Qualifying Printhead-Ink Combinations for Industrial Printing

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Abstract

With the spectrum of inkjet printing applications broadening, novel ink formulations and demanding application requirements continuously challenge printhead designs. To succeed in the industrial inkjet printing business, printhead manufacturers need to systematically integrate and qualify printhead-ink combinations optimally suited to specified application targets. This paper presents the approach taken by FUJIFILM Dimatix, Inc. in achieving this goal.

Introduction

As piezoelectric drop-on-demand (DOD) inkjet printing technology continues its expansion into image and documentation printing, it has also penetrated into industrial printing domains such as printing on textiles, ceramic tiles, food, and other very exciting areas [1-13].

The basic operation of piezoelectric DOD technology involves managing the ejection of little droplets, less than 100 µm in diameter, in a desired fashion accurately and reliably onto a targeted location. The fundamental aspects of DOD drop formation processes, including liquid ejection, capillary breakup, thread retraction, satellite formation, etc., have been studied over the last two decades in great detail [14-18]. The basic mechanisms underlying the operation of piezoelectric DOD inkjet devices also have been studied extensively [19, 20]. The fluid properties (surface tension, viscosity, and bulk modulus) and the operating conditions (actuating waveform, jetting frequency, jetting voltage, and temperature) were found to greatly affect DOD drop formation process, including the evolution of ejected ligament, nozzle plate wetting, jet straightness, and sustainability [21-29, 33-36]. The studies have also shown that drop formation characteristics are highly dependent on inkjet ink formulation and printhead operating conditions. The differences in drop formation characteristics are significant from one printhead-ink combination to the other. Thus, the understanding of printhead-ink interaction is critical to fulfill the image quality requirement of each appliaction.

Application targets dictate printhead capability and ink functionality. One application may require a printhead-ink combination to obtain higher productivity with acceptable image quality, while another may demand superior material addressing accuracy with reasonable throughput. A faster printing speed may suggest the usage of a faster drying and/or curing ink. However, that same choice may lead to a shorter open time and a narrower operating window for a given printhead design.

In order to reach to a balance between jettability and functionality, a successful integration of a printhead-ink combination requires 1) working from both ends, namely, printhead design and ink formulation, to satisfy the application needs, and 2) qualifying the printhead-ink combination based on the application requirement as it evolves during each step of the technology development process.

This paper focuses on the second issue mentioned above in terms of the instrumentation and methodology developed at FUJIFILM Dimatix, Inc. to study and analyze the performance of printhead-ink combinations. These techniques are capable of qualifying printhead and ink designs as well as recommending solutions for individual customers' needs.

This paper starts with a discussion on why different inks must be treated differently, follows with the basic principles guiding how we approach the printhead-ink interaction, and presents the data and information used to qualify a printhead-ink combination using various kinds of tools.

Why Inks Behave Differently

The jetting performance of an inkjet ink is defined here by four major components: drop formation, nozzle plate wetting, jet straightness, and sustainability. All the jetting conditions, including actuating waveform, jetting voltage, jetting frequency, image pattern, and temperature, have effects on the jetting performance. It was found that under the same jetting condition, inks with similar static fluid properties often behave differently compared to each other. This is due to the complexity of piezoelectric DOD drop formation process.

For the DOD drop formation process, the length scale is ~ O(10 µm), confined by the nozzle size, and the time scale is ~ O(100 µs), depending on the jetting frequency. In this process, the shear rate can be as high as 10^6 s^{-1} [1, 30] and the rate of surface dilatational deformation can be as high as 10^5 s^{-1} [30]. Under such conditions, inkjet inks are typically not Newtonian fluids and do not have constant interfacial energies when contacting with other phases. Due to the existence of microstructures formed by pigment particles, latex particles, polymers (with varied weight fraction, molecular weight, molecular structure and conformation in solution), surfactant, etc., inkjet inks may exhibit various non-Newtonian and dynamic interfacial behaviors, such as dependence of viscosity on shear rate [30] and/or shearing time [30], viscoelasticity [29, 31, 32], varying extensional viscosity [32], dynamic surface tension [33] and interfacial energy [34]. Moreover, at the nozzle, solvent evaporation (such as in solvent and aqueous ink) and polymerization (such as in UV-curable ink) of one or multiple components of the ink may change ink stability and, thus, fluidic and interfacial properties [35, 36]. Nozzle plate wetting, which is closely related to printhead operating conditions and ink properties, is found to affect not only the drop formation process but also jet reliability [33-36]. Speed of sound of the ink varies depending on the jetting temperature and ink formulation, which leads to differences in printhead frequency response.

Thus, the jetting performance is hardly repeatable among various ink formulations.

Defining Printhead-Ink Interaction

Printhead and ink are typically studied separately. For printheads, their performance may be qualified using a simple Newtonian fluid, which is a common practice in printhead R&D and manufacturing qualification processes. This approach is economically sound and has been proven to reliably provide data for quality control. For inkjet inks, static fluidic properties (primarily, viscosity and surface tension) are characterized as baselines for matching the requirements of the printhead specification. Information obtained from above two approaches may be used as guidelines for setting expectations and explaining the jetting performance of real inks.

However, as discussed previously, unexpected jetting performance is often observed for real inks, leading people to study the dynamic properties of inkjet inks and their effects on jetting performance. Wang et al. [37] developed a capillary viscometer specified for measuring high shear-rate viscosity of inkjet inks. They found that shear viscosity of inkjet inks decreases significantly at high shear rates depending on particle loading. The drop formation characteristics of a simple Newtonian liquid were compared with that of a colloidal suspension system which has the same low-shear-rate viscosity, but significantly different high-shear-rate viscosity. However, it was found that the drop formation dynamics of the pigment-loaded suspension was similar to that of a Newtonian liquid. Hoath S. and Martin, G. [29] utilized piezoelastic axial vibrator (PAV) [38] to measure the high-frequency rheological properties of model viscoelastic fluids containing linear polymers with various molecular weights and studied the jetting performance of those fluids. They found that, although the jetting behavior was well correlated with the high frequency rheological properties measured at 5kHz, it showed no correlation with low shear-rate conditions. Vadillo et al. [31] also utilized PAV to measure the high-frequency response of model inkjet inks and they used the “Cambridge Trimaster” [32] to characterize the high speed stretching and break-up behavior of those fluids. Both apparatuses were found to provide valuable data to correlate the coupling of inkjet rheology and jetting properties. However, no commercially available instrument is capable of measuring dynamic surface tension at the surface dilatational rate encountered in DOD drop formation process. de Jong et al. [33] studied nozzle plate wetting and attributed the observed Maragoni flow to an effective lower surfactant concentration of the ink around the nozzle while jetting occurs.

The discrepancy of jetting performance between simple Newtonian fluids and real inks is fundamentally due to the following: 1) the microstructures in real inks response to bulk motions, which leads to dynamic bulk and interfacial properties; 2) such a response takes time under sufficiently high hydrodynamic motions and relaxation of microstructure occurs once external forces disappear; and 3) the jetting process is not only short in both length and time scales, but also transient without steady state flow profiles. The microstructural rearrangement and relaxation from one ink to another vary, leading to differences in jetting performance. And such an existence may or may not be observed by instrumentation, as the response time of the instrumentation may be longer than the time duration of the microstructural rearrangement itself, and the transient flow profile in the jetting process is hardly reproducible in the flow characterization processes. Moreover, the material properties, geometries and dimensions of the fluid path are different from one printhead to another. The stability of the ink may be time dependent and varies among ink formulations. One ink may be able to flow through one printhead and be jettable for a long period of time; however, it may lead to clogging or even corrosion in another printhead. Thus, it is more effective and trustworthy to study the printhead and ink interaction directly through jetting.

Characterization of Drop Formation

The raw data of DOD drop formation process are obtained by visualizing the evolution of ejected liquid ligaments from single inkjet nozzles under given jetting conditions. Depending on the requirement of information extracted from the raw images, the resolution of the images and, thus, the capability of the equipment for obtaining the images vary. Based on the flash photography technique, FUJIFILM Dimatix, Inc. has developed a group of workstations capable of visualizing DOD drop formation processes (see Figure 1 as an example) with different levels of spatial and temporal resolutions. The information obtained may include the following:

1) For single nozzle: primary drop velocity, tail velocity, number of satellites, drop volume and mass (primary drop and satellites), nozzle break-up time, tail break-up details (e.g., mists), drop coalescence, and meniscus motion;

2) For a row of nozzles: uniformity of drop mass and drop velocity from nozzle to nozzle;

3) For multiple rows of nozzles: uniformity of drop mass and drop velocity from row to row.

Actuating waveform, jetting voltage and frequency, crosstalk, and temperature have great effects on these aspects. Also, jetting may become inconsistent or unstable after a period of time, which is also part of data collection in characterizing DOD drop formation. In the mean time, jetting conditions are developed to optimize the DOD drop formation process oriented toward application requirements. The data and observations collected for each printhead-ink combination become part of the knowledge base for accelerating the future integration of new printhead-ink combinations.

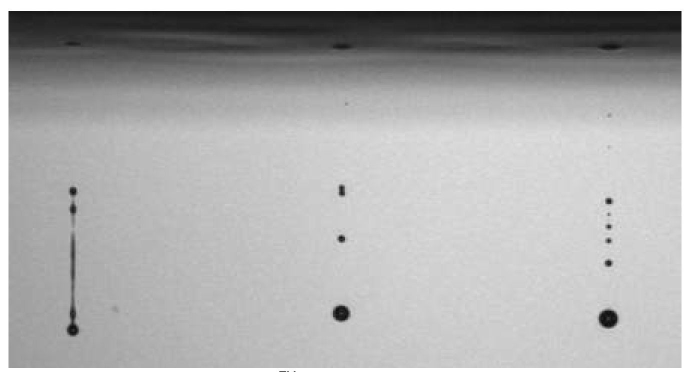


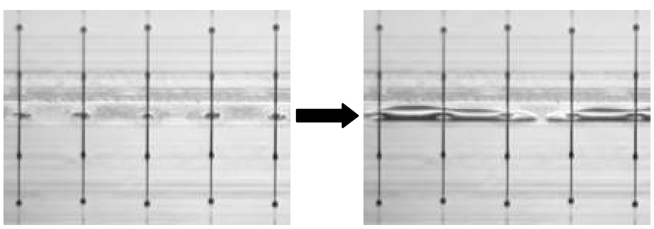
***Figure 1**. Example of Versadrop^{TM} technology. Three different drop sizes are generated for greyscale printing.*

Characterization of Nozzle Plate Wetting

Normally, before operation, a maintenance cycle is performed and the nozzle plate is cleaned. Once jetting starts, nozzle plate wetting (see Figure 2 as an example) begins to develop. Surface wetting may affect drop formation, jet straightness, and sustainability. To solve this problem, one treatment is to apply a non-wetting coating on the nozzle plate to increase the contact angle between nozzle plate and inkjet ink, so that the wetting may be reduced. However, non-wetting coatings have one major issue: their stability may be sensitive to ink formulation, making it hard to achieve long-term durability.

Direct visualization of wetting formation is required to facilitate the tune-up process. The qualitative observations are also used as a reference to explain other jetting performances including drop formation, jet straightness, and sustainability. It was found that by modifying jetting conditions (actuating waveform, jetting voltage and frequency, and jetting temperature) and ink formulation, surface wetting formation can be controlled and improved to enable desired jetting performance. It was also found that different inks with similar static surface tension may behave drastically differently on the same printhead nozzle plate under the same jetting conditions. Chemistry of the inkjet ink plays a great role in determining wetting formation dynamics. The interfacial properties and characteristics of the nozzle plate also dictate the phenomenon. By utilizing silicon as the base material for printhead fabrication, the versatility of physical and chemical surface modification enables the control on surface wetting characteristics toward more favorable scenarios.

The fundamental understanding of the mechanism of surface wetting formation under varied jetting conditions and ink formulations is being developed. The awareness and information collected for its existence facilitate the integration of printhead-ink combinations.



(a) (b)

***Figure 2**. An example of nozzle plate wetting formation. Image (a) was taken right after nozzles started jetting and image (b) was taken after jetting for a period of time.*

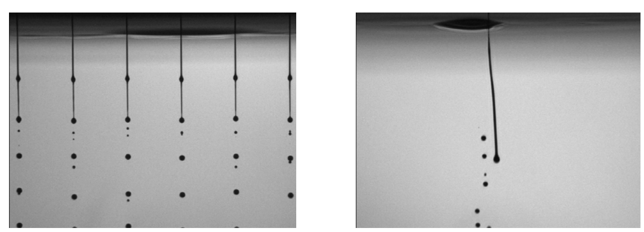
Characterization of Jet Straightness

Jet straightness (see Figure 3 as an example) defines how accurately the ejected fluid addresses the targeted location on the substrate and is evaluated through image quality assessment. Jet straightness needs to be well controlled for printer manufacturing, so that multiple printheads can print evenly spaced lines when being mounted in one print bar.

Jet straightness is defined as the orthogonality of the flying trajectory of the ejected ligament relative to the nozzle plate. Two kinds of jet straightness exist, which are static and transient jet straightness. Static jet straightness is independent of jetting conditions and is proven to be mostly related to the intrinsic concentricity of the inkjet nozzle and other external factors, such as nozzle damage, non-removable nozzle contamination or imperfections in or around the nozzle. Different approaches are used in FUJIFILM Dimatix, Inc. to measure static straightness for qualifying printhead nozzle manufacturing technology, including visualization of the ejected drops and measurement of lines printed on paper with the printhead oriented with an angle.

Some printhead nozzle fabrication technologies are less capable of controlling the nozzle concentricity, leading to poor jet straightness and deteriorated image quality. It was found that a slight error in concentricity between the top and bottom openings of the inkjet nozzle can generate an unacceptable static jet straightness error, demonstrating a high tolerance for nozzle geometry control. It was found that the utilization of silicon as the base material for nozzle fabrication enables better control on both the concentricity of the nozzle and the uniformity of nozzle size across a nozzle plate, so that not only jet straightness but also drop speed uniformity across the whole printhead are highly controlled.

Transient jet straightness is defined as when a jet that is straight immediately after a maintenance cycle becomes crooked after a period of jetting. These jets may or may not self-recover to straight jetting and usually, once transient straightness occurs, it becomes worse and worse over time. Various things can cause this problem, including nozzle plate wetting formation, accumulation of particles or dirt around the nozzle, etc. [34, 36]. Also, after a maintenance cycle, transient jet straightness may be deteriorated by the so called "first drop problem" [28] for both solvent and aqueous ink, and sometimes even UV ink. Continuously refreshing the base fluid around the nozzle and supplying base fluid to compensate the loss of solvent due to evaporation can reduce and even eliminate "first drop problem". It is important to measure jet straightness as a function of jetting time. To achieve this measurement, two approaches are used. One is to print images onto paper (see Figure 4 as an example) and the other is to visualize the ejected drops using a camera. The latter more environmentally friendly approach eliminates the need to use paper and enables unlimited test time. The camera can also be used to monitor more than one printhead's performance automatically at the same time.



(a) (b)

***Figure 3**. Straight jetting vs. non-straight jetting.*

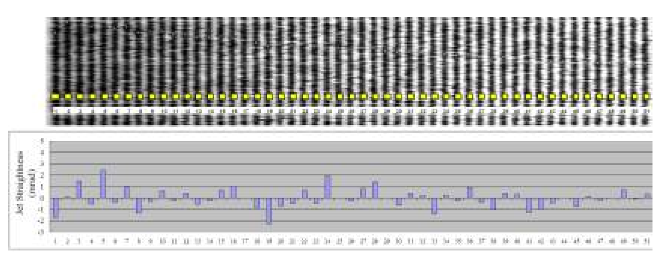


***Figure 4**. Jet straightness measurement by printing lines on paper and defining the spacing between neighboring lines.*

Characterization of Jetting Sustainability

Jetting sustainability involves the ability of the jet to print continuously. Characterization of sustainability requires measuring the percentage of jets that remain firing after a defined period of time under certain jetting conditions. If a jet fails to fire due to, for example, rectified diffusion, nozzle surface wetting, and nozzle contamination, it is important to know under what conditions this will happen and how to reduce nozzle failure by adjusting ink properties and/or jetting conditions. The two approaches used for measuring jet straightness mentioned above may also be used for quantifying sustainability.

Each application demands a specified target for sustainability. Thus, it is important to plan a sustainability test oriented toward the application requirements. The printed image may have one drop size for all nozzles with a certain duty cycle or multiple drop sizes (greyscale printing) stochastically blended. Sustainability tests need to be done over a population of printheads for different colors in one ink set, e.g., CMYK. The amount of work required to qualify the sustainability for a printhead/ink combination could be so large that an automatic test routine for multiple printheads at the same time is required. We have developed workstations capable of monitoring the sustainability performance of multiple printheads for unlimited test time without using paper.

Conclusions

Printhead-ink combinations need to be qualified for application requirements. Due to the unique characteristics of piezoelectric DOD drop formation process, different inks with similar static fluidic properties may behave differently under the same jetting conditions. Thus, the qualification process has to be done through jetting. Such a process involves the following four aspects: DOD drop formation dynamics, nozzle plate wetting formation, jet straightness, and jetting sustainability.

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