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A novel methodology for assessing the latency of water-based inkjet inks

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Abstract

The use of digital printing in the printing industry continues to expand and evolve, largely due to the versatility of inkjet technology, which offers extensive possibilities in terms of customisation and a wide range of applications compared to conventional printing techniques. Moreover, growing environmental awareness drives the development of water-based inks. However, the use of aqueous inkjet inks requires considerable expertise in the drop-on-demand ejection process. Indeed, a common issue with inks of this nature is the generation of defects in printed designs, such as missing areas and lines, often caused by nozzle latency. The latency phenomenon occurs when nozzles fail to fire drops after a period of inactivity (idle time). This paper presents two innovative quantitative methods to assess the latency phenomenon of water-based inkjet inks: one involving direct observation of printed results thanks to a specific test form, and another focusing on the observation and analysis of the drop ejection. These techniques can help ensure a reliable ink ejection in an industrial production context.

Keywords: digital printing, water-based inks, latency, idle time, drop

1. Introduction

Printing with water-based and pigmented inkjet inks can be challenging due to the narrow specifications required for physicochemical parameters such as density, viscosity, and surface tension (Hoath, 2016). The viscosity must be extremely low and generally around 10 mPa·s. Surface tension is also a critical parameter that requires careful management, as surfactants must be added to lower the surface tension of the water. This addition of surfactant can lead to destabilisation, which is why the formulation of this type of ink is critical. Latency is a common printing defect often encountered with water-based inks. It is characterised by the reduction in printing performance after a certain idle time. The latency phenomenon can result in modifications of drop velocity, drop volume, or even in the complete failure to eject drops when the nozzle is reactivated. Such issues are particularly critical for graphical or printed electronic applications, as they lead to unprinted lines or areas in the final printed design (Figure 1).

The origin of latency is not much disputed in the literature; in the case of water-based inks, it is generally attributed to drying phenomena, where evaporation of water at the meniscus is thought to increase the concentration of ink solid content

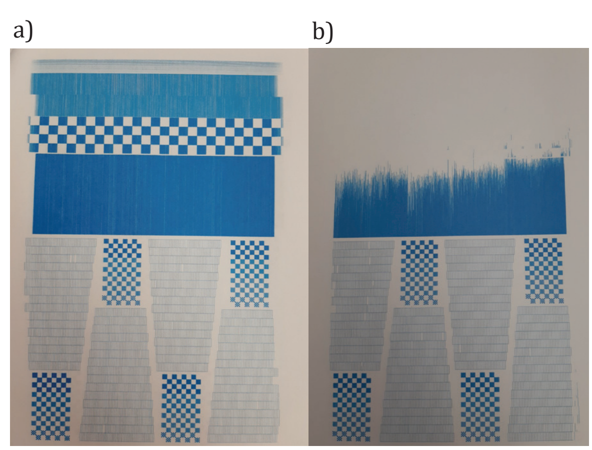

Figure 1: Pattern printed without latency (a) and with latency (b)

(Magdassi, 2010; Thakkar and Sun, 2003; Kamyshny et al., 2022). Efforts are being made to control and reduce this drying phenomenon, as Brust et al. (2009) did in their patent by adding glycerol humectant in combination with a 1,2-alkanediol. Other methods have been tested so far to reduce latency, for example, the use of counter-ions and the control of the hydration radius (or Stern layer). According to Kabalnov and Wennerstrom (2006), the larger this radius, the lower the possibility of pigment particles aggregating or separating from the ink vehicle, which would imply latency. However, to the best of our knowledge, the hypothesis of drying has not yet been conclusively demonstrated. Besides, solutions to reduce the occurrence of the latency phenomenon are discussed in the literature. For example, as suggested by Jackson (2016), ink formulation can be improved by incorporating humectants or using specific counter-ions to neutralise the dispersing agents. Enhancements to the drop-on-demand inkjet process, such as employing recirculating printheads or applying tickling waveforms during idle time, have also been proposed. Hirakata et al. (2014) highlighted the importance of recirculation to reduce the latency, using drop velocity as an indicator to detect this phenomenon. Their findings showed that the speed of the first ejected drop decreased as idle time increased.

This research introduces two novel quantitative approaches for evaluating latency effects in water-based inkjet inks: a direct method that examines printed output through specialized test patterns, and an indirect method that monitors and analyzes droplet ejection behavior. The study provides a critical evaluation and comparison of both methodologies to determine their effectiveness in ensuring consistent ink ejection performance for industrial manufacturing applications.

2. Materials and Methods

2.1 Inks

Three inks with different levels of latency were prepared (Table 1).

Table 1: Formulations of water-based and pigmented inks for latency determination

Component (wt %)	Ink 1	Ink 2	Ink 3
ProJet ADP 1000 Cyan	3	3	3
Dispersing agent	0	1	3
Polyurethane binder	4	4	4
Humectant 1	24	24	24
Humectant 2	2	2	2
Humectant 3	3	3	3
Silicone surfactant	1	1	1
Deionized water	63	62	60

The ProJet ADP 100 Cyan dispersion was provided by Fujifilm. The dispersing agent was a styrene-acrylic copolymer supplied by BASF. The dispersion manufactured by Fujifilm did not contain any excess dispersing agent (also made with a styrene-acrylic copolymer). This means all the dispersing agent was properly bonded to the pigment particles. Furthermore, this component has undergone a crosslinking step to prevent destabilization. A patent protects this innovation (Dimotakis et al., 2018). Under the standard way of production, dispersions and inks may contain some excess dispersant that is not anchored to the pigment. This is why this component was intentionally added in formulations Ink 2 and Ink 3. The polyurethane binder was supplied by Covestro. The three humectants were a mixture of glycol(s) and diol(s) and were bought from Sigma-Aldrich. The silicone surfactant from Byk allowed to match surface tension requirements. All the components, except the pigment dispersion, were mixed with a stirrer up to homogenization. Then, the dispersion was added under stirring. The mixture was stirred for about 10 minutes. Finally, the ink was filtered through a 25 mm diameter WHATMAN 1 µm GF/B w/GMF filter with the help of a peristaltic pump at room temperature. The typical flow rate to filter the inks was 0.25 $g \cdot s^{-1}$.

2.2 Characterization of the inks

Before printing, the physicochemical and rheological properties of the inks were thoroughly characterized. The mean particle size (D50) was determined using a dynamic light scattering particle size analyser (Nanotrac Flex, Microtrac MRB) at ambient temperature. Density (ρ) measurements were conducted with a DMA 35 portable densimeter, from Anton Paar, at ambient temperature. The pH was measured using a Checker portable pH meter (Hanna Instrument) at ambient temperature. For rheological properties, a high-frequency rheometer (TriPAV, TriJet Limited) was used to measure complex viscosity (η), loss and storage moduli and loss angle at 32 °C over a frequency range of 1 Hz to 10 000 Hz. For water-based inks, reliable data are typically obtained up to 5 000 Hz due to their low viscoelastic character. In this study, we specifically focused on values at 500 Hz. Finally, the dynamic surface tension was evaluated using a bubble pressure tensiometer (BP100, Krüss) across a timescale of 10 ms to 10 000 ms at 32 °C.

2.3 Inkjet printhead and printing parameters

The inkjet printhead used was a non-recirculating model with 10 µm diameter nozzles and a resolution of 600 dpi. The inks were jetted at a temperature of 30 °C and a frequency of 500 Hz. Environmental conditions were maintained as recommended by the printhead manufacturer, with a room temperature of 24–25 °C and a humidity rate of 40–45 %.

2.3.1 Method 1: Analysis of printed patterns

A JetXpert platform equipped with a printing station was used to evaluate latency.

A specific test pattern, shown in Figure 2, was printed after cleaning the printhead and adjusting the meniscus pressure. Then, the pattern was printed at different idle times, during which the nozzles of the printhead remained inactive. Latency assessment was based on the number of lines successfully printed: if the first sixteen lines were correctly printed, the ink exhibits no latency. On the other hand, missing lines indicate a latency issue. To quantify it, a latency index $I_{latency}$ was defined, as shown in Equation [1]. The number of missing lines over the 16 lines that should be printed were counted. When $I_{latency} = 1$, the jetting was ideal but when $I_{latency} = 0$ the pattern was incomplete, indicating a high level of latency.

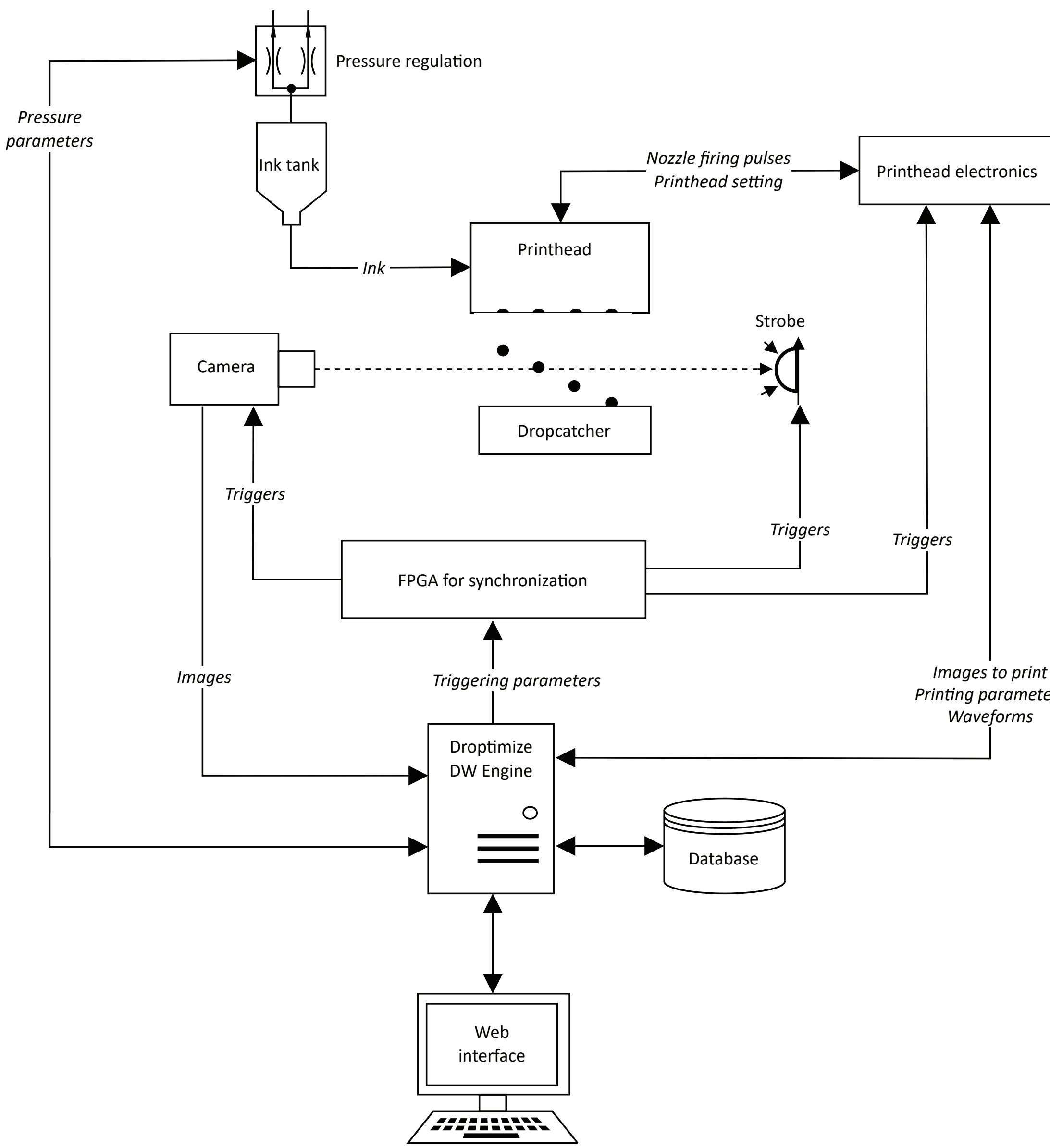

Figure 3: Latency determination workflow. The system uses an FPGA (Field-Programmable Gate Array) for synchronization and the Droptimize DW (Drop Watcher) Engine for droplet analysis and control.

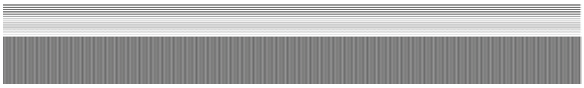

Figure 2: Top of the pattern used for evaluation of latency by the printing method

$$I_{\text{latency}} = \frac{\text{number of missing lines}}{16} \quad [1]$$

Printing observations were conducted using a Keyence VHX 6000 microscope. Each print was performed at least three times to ensure reproducibility and reliability of the results.

2.3.2 Method 2: Droplet formation observation

A Droptimize platform and a Graphical Interface System driver were used to capture the drop formation. This method was expected to be more precise than method 1. The Droptimize system allowed counting the number of non-firing strokes before the first drop. From this, the loss of printed area can be calculated. The procedure is visualized in Figure 3.

The procedure is very similar to the printing observation method. The print head was cleaned by purging the ink through the nozzles and passing a DYNOclean Swab Poly 714 from DYNOVO over the plate. Then, the pressure meniscus was adjusted to avoid ink leaking. The nozzles were activated by the waveform associated with the printhead used, between different idle periods. When the nozzles started to fire, an image was taken each 0.05 s during 1 s. The time of 1 s was determined as sufficient to see the missing printed area in the design. At a frequency of 500 Hz, 21.1 mm were printed.

During this measurement, the position of the drops from the nozzle plate was analysed. To recover all the nozzles between two idle times, a printing purge of 1 s was made after the analysis. The number of pulses (N_{nfs}) required before the first drop emerges from the nozzle was calculated as a function of the print frequency and the time elapsed between the start of printing and the appearance of a drop on the image as given in Equation 2, where n is the number of the first image where droplets were observed and Fq was the operating printing frequency.

$$N_{\text{nfs}} = n * 0.05 * \text{Fq} \quad [1]$$

This operation was repeated at least three times. Inks with a number of non-firing strokes close to 0 had a low level of latency and were therefore less likely to have printing problems than inks with N_{nfs} close to 1.

3. Results

3.1 Ink characterization

Table 2: Physicochemical and rheological properties for the three studied inkjet inks

Parameter	Ink 1	Ink 2	Ink 3
D50 (nm)	71	82	78
ρ (kg·m^{-3})	1 048	1 050	1 050
pH	8.7	8.2	8.3
η (mPa·s)	1.84	3.08	4.79
γ (mN·m^{-1}) @10 ms	38.1	37.3	37.8
γ' (mN·m^{-1}) @10 000 ms	24.6	24.3	25.6

To avoid nozzle clogging, the mean particle size should be under 150 nm (depending on the printhead type used), which was the case for the three formulated inks (Table 2). The printhead supplier recommends using inks with a neutral pH and a density between 1 000 and 1100 kg·m^{-3}. In this study, inks had a pH ranging from 7 to 9 and a density of approximately 1 050 kg·m^{-3}, meeting the specified criteria. The dynamic surface tension at 10 and 10.000 ms (which is close to static surface tension) were similar for the three inks, aligning with the recommended specification for the static parameter, which is between 21 and 25 mN·m^{-1}.

Only the complex viscosity, η, was significantly different between inks. The presence of a free dispersing agent increased the viscosity of formulations 2 and 3. However, the recommended dynamic viscosity at 32 °C should be between 5 and 6 mPa·s. None of the inks had a viscosity above the required range. Concentrations of humectants and additives were kept equal across all three formulations to not influence the results.

3.2 Printing observation (method 1)

The images in Figure 4 were taken using a Keyence VHX 6000 microscope, which allowed to count precisely the printed lines and therefore to assess the performance of the different inks under varying idle times. As can be seen in Figure 4, Ink 1 showed an excellent printing stability, maintaining well-defined printed lines even after 60 s of idle time. This indicates that Ink 1 offers consistent performance after prolonged idle periods. This was not the case for the two other inks. Indeed, Ink 2 begins to show performance degradation at 60 s of idle time, with the first printed line becoming faint or partially missing. Ink 3, however, exhibited significantly poorer performance. At just 20 s of idle time, more than half of the printed lines were already missing and by 60 s of idle time, Ink 3 failed, with none of the lines being printed (not shown).

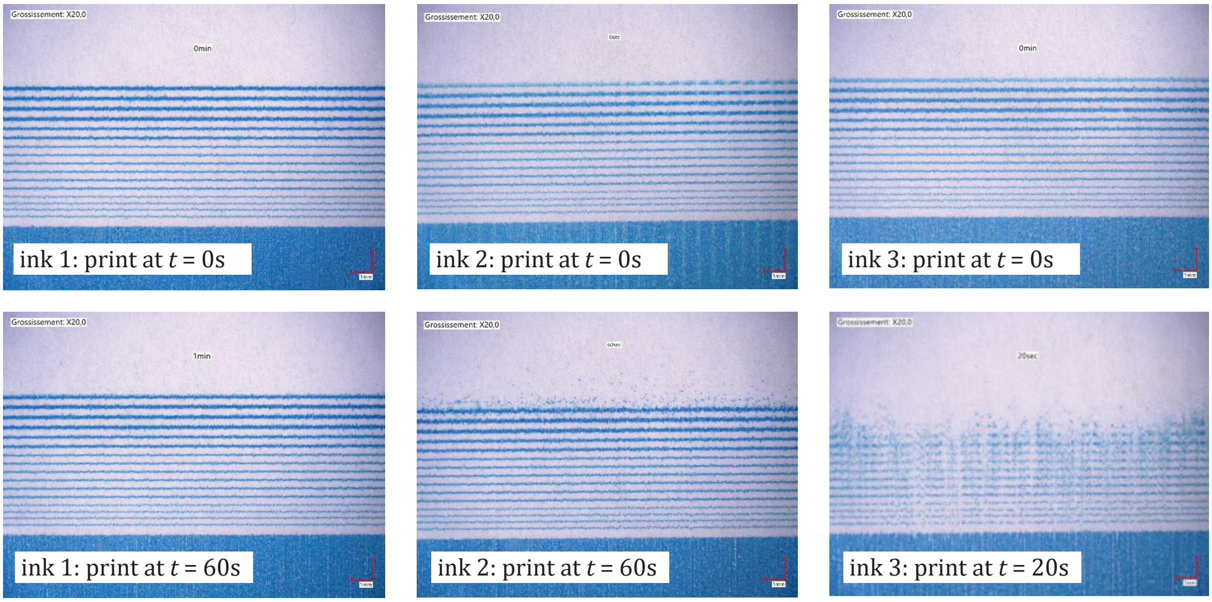

Figure 4: Latency pattern printed at various timeframes for the three inks studied

The latency index ($I_{latency}$) provided a straightforward method for comparing the latency level for multiple inks under similar idle time conditions, as illustrated in Figure 5. For Ink 1, $I_{latency} = 0$ regardless of the idle time. This result was expected since this ink demonstrated no latency issues, maintaining stable and continuous printing performance over extended idle durations. With the addition of 1 wt.% of free dispersant, the latency index remained stable at first and begun to increase after 60 s of idle time. At this point, latency issues started to appear, impacting print quality. After 300 s of idle time, none of the sixteen lines were printed anymore for Ink 2. When the free dispersant concentration was increased to 3 wt.%, the latency index begun to increase much earlier, indicating more rapid deterioration of the printing; $I_{latency}$ was already at its maximum value only after 30 s idle time.

These observations demonstrate that the latency index is a valuable metric for quantifying and comparing ink performance under different idle conditions.

3.3 Droplet formation observation (method 2)

Figure 6 illustrates the number of non-firing strokes (N_{nfs}) before the first ejected drop was detected, plotted as a function of idle time up to 600 s. For Ink 1, N_{nfs} was not consistently zero as expected for an ink with no latency. This can be attributed to the occa-

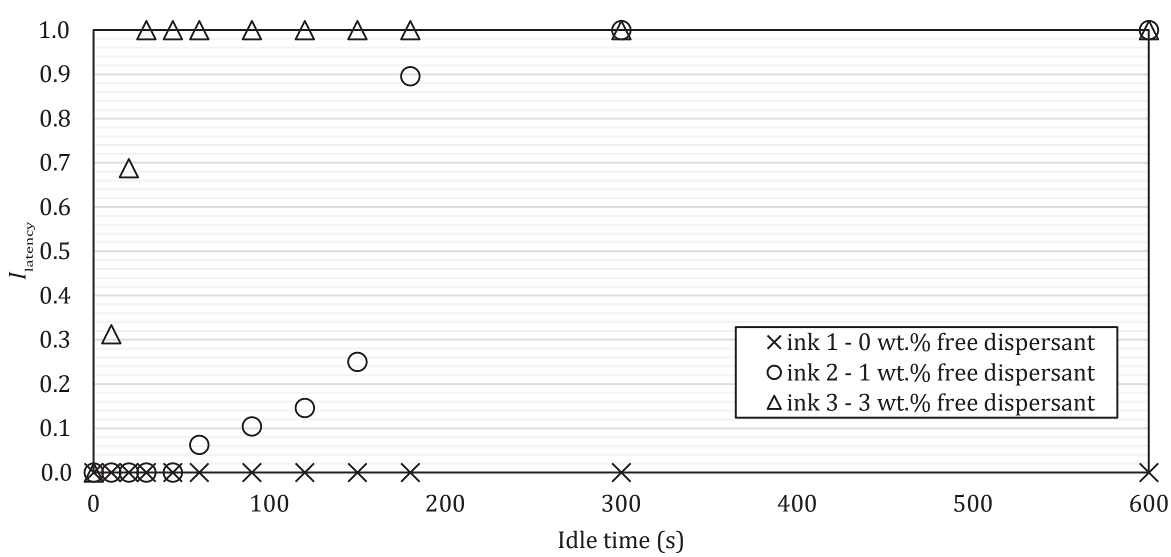

Figure 5: Latency index vs. idle time for inks with different levels of latency

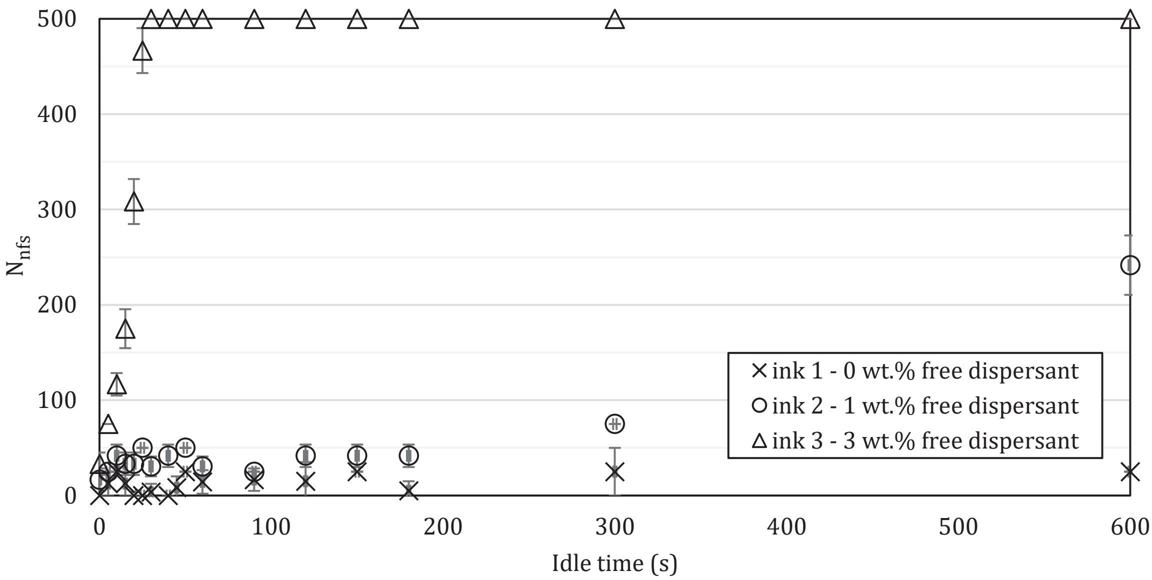

Figure 6: Number of non-firing strokes before first drop vs. idle time for inks with different levels of latency

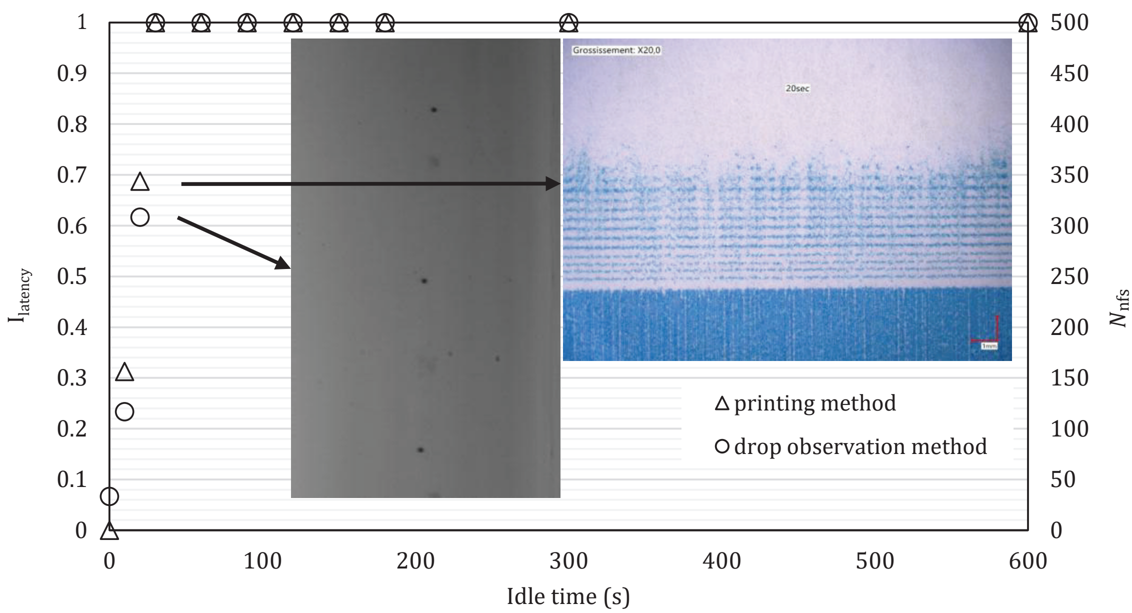

Figure 7: Comparison between the printing method ($I_{latency}$) and the drop observation method (N_{nfs}) for Ink 3

sional failure of the Droptimize platform to detect the first drop. When this occurs, N_{nfs} should be 25, calculated using Equation [2]. To account of this, it was assumed there is no latency when $N_{nfs} \leq 25$ drops when the frequency was 500 Hz. Based on this assumption, Ink 1 demonstrated no latency across all idle times. Latency begun to appear when free dispersant is added to the formulation. Indeed, for Ink 2, the latency level goes above the limit value of 25 but remains quite low with a N_{nfs} that only reaches 50 after 600 s idle time. This indicates that, while Ink 2 starts to show some latency behaviour, its performance remains relatively stable under prolonged idle conditions. For Ink 3, N_{nfs} number increases rapidly and reaches 500 after only 60 s of idle time. At a printing frequency of 500 Hz, $N_{nfs} = 500$ represents the maximum possible value. It means that no droplets are ejected from the nozzle during 1 second of continuous printing and it suggests severe latency or a complete nozzle clogging.

For Ink 1, the test was extended to assess latency up to 6 hours of idle time. The results show that the number of non-firing strokes before the first ejected drop remained below 25 throughout all this extended idle time period. Ink 1 exhibits therefore an excellent and very stable behaviour toward the inkjet printing process without disruption in droplet ejection over prolonged idle time.

3.4 Comparison of the two methods

Figure 7 compares the two methods proposed to evaluate the latency level: the printing ($I_{latency}$) and the drop observation (N_{nfs}) methods. The data reported on the graphic for Ink 3 shows a strong correlation between these two approaches. For each idle time, $I_{latency}$ and N_{nfs} feature the same trend, reflecting the progressive worsening of latency. At 60 s of idle time, both parameters reach their maximum values. Indeed, for $I_{latency} = 1$ and $N_{nfs} = 500$, the nozzles do not fire anymore: the latency phenomenon is critical as it will lead to unacceptable printing defects, impacting then the reliability and quality of the printed outputs. In an industrial context, where speed and reliability are key, inks with such latency performance can lead to production inefficiencies, higher waste rates, and reduced customer satisfaction. Addressing latency through optimized ink formulations and improved printing techniques is therefore essential.

To ensure the robustness of these methods, additional tests were conducted using other inks, which are not shown in this article. The results confirmed the applicability and consistency of these techniques, suggesting they can be widely implemented to evaluate the latency of any water-based inks designed for drop-on-demand inkjet printing.

4. Conclusion

This paper introduces two assessment methods to evaluate the latency issue encountered with the use of aqueous inks in drop-on-demand inkjet printing. These methods are particularly relevant in the field of applications such as printed electronics, high-quality printing, etc. where no missing areas in the printed pattern can be tolerated. Despite the critical aspect of this issue, the origins of the missing droplets and the missing printed areas were not identified nor quantified. The qualitative method (printed approach) can be used to quickly identify inks with significant latency problems. It offers an initial screening and allows easy comparison of inks towards their stability against different idle times. The quantitative method (droplet observation) provides a more precise measurement of the number of lost pulses that fail to eject drops, yet it requires a specific platform. The complementary use of the qualitative and quantitative methods offers then a full and accurate description of the latency issue for a given ink. Moreover, the developed methods can be extended to any kind of drop-on-demand inkjet inks and could benefit industrial users, improving the reliability of their production.

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