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The TriPAV: A High-Frequency Rheometer for Precision Inkjet Characterisation and Waveform Optimisation

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Abstract

Inkjet printing involves the complex interaction of mechanical, acoustic, and fluidic phenomena operating on microsecond timescales and micrometre length scales. Within a printhead, inks experience pressure oscillations approaching 100 kHz and shear rates up to 10^6 s^{-1}: these result from nanometre-scale deformations of the ink channel walls. These conditions impose viscoelastic stresses that are not captured by conventional rheometers, which are typically limited to oscillation frequencies below 100 Hz. Consequently, many inks that have apparently identical bulk rheology may exhibit very different jetting behaviours.

The TriPAV High-Frequency Rheometer was developed to bridge this gap by characterising low-viscosity fluids under realistic inkjet operating conditions. TriPAV uses solid-state piezoelectric excitation to measure the linear viscoelastic properties (G', G", η) of inks and functional fluids across frequencies from 1 Hz to 10 kHz—a frequency range much closer to those encountered during waveform actuation in Drop-on-Demand (DoD) and Continuous Inkjet (CIJ) systems. The instrument completes a full frequency sweep in under five minutes using <0.1 mL of sample and operates over 5–80 °C, enabling analysis of volatile or reactive inks, UV formulations, and solvent-based coatings.*

In its rapid step strain Printhead Mode, the TriPAV reproduces the acoustic excitation within a printhead channel. Controlled step-strain waveforms applied via a piezo actuator, and measured by a passive sensor, yield fluid response parameters—peak amplitude, peak time, and relaxation time—that correlate directly with waveform features such as drive voltage, pulse width, and wait time. Temperature-dependent tests (20–60 °C) further identify conditions that maximise pumping efficiency, meniscus stability, and droplet reliability.

Introduction

Inkjet technology requires precise control of droplet formation processes governed by the coupled effects of pressure, viscosity, surface tension, and viscoelasticity. Modern printheads operate at frequencies approaching 100 kHz, where the viscoelastic response of even low-viscosity inks influences filament stability, droplet detachment, and satellite formation. Conventional rotational or oscillatory rheometers, limited to <100 Hz, are unable to provide insight into ink behaviour under these conditions.

The TriPAV High-Frequency Rheometer, developed by Trijet Limited (Cambridge, UK), provides a quantitative link between ink formulation and jetting behaviour. Its unique design enables measurement of viscoelastic properties in the true operational range of industrial printheads. By combining high-frequency rheology and printhead-mode waveform simulation, the TriPAV offers predictive tools for ink formulation, waveform design, and quality assurance.

Experimental Methodology

Instrument Design

TriPAV operates as a solid-state, piezo-driven, squeeze-flow rheometer. A small volume of liquid (< 0.1 mL) is confined between two parallel plates separated by a 10–500 µm gap. The lower plate, coupled to an active piezoelectric element, is oscillated with nanometre amplitude (< 10 nm, 0.01–0.2 % strain). The upper plate carries a passive piezo sensor that records the transmitted stress response. Figure 1 shows the complete set of TriPAV equipment.

Using a lock-in amplifier, the system resolves both amplitude and phase shift between excitation and response, allowing calculation of the storage modulus (G′), loss modulus (G″), and complex viscosity (η)* over a 1 Hz–10 kHz frequency range.

Figure 1. *TriPAV equipment with lock-in amplifier, thermostat circulator, digital thermometer.*

Figure 2 highlights the usefulness of high-frequency data in distinguishing between seemingly identical inks [1]. The blue and black ceramic inks shown, both from the same supplier, exhibit similar bulk and low-frequency rheological behavior, yet display pronounced differences in elastic modulus (G') and complex viscosity at higher frequencies. Tests with a standard rheometer, spanning the frequency range shown in blue, would conclude that there is very little rheological difference between the two inks. TriPAV data, however, demonstrates that the blue ink has an elastic response ten times greater than the black ink on the timescale that becomes important for inkjet printing. This difference may lead to the blue ink not being fit for purpose.

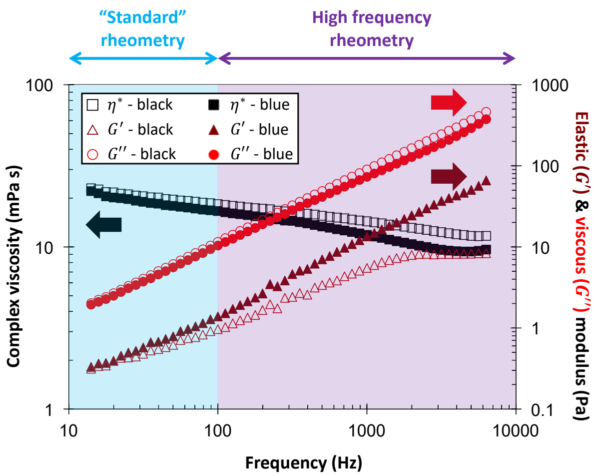

Figure 2. *PAV oscillatory linear viscoelastic data showing subtle differences between a set of ceramic blue and black inks from the same supplier at higher frequencies which otherwise had similar bulk properties.*

Printhead Mode (Waveform Simulation)

In Printhead Mode, the TriPAV mimics printhead actuation by applying a controlled square or step waveform (± 2 V) to simulate the piezo deformation within a printhead channel. The resulting fluid response—measured as voltage across the passive element—provides insight into the transient dynamics of the fluid.

Figure 3 shows a typical fluid response obtained from the TriPAV operating in step-strain printhead mode. Here, the blue curve is the applied waveform, consisting of a step change in voltage, and the brown curve is the inverted fluidic response .

The response curve parameters correspond to the:

- peak amplitude → effective pumping capacity (∝ 1/viscosity);
- peak time → acoustic transit time (related to the speed of sound and the channel length);
- relaxation time → meniscus damping and droplet stability.

These parameters can be directly translated into drive voltage, pulse width, and wait time for waveform design.

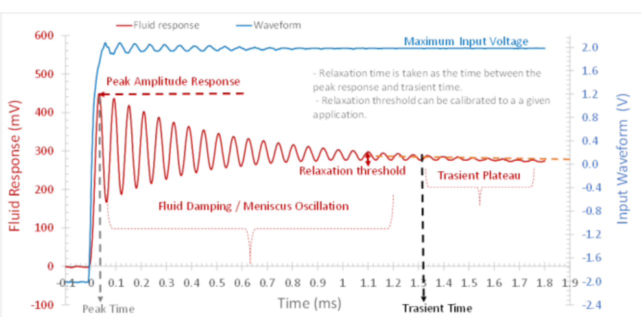

Figure 3. *Typical fluid response in TriPAV printhead-mode showing peak amplitude, peak time, and relaxation time.*

Operating Conditions

All experiments were conducted between 5–80 °C using a temperature-controlled circulator. Frequency sweeps required less than five minutes, while Printhead Mode temperature ramps (20–60 °C) were completed in under 30 minutes per sample.

Results and Discussion

Case Study 1 Showcasing TriPAV High Frequency Rheology of Aqueous CMYK Inks

A CYMK (cyan – magenta – yellow – key black) set of water-based inks for use in an inkjet printing press had been received from a supplier. Whilst the magenta, yellow and black inks printed as expected, the cyan ink did not. Conventional rheological testing, using steady shear and dynamic tests, could not detect any differences between the four inks.

Figure 4A shows a collage of rheological response for all four inks [2]. Here, the trends of complex viscosity, η*, as a function of frequency are shown as open squares and the trends of viscous modulus, G", as a function of frequency are shown as filled circles. Where it is present, the trend of elastic modulus, G', as a function of frequency is shown by filled triangles. The colour of each symbol denotes the ink type. While all four inks (C, M, Y, K) had similar low-frequency viscosities, only cyan displayed measurable elasticity (G′ > 0) at high frequencies (>1 kHz). This correlated with unstable jetting behaviour. Figure 4B shows the rheological response of the reformulated cyan ink.

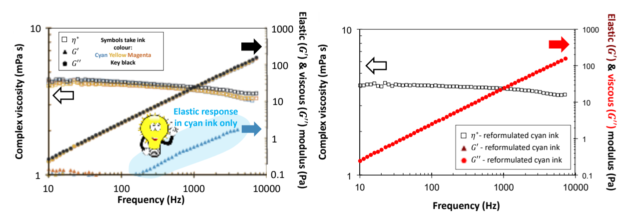

Figure 4. *TriPAV complex printhead-mode showing peak amplitude, peak time, and relaxation time.*

TriPAV testing demonstrated that a high frequency elastic response in the original cyan ink was responsible for the observed jettability problems.

Use of the TriPAV as part of ink the reformulation process allowed a replacement cyan ink to be designed that behaved identically to the remaining inks in the colour set.

Case Study 2 Showcasing TriPAV Printhead Mode Short Timescale Step Strain Data

In order to successfully jet an inkjet fluid, the fluid viscosity must lie within a range that is able to be jetted by the printhead. Whilst there are ways to design and operate a printhead such that it can be used with high viscosity fluids, fluid viscosity can also be manipulated to be compatible with existing print systems. One way in which this can be done is to use heat! Typically, fluid viscosity decreases with increasing temperature, which allows ink viscosity to be matched to printhead requirements.

The plots shown in Figure 5 demonstrate how the response to a step strain test differs for two inks, A and B, at three temperatures

[2]. The response voltage is plotted as a function of time on the primary y-axis in various shades of red, and the step change in driving voltage is shown on the secondary y-axis in blue.

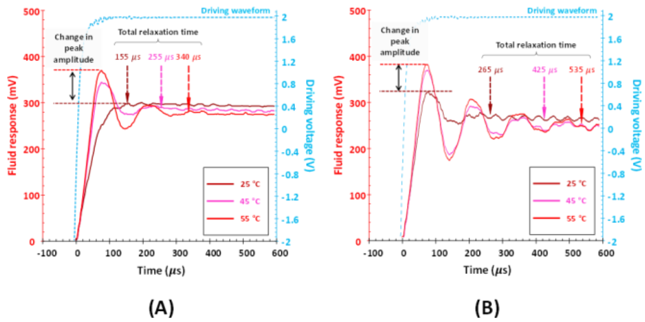

Figure 5. *Typical fluid response in TriPAV printhead-mode showing peak amplitude, peak time, and relaxation time (A) Ink A, and (B) Ink B.*

For ink (A) at 25°C, no oscillatory response can be seen. This infers that the energy transfer from the piezo actuator to the ink is poor and insufficient to result in jetting. As the ink temperature is increased, the amplitude of the first peak increases, indicating that more energy is being transferred to the liquid. These higher peak amplitudes correspond to conditions where jetting would occur in a printhead. It can also be seen that the hotter inks tend to "ring" for a longer period of time, with the oscillatory response damping out at 255 μs at 45°C and 340 μs at 55°C. These oscillations can be linked to the movement of the fluid meniscus within an inkjet nozzle. For reliable jetting, this movement is usually allowed to decay before another driving pulse is applied. The longer this decay time, the slower the printing process! The choice of temperature is a compromise between energy transfer to allow jetting and print speed. A similar set of trends can be seen for ink (B) except that the total relaxation time – the time required for oscillation to decay – is longer at every temperature.

Printhead mode step strain tests on the TriPAV can quickly identify the optimum jetting temperature for an inkjet fluid. The optimum temperature is a compromise between transferring enough energy to pump the fluid, and having a relaxation time short enough for the desired print speed.

Case Study 3- Optimising the Jetting Temperature of UV Inks

A yellow and a black UV-curable ink both had manufacturer's recommended jetting temperatures of 35°C. When these inks were trialled in a printing application, it became evident very quickly that there was a problem! At 35°C, the black ink failed to print and the print quality of the yellow ink was sub-optimal. A programme of investigation was started to understand why this was case and how to solve the problem.

Peak amplitude as a function of temperature from TriPAV step strain testing of both inks is shown in Figure 6A, with the total relaxation time for both inks as a function of temperature being shown in Figure 6B. The sequence of images in Figure 7 show droplet flight behaviour for both inks at three selected temperatures within the testing range.

The energy transfer to the inks, as evidenced by an essentially stable peak voltage, does not change significantly above 30°C. For the yellow ink, a change in the trend of relaxation time – indicating the onset of "ringing" - happens between 28°C and 31°C, with a similar change happening for the black ink between 41°C and 44°C. From the images, one can see that the onset of "ringing" corresponds to successful jetting. Temperatures above this onset temperature infer increasing meniscus oscillation, which can lead to misfiring and print quality problems.

TriPAV printhead mode tests (Figure 6A) quickly identified the optimal jetting temperature for both inks. A (time consuming) set of visualisation studies (Figure 7) confirm the choice of ink temperature.

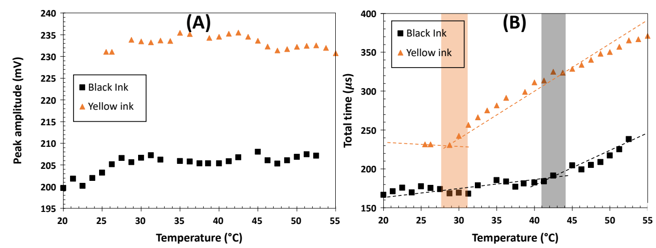

Figure 6. *TriPAV printhead mode data for UV yellow and UV black as a function of temperature showing (A) peak amplitude and (B) total time (peak time + relaxation time).*

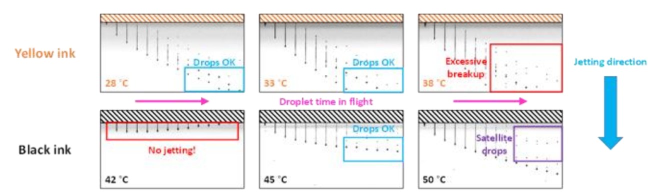

Figure 7. *In-flight jetting images of the UV yellow and black inks using a Ricoh Gen 5 printhead.*

Case Study 4- Jetting of High Viscosity Inks

Inkjet printing technology is being applied to an ever-wider range of applications, including additive manufacturing. This application provides a wealth of challenges and opportunities for the industry as fluids used for additive manufacturing can be orders of magnitude more viscous than traditional inks. Transferring a sufficient amount of energy from the printhead to the fluid for jetting to occur can be a significant challenge! Tailoring the formulation of an ink can make the difference between an ink that jets and one that does not.

Figure 8A shows the TriPAV complex rheology data for a jettable (closed symbols) and a non-jettable (open symbols) high viscosity fluid, and Figure 7(B) and (C) give TriPAV printhead mode step strain data for both fluids.

The complex viscosity for the jettable fluid is higher than that for the non-jettable fluid, but its formulation has been designed to produce an elastic response at the timescales relevant to jetting within a printhead ($G' \gg 0$ for $f > 2$ kHz). The effect of this high frequency elastic response is to enhance the energy transfer from the printhead to the fluid, resulting in high viscosity jettability.

TriPAV frequency sweep data combined with TriPAV printhead mode step strain data is a powerful tool to assist the development of inkjet fluids for use in challenging processes.

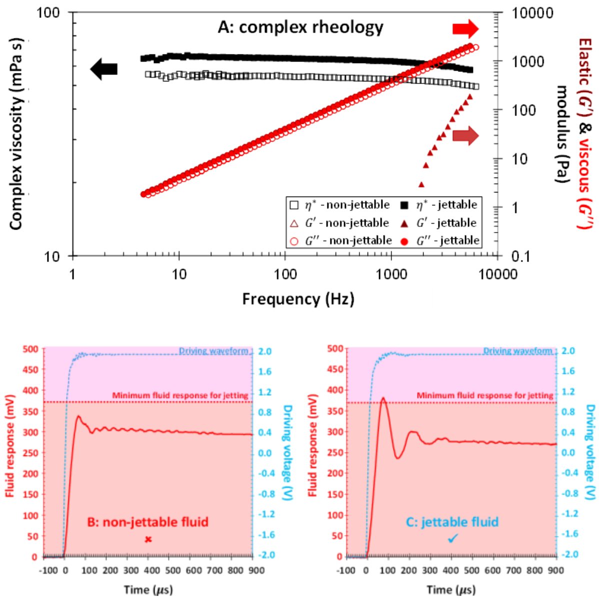

Figure 8. *(A) TriPAV complex rheology of jettable and non-jettable ink, (B -C) TriPAV printhead mode step strain data of both fluids.*

Conclusions

The TriPAV high-frequency rheometer introduces a new paradigm for understanding inkjet ink behaviour under realistic operating conditions. By extending rheology into the high-frequency regime relevant to inkjet printheads, the TriPAV provides a quantitative link between formulation, structure, viscoelastic response, and droplet dynamics.

The TriPAV printhead mode step-strain temperature sweep, which can be done in less than 30 minutes, supports real-time formulation screening and production QC, allowing early detection of formulation drift or additive incompatibility. This approach transforms waveform optimisation from empirical tuning to a quantitative, measurement-driven process.

Key outcomes include:

- Differentiation of inks with similar bulk rheology but different jetting outcomes;
- Predictive optimisation of waveform parameters (drive voltage, pulse width, wait time);
- Identification of optimum jetting temperature for each formulation;
- Reliable QC metrics for production environments.

The TriPAV's combined high-frequency and printhead-mode analysis thus accelerates ink development, improves process reliability, and supports growing industrial demand for predictive, data-driven inkjet characterisation.

Acknowledgements

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References

[1] T R Tuladhar, "Metrology- Measurement of Complex Rheology and Jettability of Inkjet Inks" Chap. 22 in "Handbook of Industrial Inkjet Printing", edited by W. Zapka, pp 411-429, ISBN: 978-3-527-338320, Wiley-VCH, (2017).

[2] Extreme Rheology with the TriPAV rheometer, www.trijet.co.uk, 2025.

Author Biography

Dr. Tri Tuladhar holds a Ph.D. in Chemical Engineering from the University of Cambridge and bachelor's degree at RMIT University, Australia. With over 25 years of R&D experience in both academia and industry, he has specialised in the complex rheology of inkjet inks since 2005, pioneering methods that link fluid rheology to jetting performance.

As Founder and Head of Trijet Limited, Dr. Tuladhar leads advanced rheological characterisation and optimisation of inkjet inks, formulates specialty paints, glass enamels, and functional inks, and designs bespoke rheological tools. He also delivers workshops and training courses for industrial clients, sharing his expertise in ink formulation and jetting process optimisation.