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Development of a Multi-Nozzle Hybrid Inkjet Printhead Enabling Droplet Ejection up to 200 cP Using Piezoelectric-Electrohydrodynamic Mechanism

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Abstract

Inkjet printing is widely used due to its high precision in depositing ink at specific locations. However, it is limited to low-viscosity inks below 20 cP, restricting its compatibility with various functional materials. In contrast, electrohydrodynamic (EHD) printing allows jetting of inks with viscosities above 50 cP, but its short working distance (≤100 μm) and low throughput hinder large-scale application.

To overcome these limitations, we have developed an innovative hybrid inkjet printhead that integrates the benefits of both conventional piezoelectric and EHD printing mechanisms. Utilizing this advanced system, we conducted experiments on the ejection of 200 cP viscosity inks, a feat challenging for conventional piezoelectric-actuated systems.

The proposed hybrid inkjet printhead equipped with both piezoelectric actuators and EHD electrode to achieve a synergistic effect combining mechanical and electrical forces. The hybrid inkjet printhead enables stable ejection of high-viscosity inks (≤200cP) through 16 nozzles and 100 npi simultaneously. Also, this hybrid inkjet printhead can eject droplet volume range between 10 and 12 pL at a working distance exceeding 1 mm. Therefore, the ability to eject from multiple nozzles and high viscous ink concurrently enhances productivity, expanding the potential for applications across various industrial sectors.

Introduction

Inkjet printing systems, as digital and non-contact deposition platforms, have been widely adopted across various industrial sectors such as displays, semiconductor packaging, printed circuit boards (PCB), sensors, and biomedical devices due to their high printing speed, cost efficiency, and compatibility with a wide range of substrates [1-2]. In particular, in additive manufacturing and printed electronics, inkjet printing is gaining increasing attention as a key enabling technology for direct patterning without the need for complex masking or lithographic steps, thereby reducing process complexity while facilitating the fabrication of flexible electronic devices [3].

However, the most widely utilized drop-on-demand (DOD) inkjet systems based on piezoelectric actuation inherently suffer from rheological constraints, especially in terms of ink viscosity [4]. Commercial piezoelectric inkjet printheads are generally limited to fluids with viscosities below 20 cP, confining their operation to low-viscosity solvent-based inks. As a result, the precise patterning of high-viscosity functional materials—such as conductive adhesives, metal nanoparticle suspensions, and polymer-based bioinks—remains challenging [5-6].

In contrast, electrohydrodynamic (EHD) printing systems exploit electric field-induced stresses at the meniscus to eject liquids with viscosities exceeding 100 cP [7]. Moreover, EHD actuation can achieve sub-10 μm feature resolution, even below the physical nozzle diameter, making it a promising technology for ultrahigh-resolution patterning [8]. Nevertheless, EHD-based printing is constrained by its strong dependence on the applied electric field, resulting in restricted stand-off distances of only a few millimeters and relatively slow jetting speeds, which limit its applicability in high-throughput manufacturing. Furthermore, electrical interference between adjacent nozzles makes it difficult to scale EHD systems into multi-nozzle arrays, hindering their transition toward industrial continuous production [9].

Recent studies on hybrid printing strategies have demonstrated that applying an auxiliary electric field to a piezo-driven system can effectively suppress satellite formation in high-viscosity jetting. However, most of these demonstrations have been limited to single-nozzle configurations, and no scalable architecture capable of extending the concept to multi-channel arrays without nozzle-to-nozzle interference has been established to date [10].

Meanwhile, the demand for high-viscosity precision jetting is rapidly increasing in applications such as printed electronics, flexible packaging, micro-LED bonding, and hydrogel bio-fabrication. Consequently, hybrid inkjet systems that simultaneously leverage the high-speed stability of piezoelectric actuation and the high-viscosity jetting capability of EHD actuation are emerging as next-generation core technologies for digital additive manufacturing.

In this study, we propose a multi-nozzle hybrid inkjet Printhead (Model: EHDison-H16) that simultaneously employs piezoelectric pressure actuation and electric field assistance. We demonstrate that this approach enables stable ejection of inks with viscosities up to 200 cP. The proposed system effectively overcomes the viscosity limitations of conventional inkjet systems while maintaining compatibility with industrial multi-nozzle architectures, offering high scalability and practical applicability for future manufacturing platforms.

Furthermore, reliability evaluations are concurrently being conducted on the 512 nozzles large area printhead developed by ENJET. This printhead is designed to simultaneously achieve high-resolution and high-speed printing performance and is being assessed under actual industrial process conditions in terms of stable operation, nozzle-to-nozzle uniformity, and long-term continuous jetting characteristics. Such parallel studies serve as an important step in demonstrating that the proposed hybrid actuation scheme can be stably applied not only to small-scale single-nozzle heads but also to large-area multi-nozzle printheads.

Printhead Design

16 Nozzles & 512 Nozzles Hybrid Head

The proposed hybrid printhead, named EHDison-H16, is developed and commercialized by ENJET Co., Ltd. The EHDison-H16 printhead features a linear array structure with 16 nozzles arranged at a pitch of 100 NPI (Nozzles Per Inch). Each nozzle is precisely fabricated using MEMS technology, minimizing crosstalk and ensuring uniform droplet formation across the array. The printhead employs a hybrid actuation mechanism that separates the roles of the Piezoelectric (Piezo) actuator and the Electrohydrodynamic (EHD) electrode. The Piezo actuator instantaneously increases the chamber pressure to form the initial meniscus at the nozzle outlet. Once the meniscus is established, a high voltage is applied to the EHD electrode located at the nozzle gate, elongating the meniscus and enabling stable jetting even with high-viscosity inks. The EHD electrode is positioned near the nozzle exit and generates a strong electric field when high voltage is applied. The nozzle and EHD electrode are electrically insulated, allowing independent control of the electric field strength without interfering with the piezoelectric actuation. A Driver-Per-Nozzle (DPN) control circuit is implemented, enabling each nozzle to be independently driven by a customized piezo waveform. This allows optimization of jetting conditions for both high- and low-viscosity inks. The head also integrates a built-in heating structure, with a temperature sensor installed inside the ink chamber. The ink temperature can be adjusted up to 50 °C, enabling viscosity control and improving jetting stability. Unlike conventional cartridge-type systems, the EHDison-H16 adopts a refillable ink supply structure, which supports long-term continuous operation and repeated experiments with various functional materials.

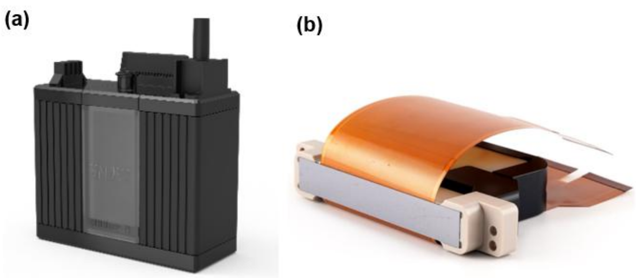

Figure 1. *(a) EHDison-H16, (b) 512 Nozzles Head*

The 512-nozzle (512Nz) large-area printhead is currently undergoing long-term reliability evaluation. It features a linear array of 512 nozzles with a pitch of 200 NPI (Nozzles Per Inch). A degasser is integrated into the system, which effectively removes bubbles from the ink and reduces bubble inflow into the head, thereby enabling stable and continuous jetting. The printhead is designed to simultaneously achieve high resolution, large-area coverage, and high-speed printing performance, and is being evaluated under actual industrial process conditions in terms of stable operation, nozzle-to-nozzle uniformity, and long-term continuous jetting characteristics.

EHDison-H16 Mechanism

The EHDison-H16 printhead integrates Piezoelectric (Piezo) and Electrohydrodynamic (EHD) actuation mechanisms within a single hybrid platform. Structural optimization of the actuator was performed using Finite Element Method (FEM) analysis. A comprehensive multiphysics simulation was conducted using the COMSOL Multiphysics® module, which included electrostatics, solid mechanics, and fluid dynamics. The simulation process was divided into multiple stages to accurately capture the droplet formation mechanism. Based on the simulated jetting behavior, the nozzle geometry and chamber dimensions were optimized to achieve stable droplet ejection. Similarly, the EHD electrode was optimized through detailed parametric analysis using coupled electrostatic–fluid simulations. The effects of electrode spacing, height offset, and electric field distribution were analyzed to determine the optimal configuration that enhances electric field uniformity and minimizes fluidic disturbance. The fabrication process employed Micro-Electro-Mechanical Systems (MEMS) technology. Three wafers—the chamber wafer, nozzle wafer, and EHD electrode wafer—were individually processed and subsequently bonded to form the final head assembly. A custom-designed FPCB and nozzle surface layout were developed to match the electrical and mechanical interfaces of the fabricated head. The housing structure was carefully designed to ensure that the Piezo and EHD electrodes operate independently without electrical or mechanical interference. The jetting performance of the EHDison-H16 was evaluated using a drop-watcher visualization system. Experimental results showed that the droplet velocity increased by up to 70% when the EHD voltage was applied in conjunction with Piezo actuation, compared to Piezo-only operation.

During hybrid operation, a unipolar trapezoidal waveform was applied to the Piezo actuator to generate pressure within the chamber and form a meniscus at the nozzle orifice. Once the meniscus was established, a synchronized EHD electric field was applied, which elongated the meniscus and enabled stable droplet ejection even for high-viscosity inks. Unlike the continuous cone-jet mode observed in pure EHD systems, the hybrid EHDison-H16 platform allows flexible operation in selective ejection mode, enabling Piezo-only, EHD-only, or simultaneous hybrid actuation depending on the ink properties and process requirements.

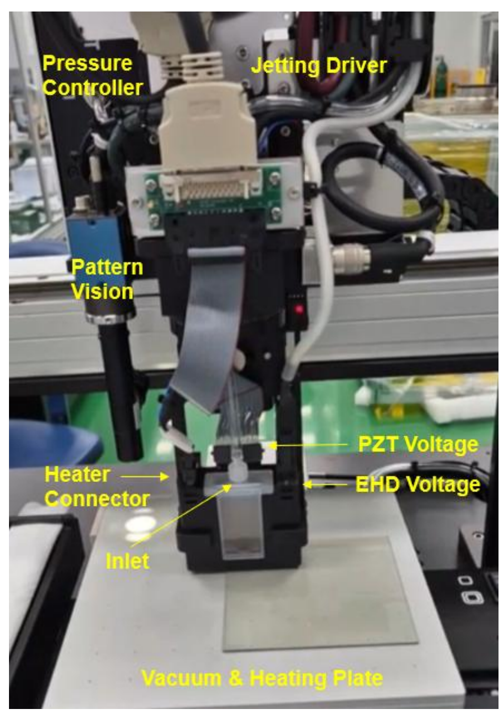

Figure 2. *EHDison-H16 Printer for R&D Printing*

Experimental Setup

To evaluate the jetting performance of the EHDison-H16 hybrid printhead, standard reference solvents covering a wide viscosity range from 4 cP to 200 cP were prepared in-house.

The rheological and physicochemical properties of the inks were characterized using in-house measurement equipment. Viscosity was measured with a CAS CL-1 viscometer, surface tension with a SITA DynoTester+, electrical conductivity with a Mettler Toledo SevenDirect SD30, and dielectric constant with an 871 Liquid Dielectric Constant Meter (Sanyo Trading Co., Ltd.).

Droplet formation and jetting behavior were visualized using a CCD (Charge-Coupled Device) camera system, which enabled real-time observation of droplet volume, ejection angle, and velocity. Sequential imaging and time-resolved velocity measurements were also employed to analyze droplet dynamics under various operating conditions.

Results and Discussion

Jetting of Viscosity Variable Standard Solvents

The jetting characteristics of viscosity-standard solvents were analyzed using the EHDison-H16 hybrid printhead. The results demonstrate that the hybrid actuation (Piezo + EHD) enables stable droplet formation even for inks with high viscosity (up to 200 cP), whereas the Piezo-only mode failed to eject beyond 30 cP.

The jetting behavior of viscosity-controlled standard solvents in the range of 4 cP to 200 cP was observed using a Drop-watcher system (see Figure 3). Stable droplet ejection was achieved using only the piezo actuator up to a viscosity of 30 cP. However, for inks exceeding 50 cP, piezo actuation alone was insufficient to generate droplets, and an auxiliary EHD voltage was applied. The applied waveform conditions were adjusted depending on viscosity. The piezo waveform included rising, dwell and falling times in the microsecond range, with voltage amplitude sufficient for stable actuation. For higher viscosities, an additional EHD waveform with extended dwell time and higher amplitude was used to optimize ejection.

The average droplet velocity across the viscosity range was measured to be approximately 2.5–3 m/s, and the average droplet volume was 10 pL. Furthermore, the jetting performance was evaluated at increasing actuation frequencies to verify stable droplet ejection without any anomalies in the printhead. A high-speed camera was employed to accurately observe droplet formation, and stable ejection was confirmed up to a frequency of 30 kHz (see Figure 4).

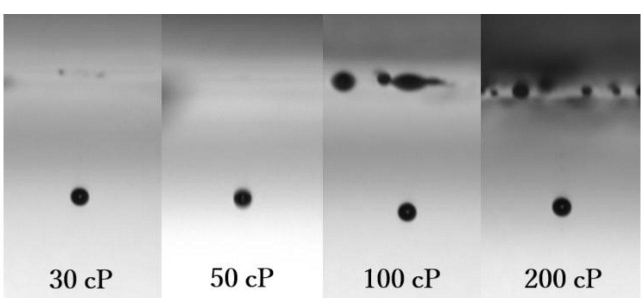

Figure 3. *Jetting Performance by Ink Viscosity*

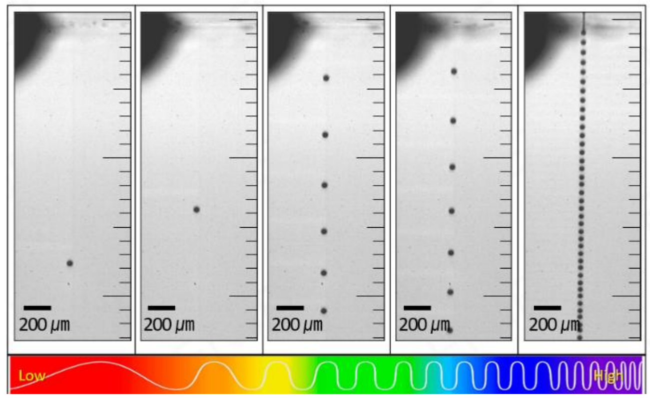

Figure 4. *Droplet Ejection Results by Frequency*

Inkjet printing of the ENJET logo and electrode patterns was performed on hydrophobically coated substrates using inks of varying viscosities. The substrates exhibited a Di-water contact angle of 100–110°, and the diameter of individual droplets was measured to be approximately 30 μm. Printing with multi-nozzle operation produced uniform patterns without satellite droplets, demonstrating precise and consistent droplet deposition. These results indicate that high-resolution and uniform printing can be achieved across a range of ink viscosities (see Figure 5, 6).

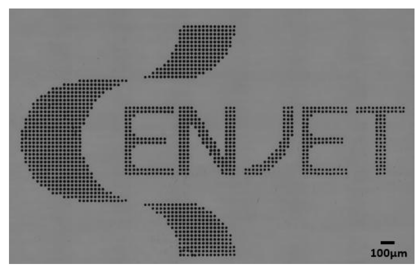

Figure 5. *ENJET Logo Printing Image*

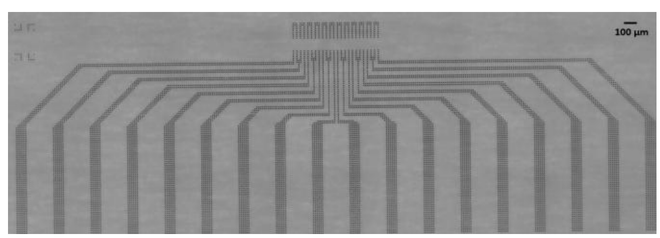

Figure 6. *Electrode Pattern Printed at 600 dpi*

512 Nozzles Printhead Jetting Test

To evaluate high-speed jetting performance, the 512Nz printhead was used to dispense the same viscosity-controlled standard solvents. The actuation frequency was increased up to 30 kHz, and nozzle uniformity and stability were monitored using a CCD camera. Figure 7 and 8 shows representative droplet images at 20 kHz and 30 kHz. All nozzles ejected droplets consistently, maintaining uniform droplet size and velocity across the array. These results demonstrate that the 512Nz printhead can achieve high-throughput printing while preserving droplet uniformity for viscosity-controlled solvents.

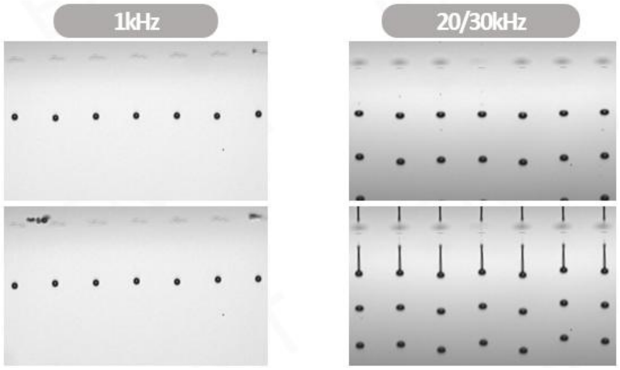

Figure 7. *512Nz printhead droplet ejection at 20 kHz and 30 kHz*

	Volume[pl]	Speed[m/s]
Average	10.72	2.89
Standard Deviation	0.63	0.27

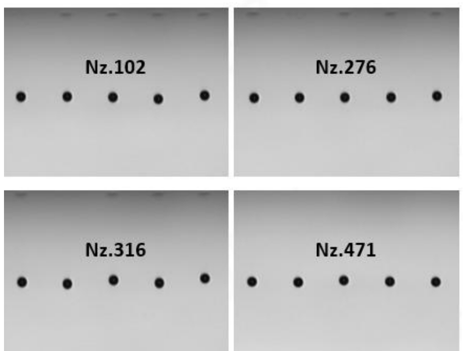

Figure 8. *Droplet velocity uniformity of the 512Nz printhead*

Conclusion

In this study, we successfully developed and evaluated a multi-nozzle hybrid inkjet printhead, the EHDison-H16, capable of jetting a wide range of ink viscosities from 4 cP to 200 cP. The hybrid actuation strategy, combining piezoelectric pressure actuation with electrohydrodynamic assistance, enabled stable droplet formation across all tested viscosities. Comprehensive jetting and printing experiments demonstrated that the printhead can reliably handle viscosity-controlled functional inks. Continuous droplet ejection tests confirmed long-term nozzle reliability, and practical printing experiments on substrates such as PCB, PET, and glass verified precise droplet placement and high-quality pattern formation.

These results highlight the versatility and robustness of the EHDison-H16 hybrid printhead in addressing the limitations of conventional piezoelectric and EHD-only systems. Moreover, the platform shows potential for scalability and high-speed operation with larger multi-nozzle arrays, such as the 512Nz printhead, which is currently undergoing long-term reliability evaluation.

Overall, the EHDison-H16 platform provides a scalable and industrially applicable solution for next-generation digital printing technologies, bridging the gap between laboratory research and practical manufacturing environments.

Acknowledgments

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