Re} = \frac{\rho d v}{\mu} \qquad [2]$$

$$\mathrm{We} = \frac{\rho v^2 d}{\sigma} \qquad [3]$$

$$Z = \frac{\mathrm{Re}}{\sqrt{\mathrm{We}}} = \frac{\dfrac{\rho d v}{\mu}}{\sqrt{\dfrac{\rho v^2 d}{\sigma}}} = \frac{\sqrt{\rho \sigma d}}{\mu} \qquad [4]$$

$$\mathrm{Oh} = \frac{1}{Z} = \frac{\mu}{\sqrt{\rho \sigma d}} \qquad [5]$$

To investigate what factors influence an ink's printability many researchers have developed printability windows, which is a Z number range in which an ink should be printable. The most cited printability window was created by Brian Derby, who calculated the Weber number and Reynolds number for a wide range of solvents commonly used in inkjet formulations (Derby 2010). He ran print tests for all the solvents and recorded if the solutions were printable without satellites. Once this was complete, he recorded his finding in a Re vs We graph, with the revised graph shown in Figure 1 (Derby 2015). The graph identified a window in which the solutions were printable. Thus, $1 < Z < 10$ is an accepted printability range.

4. Predicting printability challenges

Throughout the years, different printability windows have been suggested. Jang et al. (2009) reported a range of Z between 4 to 14. Nallan et al. (2014) created a jettability window based on Derby's research but used the Capillary number instead of the Reynolds number. Using the Capillary number and Weber number, according to Nallan, allowed for better examination of the viscous and inertial forces that govern printability. Through a Ca vs. *We* graph a jettability range of Z between 1 and 60 was reported (Nallan et al., 2014). Liu and Derby (2019) corrected Derby's original printability window of Z = 1–10 to Z = 2–20. In their paper, Liu and Derby presented a table that comprehensively listed all of the various printability ranges suggested throughout the years. The original table is shown in Figure 2 and is a perfect example of how there is not a single universally accepted printability window.

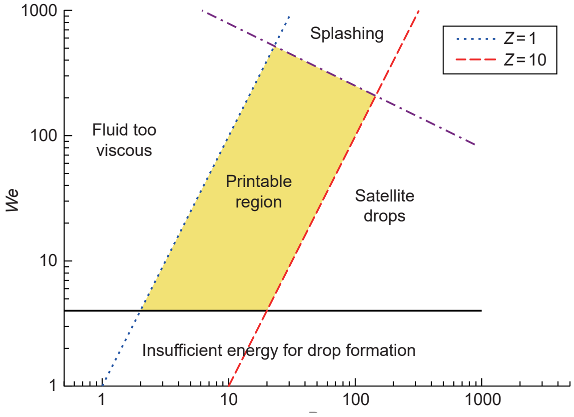


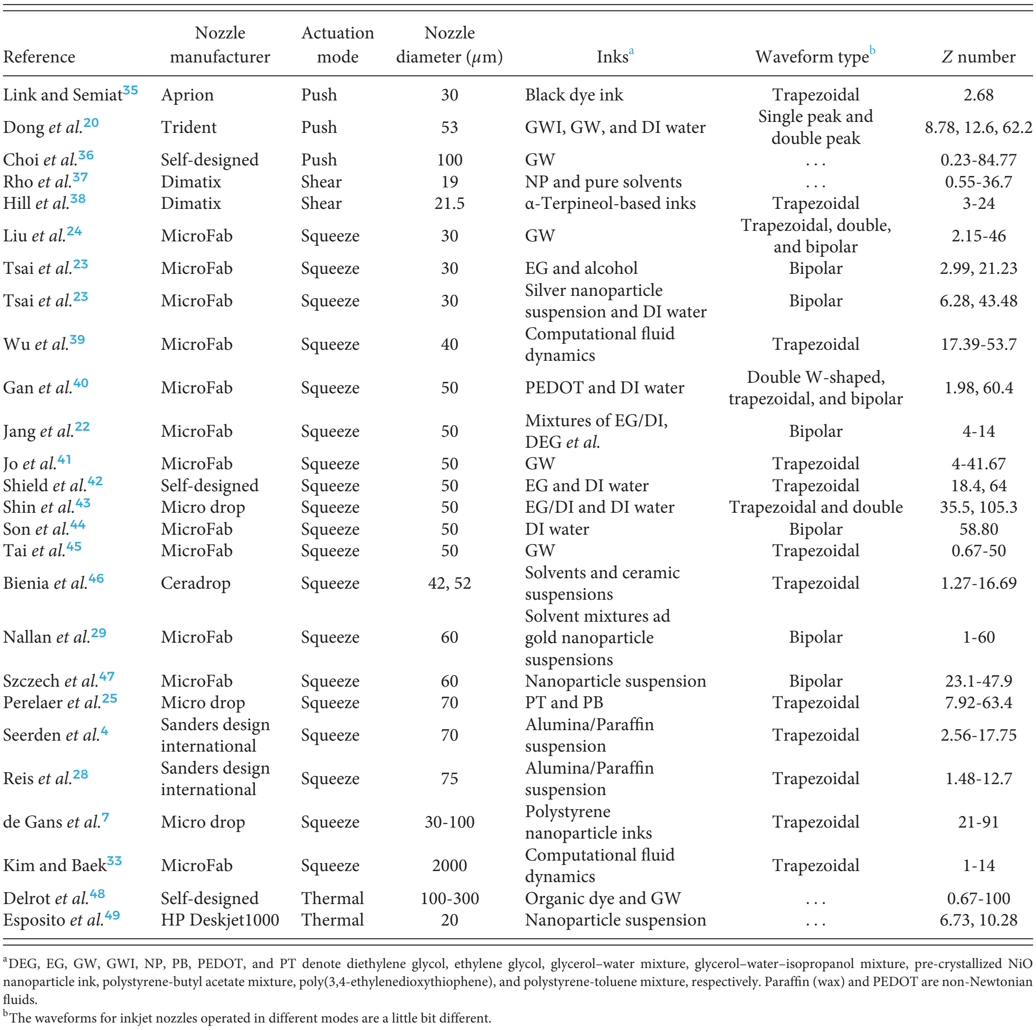
Figure 1: Printability window based on the graph of the Weber and Reynolds numbers created and corrected by Derby 2015

From Figure 2 one can see that there is a significant variation in Z number with many of the suggested ranges contradicting one another. For example, one suggested range by Kim et al. (2016) is 1–14 while another, suggested by de Gans et al. (2004) is 21–91. There is no overlap between these ranges despite both studies using a squeeze type actuation mode with a trapezoidal waveform type. The inconsistency could be explained by the other variables, such as nozzle diameter, being different. However, when we look at two studies that have the all the same variables, they still produced different Z number ranges. The studies by Jo et al. (2009) and Tai et al. (2008) both used 50μm squeeze type MicroFab printheads with a trapezoidal waveform to print glycerol–water mixture. Tai et al. (2008) produced a range of Z = 0.67–50 while Jo et al. suggested a narrower range of Z = 4–41.67. Although both ranges are similar, if all the impacting variables are the same, then why are they not identical? Why does one study indicate that a wider range of Z numbers are printable? For example, if your experiment ink had a Z number of 2 (a value that would be printable according to Nallen et al. (2014), Reis et al. (2005) and Kim et al. (2016)) then, according to Jo et al. (2009) and Hill et al. (2015), this ink would be unprintable.

The original purpose of the Z number was to indicate a region where one could be confident that their ink would be printable. But even when using the same printheads and same type of inks different ranges are suggested. These ranges then become completely different from each other when variables are varied. Which begs the question: what causes the predictions to be incorrect (Smith 2022)?

Three reasons why the Z number printability ranges exhibit such variability are proposed. The first reason is the calculations are unable to include all the factors that influence jettability. As Fromm (1984), whose work is credited as the foundation of the Z number, stated: "calculations alone cannot predict printability because they do not include external factors of the printing conditions that impact printability".

The second reason is because most printability windows were created from testing only pure solvent. Solvents are the carrier fluid for the functional materials, such as pig-



Reference	Nozzle manufacturer	Actuation mode	Nozzle diameter (μm)	Inks[a]	Waveform type[b]	Z number
Link and Semiat[35]	Aprion	Push	30	Black dye ink	Trapezoidal	2.68
Dong *et al.*[20]	Trident	Push	53	GWI, GW, and DI water	Single peak and double peak	8.78, 12.6, 62.2
Choi *et al.*[36]	Self-designed	Push	100	GW	. . .	0.23-84.77
Rho *et al.*[37]	Dimatix	Shear	19	NP and pure solvents	. . .	0.55-36.7
Hill *et al.*[38]	Dimatix	Shear	21.5	α-Terpineol-based inks	Trapezoidal	3-24
Liu *et al.*[24]	MicroFab	Squeeze	30	GW	Trapezoidal, double, and bipolar	2.15-46
Tsai *et al.*[23]	MicroFab	Squeeze	30	EG and alcohol	Bipolar	2.99, 21.23
Tsai *et al.*[23]	MicroFab	Squeeze	30	Silver nanoparticle suspension and DI water	Bipolar	6.28, 43.48
Wu *et al.*[39]	MicroFab	Squeeze	40	Computational fluid dynamics	Trapezoidal	17.39-53.7
Gan *et al.*[40]	MicroFab	Squeeze	50	PEDOT and DI water	Double W-shaped, trapezoidal, and bipolar	1.98, 60.4
Jang *et al.*[22]	MicroFab	Squeeze	50	Mixtures of EG/DI, DEG *et al.*	Bipolar	4-14
Jo *et al.*[41]	MicroFab	Squeeze	50	GW	Trapezoidal	4-41.67
Shield *et al.*[42]	Self-designed	Squeeze	50	EG and DI water	Trapezoidal	18.4, 64
Shin *et al.*[43]	Micro drop	Squeeze	50	EG/DI and DI water	Trapezoidal and double	35.5, 105.3
Son *et al.*[44]	MicroFab	Squeeze	50	DI water	Bipolar	58.80
Tai *et al.*[45]	MicroFab	Squeeze	50	GW	Trapezoidal	0.67-50
Bienia *et al.*[46]	Ceradrop	Squeeze	42, 52	Solvents and ceramic suspensions	Trapezoidal	1.27-16.69
Nallan *et al.*[29]	MicroFab	Squeeze	60	Solvent mixtures ad gold nanoparticle suspensions	Bipolar	1-60
Szczech *et al.*[47]	MicroFab	Squeeze	60	Nanoparticle suspension	Bipolar	23.1-47.9
Perelaer *et al.*[25]	Micro drop	Squeeze	70	PT and PB	Trapezoidal	7.92-63.4
Seerden *et al.*[4]	Sanders design international	Squeeze	70	Alumina/Paraffin suspension	Trapezoidal	2.56-17.75
Reis *et al.*[28]	Sanders design international	Squeeze	75	Alumina/Paraffin suspension	Trapezoidal	1.48-12.7
de Gans *et al.*[7]	Micro drop	Squeeze	30-100	Polystyrene nanoparticle inks	Trapezoidal	21-91
Kim and Baek[33]	MicroFab	Squeeze	2000	Computational fluid dynamics	Trapezoidal	1-14
Delrot *et al.*[48]	Self-designed	Thermal	100-300	Organic dye and GW	. . .	0.67-100
Esposito *et al.*[49]	HP Deskjet1000	Thermal	20	Nanoparticle suspension	. . .	6.73, 10.28

[a] DEG, EG, GW, GWI, NP, PB, PEDOT, and PT denote diethylene glycol, ethylene glycol, glycerol–water mixture, glycerol–water–isopropanol mixture, pre-crystallized NiO nanoparticle ink, polystyrene-butyl acetate mixture, poly(3,4-ethylenedioxythiophene), and polystyrene-toluene mixture, respectively. Paraffin (wax) and PEDOT are non-Newtonian fluids.

[b] The waveforms for inkjet nozzles operated in different modes are a little bit different.

Figure 2: Summary of reported Z ranges created by Liu et. al. (2019). Dor the respective references see the original paper

ments and polymers, that make up a final ink formulation. In an ink, it is the functional materials that can cause particle formation and non-Newtonian behaviour. Pure solvents are Newtonian fluids and thus would only show ideal behaviour since Newtonian fluids are fluids whose properties do not change when under stress (further information in the section 5 Rheology). Whereas, a fully formulated commercial ink contains functional materials and additives that could cause non-Newtonian behaviour, leading to the fluid exhibiting different properties under stress. Because the printability windows were created only from Newtonian fluids, or non-Newtonian fluids that were so diluted they behaved as Newtonian fluids, the reported ranges cannot represent all inks.

Which brings us to the third reason, the calculations do not account for non-Newtonian and elastic behaviour. The *Z* number printability ranges assume inks will have a constant viscosity throughout the jetting process, but this is not always the case. Non-Newtonian inks have a viscosity that changes due to the high shear rates associated with inkjet printing. The *Z* number calculation is unable to account for any changes in viscosity that occur in non-Newtonian inks since it only uses the zero-shear viscosity. Due to these three reasons several *Z* number printability ranges have been proposed over the years, indicating that either the final range has yet to be determined or that there are other factors that need to be considered.

Additionally, it is also important to note that none of the mentioned printability calculations account for particle behaviour in inks. Yet many inks are formulated with pigment particles, such as those used in graphics printing. As mentioned, particles can affect the flow of ink and even cause non-Newtonian behaviour. The flow of an ink is especially affected when particles inevitably interact by colliding and agglomerating. It is the grouping of pigment particles that often clog printheads. To prevent clogging and to lessen the effect particles have on flow, a guideline requires pigment particles to be the size of 5 % of the nozzle's diameter (MicroFab Technologies 1999).

However, this unofficial rule applies for diluted solutions. If a formulation requires a concentrated amount of pigment the particle size should be even smaller than 5 %. The behaviour of particles, and particle build up, is not accounted for in any of the printability windows, which is another reason why the printability windows can be incorrect.

5. Rheology

Rheology is the study of deformation and flow of fluids. Rheology investigates how a fluid reacts to stress, such as high shear, and elongational flows. Since inkjet printers are extremely high stress environments, understanding how an ink reacts to stress is critical for determining its printability.

The difference between Newtonian, and non-Newtonian fluids becomes apparent when investigating a fluid's rheology. A Newtonian fluid is a fluid that obeys Newton's law of constant viscosity, which means the viscosity of the fluid stays constant no matter the shear rate applied. A non-Newtonian fluid does not obey Newton's law of constant viscosity; its viscosity is dependent on the shear applied. For inkjet printing, Newtonian fluids are preferred (Magdassi 2010). Thus, most inks are carefully formulated to behave as close to Newtonian fluids as possible. However, as inkjet technology advances, non-Newtonian behaviour is not always avoidable.

An ink's functional materials, or additives, can cause the ink to exhibit non-Newtonian behaviour in which the ink's viscosity is dependent on the shear rate it experiences. Inkjet printheads have extreme shear rates of $1 \times 10^4 s^{-1}$, or more, associated with them (Wang et al. 2010). The high shear rate during inkjet printing causes the viscosity of a non-Newtonian ink during printing to be drastically different to its apparent viscosity under zero shear rates.

Having highlighted the importance of studying inks under high shear rate, it may seem obvious to test the rheology of all inkjet inks under these conditions. However, this is not always possible. The shear rates experienced in inkjet printers are often beyond what most rheometers can reach, making it practically impossible to determine a non-Newtonian ink's viscosity during printing, which explains why ink rheology is overlooked when determining printability.

Since it is difficult to examine steady shear at rates that mimic inkjet printing it tends to be easier to measure the complex viscosity of an ink instead. Complex viscosity data is obtained using high frequency rheometers. The high frequency rheometer that is the closest to mimicking environments seen in inkjet printers is the piezo-axial vibrator (PAV) rheometer. These rheometers can reach frequencies of 1 Hz to 15 kHz (Guo et al. 2017). This allows PAV rheometers to measure the complex viscosity of inks at frequencies close to those experienced inside inkjet printers. However, PAV rheometers are quite a recent development and are specialist equipment.

Complex viscosity data provides extremely valuable understanding into how non-Newtonian inks behave during the ejection process. Hutchings et al. (2009), amongst others, showed that high frequency rheology could distinguish between two polymeric ink that have identical zero shear viscosities, and help predict printability (Vadillo et al. 2010; Tuladhar et al. 2009). Hutchings et al. (2009) used a PAV to obtain values for the complex viscosity (η^*), elastic storage modulus (G') and viscous loss modulus (G''), which was used to calculate the complex modulus (G^*). The elastic ratio of G'/G^* was used to characterise the inks. From the G'/G^* characterisation they were able to distinguish between two different polymeric inks that had nearly identical values of viscosity at zero-hear. They also observed a linear relationship between G'/G^* and ligament break off. Through the characterisation they were able to prove that when a polymeric inks has a high elasticity it will be unprintable since the ligament is too strongly elastic to allow for droplet break-off. Instead, the droplet is pulled back into the nozzle, which follows the observations of previous research (De Gans et al. 2005). The reasearch of Hutchings et al. is a strong illustration of why printability analysis using only the zero-shear viscosity of non-Newtonian inks is defective. Instead of calculating the Z number, more research should be done to investigate how high frequency rheology can help predict printability for non-Newtonian inks.

6. Additional printability factors

No matter what method is used, Z number or rheology, it is very difficult to confidently predict if an inkjet ink will be printable without physical experimentation. Printability windows and rheology are great aids, but they should be used as guides for narrowing down to a printable ink and not as a 'stand-alone' perfect prediction; this is because there are more factors that affect printability than just fluid properties. Although examination of a fluid's properties provides much of the needed information to determine printability it excludes the impact of printing conditions, such as the waveform, applied voltage, and printhead geometry.

6.1 Waveforms

Waveforms determine when a droplet is ejected from a nozzle. Waveforms control the expansion of the ejection chamber, to fill up with ink, and when it contracts, to push out the ink. The timing of this process must be optimised to produce stable and uniform droplets. Unoptimised waveforms could cause the ejection chamber to contract before the ink has time to flow into, and properly fill, the expanded chamber. An expanded chamber that is not full when it starts to compress will eject an incorrect volume of ink. An incorrect volume causes the droplets to no longer be uniform in size and shape. Without uniformity the droplets produced are only unwanted satellite droplets. Therefore, the waveform must be finely tuned to the ink to be compatible and produce stable droplets.

Liu et al. (2013) proved that a waveform's parameter can alter the printability of an ink, and that the ink's fluid properties should not be the only factors considered when determining printability. In their paper, the same ink was ejected twice using the same printer and conditions but using two different waveforms. One waveform produced stable droplets while the other waveform only produced satellites. (Figure 3 is a sketch illustrating this difference.) The work of Liu et al. work shows that waveform compatibility is another factor that must be considered when trying to predict the printability of an ink.

It should be noted that optimising a waveform to an ink is standard practice for printing. It is well known that waveforms affect the printability and performance of an ink. However, it is not standard practice to factor in the energy input due to the waveform when predicting the printability of an ink.

6.2 Voltage

The voltage applied to a waveform determines the size and speed of the ejected droplets. This is because the voltage determines the displacement volume and speed of the piezoelectric crystal, which can also be referred to as the actuation. The higher the voltage, the higher the actuation, and the faster and larger the droplet. Many researchers have remarked on the effects that the applied voltage has on droplet formation and ejection. Most observe how droplet velocity and size can be controlled by the applied voltage. Increasing the voltage increases the drop velocity and the droplet size (Kang et al. 2020; Reis et. al. 2005). Therefore, the applied voltage must be considered when determining what size and speed the ink droplets should be printed at, which illustrates that fluid parameters alone do not determine if an ink is printable, but instead a combination of fluid parameters and printing conditions.

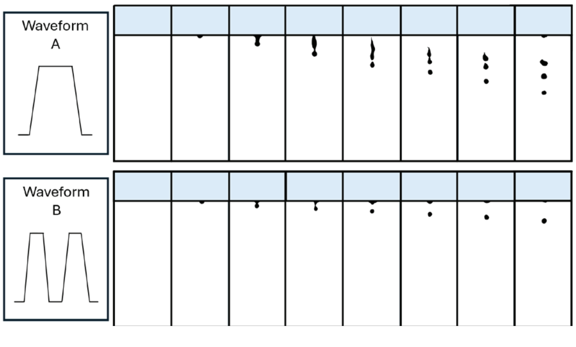


Figure 3: A sketch showing the effect of a single waveform (top) and a double waveform (bottom) on droplet formation. Liu et al. (2013) discussed similar effects.

Researchers have also found a correlation between voltage and viscosity. This correlation was predicted by Fromm (1984) when he wrote "For smaller R/W ratios, one must employ stronger driving pressures" (Reynolds number to Weber number ratios). However, when Fromm wrote this the voltages applied to inkjets were limited and could not provide the same amount of power that printers today can. It was not until the work of De Gans et al. (2004) that the relationship between high viscosity inks and very high voltages was proven. De Gans and colleagues found that using high voltages allowed for high viscosity inks, up to 160 mPa·s, to become printable. However, it is important to note that this technique of increased voltage does not work for all high viscosity inks. Optimising the voltage to enable high viscosity inks to print can often result in satellite droplets (Xaar 2024). Thus, increased voltages may allow a high viscosity ink to be ejected, but this does not mean they can produce reliable droplets for printing a product or feature with acceptable resolution. Therefore, the correlation between voltage and viscosity still needs to be explored.

6.3 Printhead geometry

Printhead geometry plays a major role in how an ink flows and determines the shear rates experienced inside the printhead. As mentioned, shear and elongational flow can dramatically change the behaviour of non-Newtonian fluids. Non-Newtonian fluids can experience shear thinning and thickening under the extremely high-shear environments inside the printhead. Since printhead geometry determines these flows, it can also impact the printability of an ink.

Studies where the same ink was used in two different printheads show the impact that printhead geometry can have. McIlroy et. al. (2013) investigated the printing regimes of polymeric inks using two different printhead. One printheads was an industrial printhead in which the ink must go through a sudden contraction before entering the nozzle. The other was a research printhead that had a cone shaped inlet to gently funnel the ink into the nozzle. When used with the industrial printhead the polymeric ink was more prone to polymer degradation, but when the research printhead was used the polymeric ink degraded less. This was due to the higher strain rates experienced in the industrial printhead from the sudden

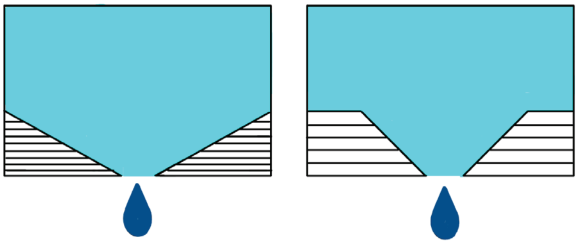


Figure 4: Drawings representing how the cone angle of a printhead can vary

contraction geometry. Bernasconi et al. (2022) also documented the effect printhead geometry can have on the printability of an ink. In their investigation the printability of a high viscosity inkjet ink was examined with four different printheads. The four printheads consisted of two different geometries and were made of two different materials. Only one of the printheads showed that it was able to print higher viscosity inks. Unfortunately, the design elements of the printhead geometries are hidden, but this research clearly showed that printhead geometry affects printability and can even increase printability ranges.

Printhead geometry can also influence ink build up and clogging inside the nozzle. Zhang (2019) investigated the effect ink and particle build up has on printhead geometry and jetability. Zhang modelled multiple printhead geometries to reflect how ink build-up changes the nozzle geometry over time. The models also served as an investigation for the best cone angle for a nozzle. Examples of cone angles are shown in Figure 4. Zhang showed that even the slightest change to printhead cone angles can change how a printhead jets inks. Thus, proving that printhead geometries have a large impact on drop formation and printability.

7. How academia and industry differ

Academic inkjet research and the inkjet industry operate very differently despite working in the same area; using different printers, inks, and evaluation methods. As a consequence of this difference, newly researched materials for inkjet printing can become unprintable when scaled up and used with high-speed industrial printers (Voit et al. 2011). This gap between how academia and industry operate is limiting the growth of inkjet technology. New materials and devices that show great promise in research labs face substantial hurdles when transitioning into the industrial marketplace. Therefore, it is important to understand the difference between small-scale inkjet systems used in academia research labs and the large-scale high-speed inkjet systems used commercially so that research can continue to support and grow the inkjet industry (Teunissen et al. 2013)

7.1 Printers

The major difference between how academic research and the industry operates is the equipment used. Different printing apparatuses, printheads and ink supply systems, are used depending on the scale of work being done. Examples are shown in Figure 5. Small-scale research printers use a single nozzle printhead directly attached to a 5–10 mL reservoir used as the ink supply system. Research labs require small volumes to limit the waste of raw materials used on reformulations. This is important because inks need to be reformulated multiple times until a successful formulation is found. Large-scale industrial printheads are multi-nozzle printheads with roughly 100–2 000 nozzles. Having more nozzles increases ink output and printing speeds. Thus, industrial production requires large volume ink reservoirs, of a litre or more, to be connected to the printhead using pumps, tubing, and filters. The added machinery means the ink is no longer directly connected to the printhead and has a much longer path it must take before being used. The drastic difference in the printing apparatuses completely changes the inks environment, and the printing conditions. As discussed previously, changing printing conditions can greatly impact the printability of inks. Which is why an ink that is successful in a research lab can fail when transferred to an industrial printer.

7.2 Inks

Another main difference between inkjet research labs and industrial production is the inks being used. In research variables need to be controlled and limited. Therefore, trial inks are formulated with the bare minimum components to control what is being observed. In most cases this means only the material of interest and a carrier solvent is used in a trial ink formulation. However, industrial commercial inks use far more than two components in their formulations. Commercial inks require other additives to assist in high-speed performance and extend shelf life.

Common additives in ink formulations include, but are not limited to, surfactants, humectants, biocides, pigments, and co-solvents (Magdassi 2010). Additives play an important role in changing ink behaviour to support large-scale production. Surfactants are added to inks to adjust and control the surface tension. Humectants have two purposes: to help adjust viscosity and to help maintain the moisture barrier. (The moisture barrier helps prevent ink from drying out and clogging the nozzle when not in use.) Biocides are used to prevent the growth of bacteria inside the ink and extend shelf life.

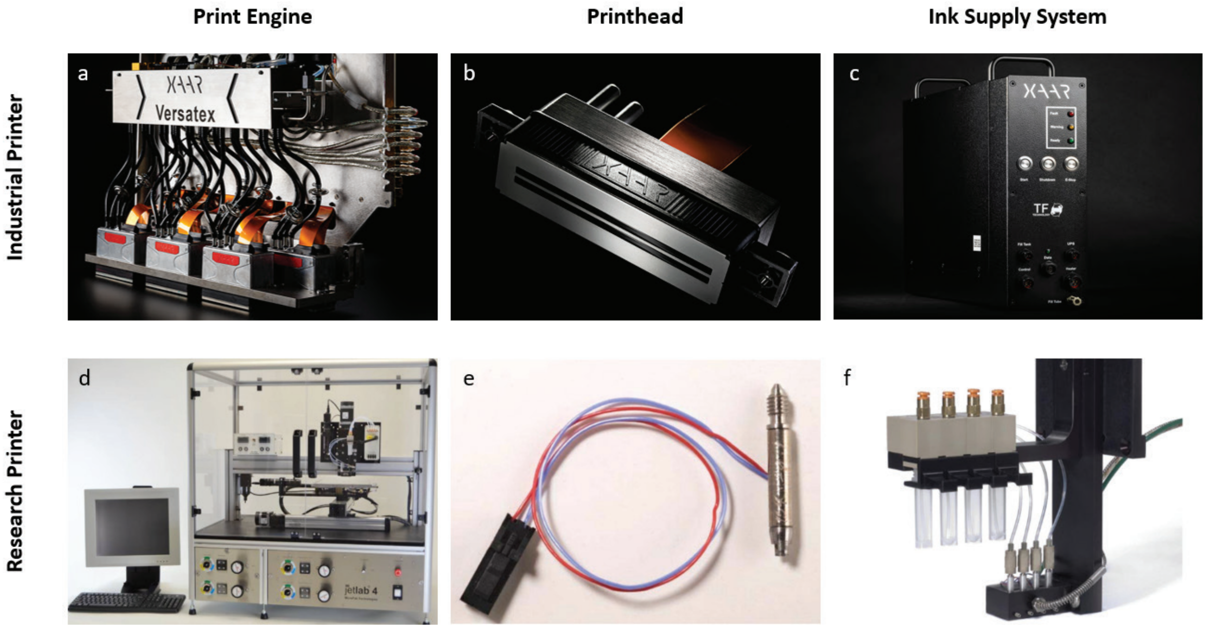


Figure 5: Industrial printer compared to research printers: top row is industrial printer parts (Xaar 2025), bottom row is a research printer (MicroFab Technologies Inc. 2025); a) print engine without housing and case; b) multi-nozzle printhead; c) ink supply system; d) print engine with housing and case; e) single-nozzle printhead; f) ink supply system and print engine

Pigments are finely milled microscopic particles that provide colour. Co-solvents are additional solvents used to support the flow of ink. Additives in commercial inks are necessary but can completely change the fluid properties and the behaviour of the ink.

However, additives are not the only difference in ink formulations, the main carrier solvent can vary significantly as well. This is due to commercial printers having a more restrictive list of compatible solvents compared to research printers. As mentioned, research printers are often glass single nozzle printheads that use small volume reservoirs (e.g. 5 ml) as an ink supply. This setup allows for a wide variety of compatible solvents. Industrial printers are often metal or ceramic multi-nozzle print-heads that connect to a large ink reservoir (e.g. 1 L) with tubing, glue, filters, and pumps. Therefore, a carrier solvent for a commercial ink must not dissolve or degrade the added machinery (Sirringhaus and Shimoda 2003).

7.3 Up-scaling

The addition of tubing, glues, filters and pumps to an ink supply system can greatly limit the solvents that can be used in a commercial ink. It is often difficult to find a solvent that is compatible with both the materials of interest and industrial printers. A great example of this is shown in the research done by Gaikwad et al. (2016) on identifying orthogonal solvents for printed electronics. The ideal solvent had to be orthogonal to the semiconductor, able to dissolve the two polymers used, and show adequate printability. The experiment started with 21 solvents that were orthogonal to the semiconductor. Of which 13 that could dissolve one polymer and 6 could dissolve another one. Once printability was considered, only 6 solvents could be used for the first polymer and only 3 for the second one. The results of this research shows how the need for a printable solvent can greatly limit the list of possible solvents.

As mentioned above, additives in commercial inks can easily change the rheology and fluid properties of newly researched materials. When new materials for inkjet inks are being researched, they are often simplified formulas that are Newtonian fluids. When these materials are translated into a commercial ink with different carrier solvents and additives, they can become non-Newtonian fluids. Non-Newtonian inks behave completely differently under high-shear environments, such as inkjet printers, than Newtonian inks. Thus, when additives are added to make a commercial ink, it can cause the material to perform completely different than it did in the research labs.

The methods of developing inks form another significant difference between academic research and the inkjet industry. Academic research lab's goal is understanding why an ink behaves the way it does, focusing on investigating the inks fluid behaviour, which is why the printability windows were created. Industrial manufacturing's goal is producing the highest quality product through a trial-and-error system. Both these worlds have the same end goal, to be able to improve and grow inkjet technology, but have different methods and priorities. Having different priorities is causing research and the industry to grow apart instead of supporting each other.

8. Conclusion

Inkjet technology is becoming an integral part of modern-day manufacturing. Inkjet technology's ability to create any design on command is a desired feature for many applications. To expand inkjet applications an increased understanding of the factors that affect inkjet ink printability is needed. Determining printability using the *Z* number has dominated academic research, however this evaluation method does not account for all factors that affect printability. Specifically, it does not include the ink's rheological response to high shear or the printing conditions, such as waveforms, of the printers. Rheology describes an ink's high-shear viscosity and elastic response. Since inkjet printers are high-shear environments, it is important to study inks rheology and not just its zero-shear *Z* number. Complex viscosity data has proven to provide a better analysis and prediction of printability then the *Z* number method. Additionally, waveforms, voltage and printhead geometry all contribute to the printability of an ink, which the *Z* number excludes. These settings must be optimised to an ink for it to be printable. By understanding all these factors, it is clearer to see how inks can be printable with one printer, but not another.

The effect of printing conditions and rheology on printability becomes especially important when transferring an ink from research labs to industrial production. Research labs and industrial production have completely different requirements when it comes to printing apparatuses and ink formulations. Using different printer conditions and ink additives greatly affect printability. While these differences are necessary for each sector to function individually it leads to a gap that is not easily crossed, which limits one inkjet sector from supporting the other. Therefore, to limit the possibility of inks becoming unprintable on the industrial scale more research needs to be done on upscaling inks.

At the moment, the best method of determining the printability of an ink for an industrial inkjet system is to use trial and error. However, this is a lengthy and costly process. Ideally there would be a mechanism for indicating the printability of a novel ink, which many researchers have tried to accomplish. The *Z* number can be a tool to help guide the first steps of formulations but cannot provide a strong degree of confidence in predicting printability. Transferring research into industrial markets can not be done in one single step due to many variables that influence printability that cannot be accounted for in the *Z* number alone. Instead, a multistep process that uses both inkjet research methods of evaluating printability and industrial trial-and-error method should be used.

The first step of transitioning research ink into an industrially usable product would be to check the ink's components for compatibility with industrial printing systems. There are many solvents used in research that are incompatible with large-scale printing systems. The next step would be to assess the ink's fluid properties. Since every printer has its own optimal ranges for properties like surface tension, and viscosity it is important to keep the intended print systems preferences in mind. Next the ink's rheology should be measured. Many inks will behave differently in the high-stress environments that inkjet operates in, than they would at zero shear. Thus, it is important to investigate how ink's properties might change when inside the printhead. The piezo-axial vibrator system that looks into the complex rheology of a fluid is a very useful piece of equipment for evaluation. The next step is waveform optimisation. This includes factors such as voltage, waveform type, and print frequency. The fluid properties and rheology data of an ink can help guide the initial stages of optimization, but a trial-and-error approach will be needed to find the ideal settings. Once all these steps are completed one may begin to be more confident in their ink's ability to be printable with an industrial print system. Once the basic formulation is compatible with an industrial printer one can start the process of including additives that are necessary for long term print performance and ink stability. During which this evaluation process should be repeated until optimal performance is achieved.

Ideally there is a mechanism/method to indicate printability before an ink is printed. The mechanism that is the most cited by researchers is the *Z* number. However, the *Z* number should be considered as forming the opening remarks of the evaluation journey of an experimental ink. Factors such as viscoelasticity and printhead geometry play a key role into printability that cannot be evaluated using the *Z* number alone. The process of ejecting an ink using a research lab system involves a complex interplay of many factors. This interplay increases in complexity when the ink is transferred into industrial systems. Active researchers in the field are advised to take these complications into account when working with new materials and novel formulations.

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