A large-scale print-head for drop-on-demand and continuous ink jet studies

J.R. Castrejón-Pita, G.D. Martin and I. M. Hutchings; Inkjet Research Centre, Institute for Manufacturing, University of Cambridge; Cambridge, United Kingdom

Abstract

A simple large-scale experimental apparatus that is capable of reproducing the jetting conditions found either in drop-on-demand (DoD) or continuous ink jet (CIJ) print-heads is presented. The design allows the direct observation of phenomena and measurement of conditions that are difficult or even impossible to record or modify in commercially available print-heads. In the DoD mode, the setup permits the observation of the meniscus motion as well as recording of the pressure pulse in the fluid inside the print-head. Backlit imaging has been used to determine the drop speed, number of satellites and droplet behaviour. In the CIJ case, the setup allows the direct measurement of the jetting pressure and the modulation amplitude in the fluid inside the print-head. These characteristics allow the determination of the break-up curve for modulated jets in terms of the pressure modulation amplitude and the modulation frequency. Measurements from this system can readily be compared with outputs from theoretical models or numerical simulations, as parameters such as speed and pressure are directly measured.

I. Introduction

The first successful attempts to commercialize inkjet print-heads were carried out by several companies during the 1960s and 70s, including A.B. Dick Videojet, Hewlett-Packard and IBM [1]. Since then, the industry has grown substantially and it is now possible to print at tens of pages per minute at resolutions up to thousands of dots per inch. As ink jet printing is a non-contact technology, it has attracted attention for new applications ranging from the printing of electronics to the deposition of biomaterials [2]. Current challenges are to improve the reliability, quality and speed of the process. Variables such as the fluid viscosity, surface tension and density as well as the print-head nozzle diameter and length play a decisive role in determining the dynamics of the droplet in both CIJ and DoD systems [3]. In addition, the driving waveform critically affects the droplet speed and the number, relative position, size and velocity of any satellite droplets. In a DoD system, the drive signal usually consists of one primary pulse to eject the droplet followed by one or more pulses to control the formation of satellites; the shape of the pulses is usually defined in terms of the pulse height and length. In a CIJ system, the drive waveform is usually sinusoidal, with the amplitude and frequency being selected to avoid satellite drops. Generally, the fluid properties and the nozzle size are chosen to control the size and speed of the main drop, while the properties of the waveform are used to control the behaviour (or existence) of satellite droplets. Optimization of the conditions is usually an empirical process. Unfortunately, the optimum parameters are often valid for a single print-head–ink system, and changes in the ink which alter any of its physical properties (e.g. viscosity, surface tension or speed of sound) result in the need for a new optimization procedure. Ideally, a computer model which incorporated a full description of the fluid properties, drive waveform and nozzle geometry would allow the optimal operating conditions to be predicted. However, such models encounter difficulties because the fluid dynamic conditions inside most print-heads are difficult to quantify and must be treated approximately; it is then not clear whether the differences found between simulations and experiments are caused by defects in the physical model, its embodiment into computer code, or the lack of reliable data on the boundary conditions relevant inside the print-head. For DoD, neither the initial position of the fluid meniscus nor the pressure response to the electrical drive signal are usually known for most commercial print heads. In CIJ, the pressure or velocity response to the electrical drive signal is also often unknown.

The apparatus described here was designed so that all the variables that are impossible or difficult to record in a typical commercial print-head are accessible to measurement and control. Briefly, this design permits the direct observation of the fluid meniscus and the direct measurement of the dynamic pressure and the fluid velocity inside the print-head at all times. In addition, the inner nozzle geometry is easily observed and modified to carry out experiments on nozzle reliability and characterization. By using suitable fluids and jetting conditions, the key fluid mechanical conditions in real printhead nozzles and jets, as represented by the Reynolds (Re) and Weber (We) numbers, can be reproduced within this large-scale model. Nozzle diameters from 100 μm to 2.2 mm were tested under conditions which covered the regime of Re and We in which most commercial print-heads operate.

II. Experimental system

Large-scale CIJ print-head systems have been built or used in the past to validate computer models or determine the parameters affecting the formation of droplets and their satellites [4, 5]. However, these studies were performed in different Re and We regimes from those relevant to the operations of typical commercial print-heads. Studies of DoD systems have described the flow structure inside a commercially-available print-head but these were restricted to a single nozzle geometry and a specific model fluid [6]. In the light of these previous investigations, the aim of the work described below was to produce a versatile and well-characterized system in which CIJ and DoD experiments can be carried out within a wide range of operating parameters, including those conditions found in typical commercial printing [7]. The system was therefore designed in such a way that the nozzle geometry, the driving waveform and the fluid properties could be easily varied. These factors determined the designed and construction of the apparatus. Most commercial print-heads do not permit optical access to the ink channels or to the regions internal to the nozzle, but the large-scale apparatus was constructed from transparent acrylic (PMMA: Perspex/Plexiglas). The use of this material allows observation of the motion of the ink meniscus and the use of velocimetry techniques such as particle image velocimetry (PIV) and laser Doppler anemometry (LDA), within the head chamber and the nozzle. It is also compatible with a wide range of fluids. The second important factor in the design was the choice of actuator, as it was required to operate in both CIJ and DoD modes. The present system utilizes an electromagnetic transducer (LDS Test and Measurement Ltd, model V201 vibrator) which is capable of operating with arbitrary waveforms within the range from 5 Hz to 13 kHz and providing a force of up to 26.7 N. The final factor was the size of the print-head, which was chosen, in combination with the fluid properties and drop ejection velocity, to allow experimental measurements of the internal velocity fields and pressure transients.

The print-head consists of three 10 mm thick acrylic plates plus the nozzle plate; the system is shown schematically in Fig. 1 and fully described in [7].

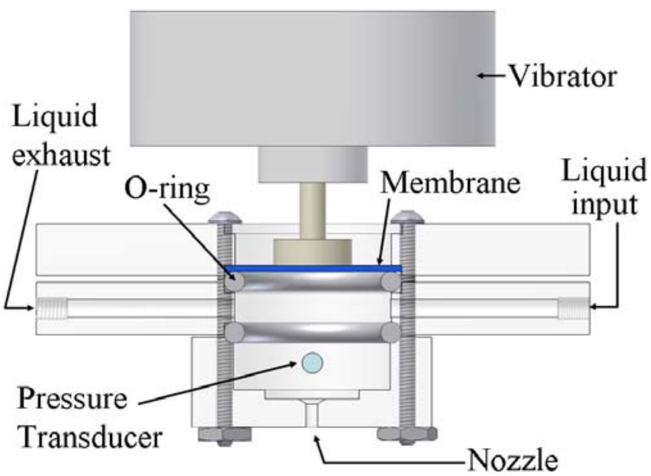

Figure 1. Cross-sectional view of the large scale print-head.

The fluid chamber is formed by a 30 mm diameter hole through the acrylic plates, which are clamped together by four stainless steel M3 screws and nuts, with sealing O-rings; the nozzle is formed in the lowest plate which is adhesively bonded to the plate above. The top of the chamber is sealed by a 1 mm thick rubber membrane which separates the fluid from the vibrator rod and transmits the pressure modulation to the fluid. The middle plate accommodates ports to supply and clear the fluid to and from the print-head. The lower plate houses a miniature pressure transducer located on its inner wall (Measurement Specialties, 5 mm EPX series) and in contact with the fluid. This transducer is used to measure the dynamic pressure in the liquid in response to the action of the vibrator, in both DoD and CIJ modes. The nozzle plate is readily exchanged and modified, which facilitates investigation of the influence of nozzle size and geometry on the jetting behavior. An example of this is shown in Section III.

The print-head is operated with the vibrator rod in contact with the rubber membrane. The vibrator is used, driven by an appropriate electrical signal, either to drive the liquid out of the nozzle in DoD mode or to modulate a continuously flowing jet in CIJ mode. Essentially, the liquid pressure in the chamber determines the jetting mode; in DoD mode this pressure is adjusted until the position of the meniscus, in the absence of any drive signal, lies at or close to the tip of the nozzle, while in CIJ mode the liquid is pumped continuously into the head, generating an internal pressure which drives the liquid through the nozzle and creates a jet of the desired speed.

III. Drop on demand mode

For drop-on-demand operation the system can be operated in pull-push, push-pull or simply in push modes. These modes are determined by the shape of the electrical drive waveform. With the meniscus initially located at the nozzle exit, the ejection of a droplet is achieved when a positive pressure transient is produced by the vibrator.

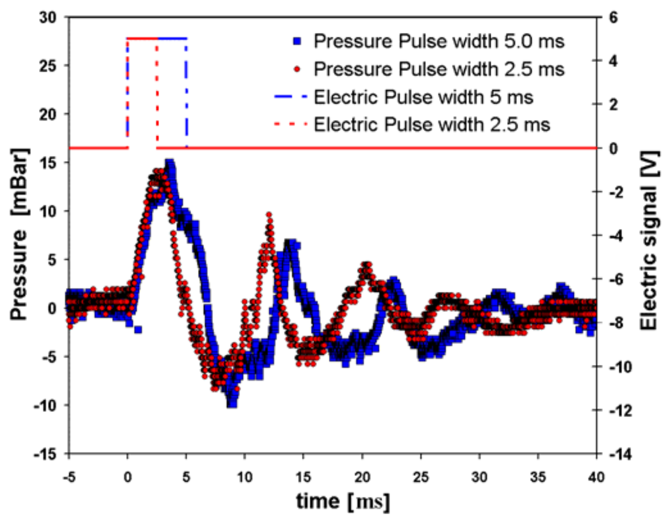

Figure 2. Two examples of the pressure response for two different electrical drive waveforms (top) for operation in DoD mode

When the system is run in DoD mode, the pressure transducer allows direct measurement of the pressure fluctuation within the chamber which leads to ejection of the fluid. Two examples, for drive signals of 2.5 ms and 5 ms duration, are shown in Fig. 2. This simple instrumentation allows the influence of waveform shape on the formation of satellite drops, for example, to be studied. It also allows direct measurement of the pressure transient in the head, and through use of suitable optical methods, velocity distributions to be determined both upstream and downstream of the nozzle. The effects of varying nozzle geometry can also easily be studied at this large scale, which facilitates the fabrication of experimental nozzles. Fig. 3 shows the differences in the ejection and evolution of two jets generated from the same experimental fluid, by the same drive waveform, but with different nozzle geometries. Significant differences are seen in main drop speed and satellite behaviour.

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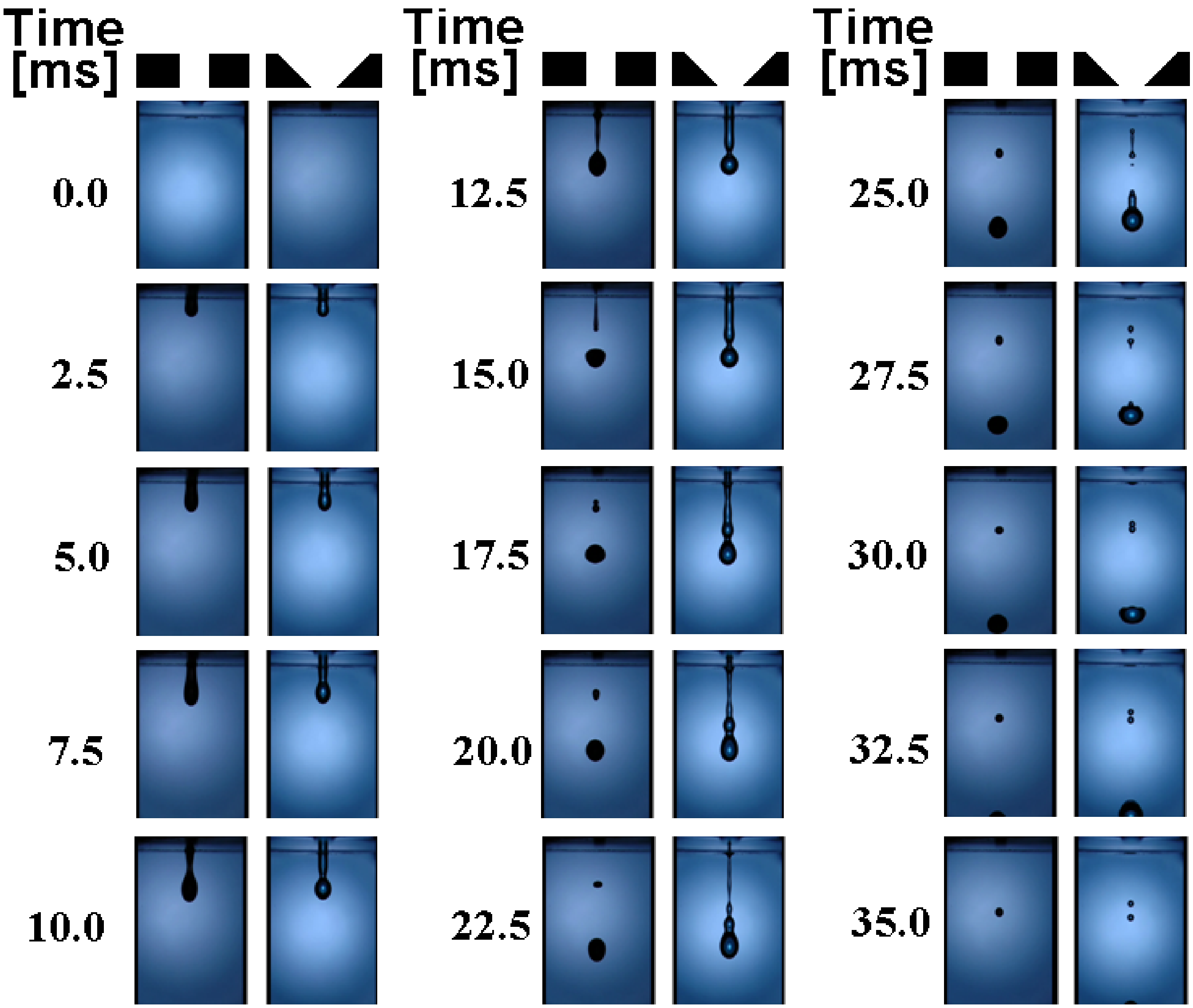

Figure 3. Examples of jet ejection from the large-scale system in DoD mode. Two 1.25 mm diameter nozzles with different inlet geometries were used: the left-hand sequence was obtained with a cylindrical nozzle, while the right-hand images relate to a conical nozzle (90 degrees included angle). Identical drive waveforms (10 V 15 ms square pulses).The fluid was a 50:50% glycerol-water mixture, with density 1208 kg/m^3, viscosity 55 mPa s and surface tension 64.6 mN/m. The main drop speeds differed by 5% (0.54 m/s vs 0.51 m/s); more importantly, the final number of satellites differed between one and two.

IV. Continuous inkjet mode

Continuous jetting in this large-scale system can be produced in various ways. The simplest is to pressurize the liquid inside the print-head; in the present experiments this was done by pumping the fluid into the print-head using a stable electric pump. The modulation required to induce the Rayleigh break-up of the jet is produced by the vibrator. In the same way as in the DoD mode, the pressure sensor in the chamber allows the direct measurement of the modulation amplitude and frequency within the print-head. This allows the break-up length for a modulated jet (i.e. the distance along the jet at which it first breaks into discrete drops) to be determined in terms of the pressure modulation amplitude, and not only in terms of the voltage input to the modulating transducer as is more common for commercially available CIJ printheads. Examples are shown in Figs. 4 and 5. This allows detailed comparison to be made with the predictions of theoretical models or numerical simulations since the break-up curve can be determined based on an intrinsic variable (pressure) [8]. Fig. 5 shows an example of a break-up curve which relates break-up position to the measured value of modulating pressure; Re and We numbers of these experiments are within the range shown by commercially available CIJ printheads running with methyl ethyl ketone (MEK) based ink .

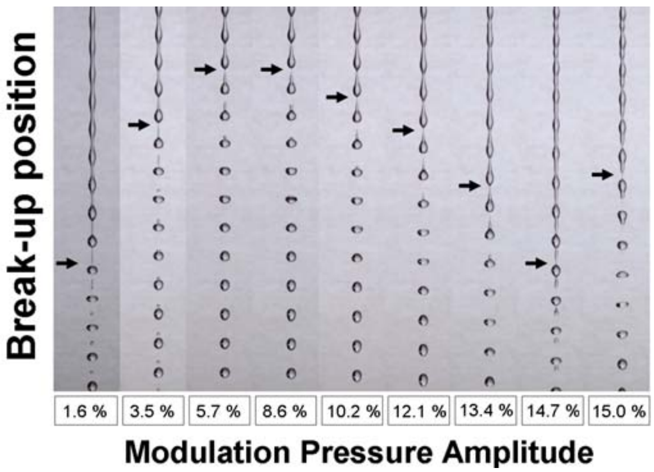

Figure 4. Images showing the response of a modulated continuous jet, from a 2.2 mm nozzle, to the measured value of modulation pressure amplitude. The driving waveform was purely sinusoidal at 333 Hz, and the droplet spacing was 9.89 mm. The images all start at a distance of 80 mm from the nozzle to focus on the break-up region.

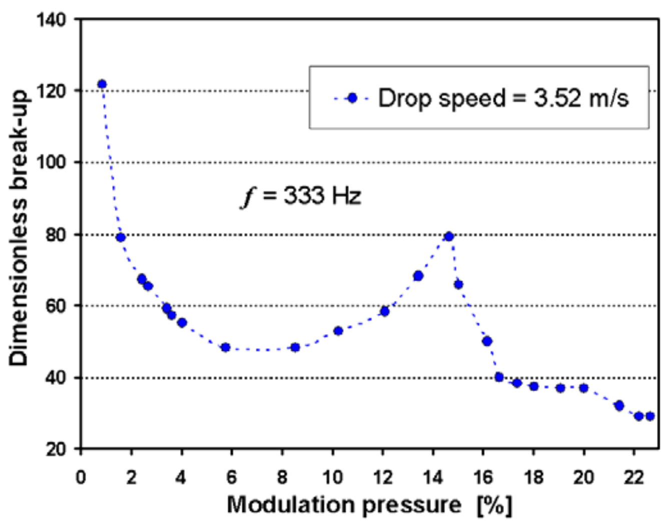

Figure 5. Break-up curve for a jet from a 2.2 mm. The dimensionless break-up length is the length divided by the nozzle diameter.

Finally, Fig. 6 compares the break-up of two continuous jets at different scales: the upper image shows a modulated jet from a commercial system with a 60 µm nozzle, and the lower images show the break-up of a 2.2 mm jet from the large-scale system with the same Re and We numbers as the first one.

IV. Conclusions and future work

The apparatus presented in this paper has wide applicability. It is currently being used to test Lagrangian numerical simulations for both the CIJ and DoD modes. For this purpose the apparatus allows velocity profiles to be measured by laser Doppler anemometry and particle image velocimetry during jetting. The apparatus can also be used to evaluate the performance of different nozzle geometries in both printing modes.

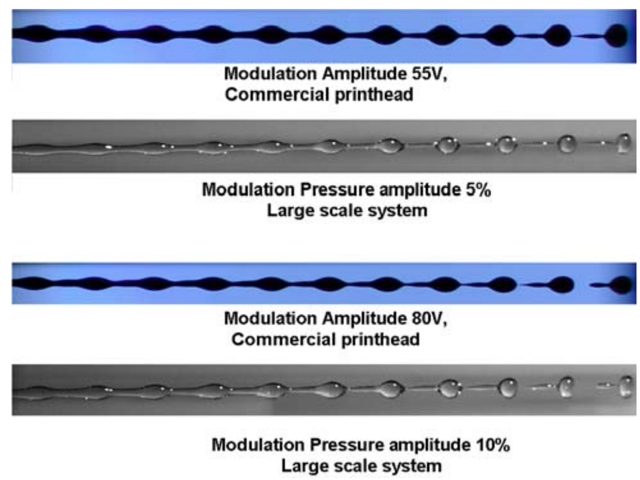

Figure 6. Comparison of CIJ jet break-up at two different scales. The upper image of each pair shows the break-up of an MEK-based ink from the 60 µm diameter nozzle of a commercial print-head, while the lower images show a jet of water/glycerol mixture from a 2 mm diameter nozzle from the large-scale system. In both cases Re = 164 and We = 409.

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Author biography

J.R. Castrejón-Pita received his MSc in Physics (Fluid dynamics) from the National University of Mexico (UNAM, 2003) and his PhD in Physics (Quantum Optics) from the Imperial College in the United Kingdom (2007). Since then, he has worked in the Inkjet Research Centre at the University of Cambridge. His current research is focused in measurement techniques in DoD and CIJ systems.