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# Ink drop motion in wide-format printers I. Drop flow from Drop-On-Demand (DOD) printing heads

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ABSTRACT

The flow of ink drops was investigated for use in wide-format printing devices. The behavior of ink drops ejected from Drop-On-Demand (DOD) piezoelectric (push-mode) printing heads was defined and measured using optical techniques. The combination of velocity measurements from the Laser Doppler Velocimeter and data captured in images taken by an Image Visualization system gave a comprehensive view of the printing head performance. The piezoelectric printing head was examined close to real operational conditions in order to determine the optimal parameters for quality printing.

The results show that printing inaccuracy is mainly caused by the appearance of satellite drops. Some recommendations are given for improving the operation of two printing heads examined.

A computer simulation of a piezoelectric push-mode Drop-On-Demand ink jet printing head was also presented. The simulation dealt with the pressure pulse causing the ejection of a single drop and its flight towards the printing medium. The simulated results showed good agreement with the experimental results, and a connection between the voltage pulses that were applied to the piezoelectric crystal and the resulting pressure was established.



## 1. Introduction

The digital printing field has advanced greatly in the past two decades and the improvement in product quality, as expressed by the accuracy of the printed image, is under constant demand.

Wide-format printing machines are used to print different applications using the Drop-On-Demand (DOD) ink jet method whereby individual drops are ejected by a pressure wave only when needed. The piezoelectric push-mode printing head in particular ejects drops by means of a pressure wave introduced by a piezoelectric crystal. This pressure must be sufficient to expel a small finite jet that converges into a single drop.

Printing quality depends greatly, among other parameters, on the velocity and shape fluctuations of the jet and drops, as well as on the existence of satellite drops. Without detailed knowledge of pressure response and velocity variations of the jet, optimal drop ejection, and consequentially optimal printing quality, cannot be assured.

The first successful product using ink jets was developed in Sweden [1]. By replacing the pen in direct writing oscillograph recorders with an ink jet, it was possible to decrease the inertia and thereby increase the upper frequency level of these recorders to 1000 Hz, a ten-fold increase over conventional recorders at that time. During the 1960s and early 1970s, four different types of ink jet printers were developed [2–5], which proved to be used much more frequently. These types were improved and altered to the ink jet systems used today.

The DOD ink jet system [5,6] is a system of great simplicity [7], consisting of an ink chamber connected to a nozzle. Part of the chamber consists of a piezoelectric element that can be excited by a short electrical signal pulse. This excitation causes a sudden change in ink pressure in the chamber, which leads to the ejection of an ink drop from the nozzle. The chamber is then refilled with ink from an ink reservoir. In all systems, the ink pressure in the chamber at rest is maintained slightly below atmospheric pressure. At the location where the nozzle is exposed to the air, a meniscus forms whose slight curvature counterbalances the negative static pressure, giving the meniscus a stable position within the nozzle [5]. Due to the slight vacuum, the meniscus' resting position is stable, regardless of whether the plate surrounding the nozzle is wettable or not.

DOD ink jets have proven to be very useful in the printing of alphanumeric characters. Since each jet system is very small and simple, a number of these systems can be combined into a single printing head that moves across a medium. Compared to continuous jet systems [8], the DOD principle is less useful for printing

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on curved surfaces or where the ink drops must traverse large distances (over 2 mm).

The performance of a pulsed chamber DOD device depends on the interaction between chamber actuation conditions and the subsequent dynamic response of the liquid contained in the system. Factors that may affect this interaction are air pockets in the chamber, shape and amplitude of the actuation pulse, and physical properties of the liquid. The response of the drops can be expressed by drop velocity and distribution towards the target and perpendicular to the direction of the flow. The larger the distribution, the greater the printing inaccuracy on the medium. This is attributed to the relative motion of the printing media in front of the printing head at a constant velocity [9,10]. Only a small amount of literature was found that related to drop velocity response to ejection pulse parameters. Most of the reported experimental work was carried out on large nozzles [11–15] – around 200 μm – although a 50-μm nozzle was considered [16], similar to this paper's objective.

In examining the literature, differences apparently exist in the behavior of the small drops produced by modern DOD devices and the larger ones described in the literature. Not only do the velocities and statistics differ from those reported, but also printing quality is demanding new approaches and a better understanding of the problem. It is therefore necessary to reevaluate the phenomena involved in order to be able to improve the product.

Theoretical analyses of various ink jet types and applications can be found. Since many types of ink jets and geometries of nozzles exist, different nozzle behaviors are expected and reported. The liquid ejection process of a novel micro-droplet generator was investigated [17] by applying a computational approach (CFD-ACE (u)®) based on the unsteady three-dimensional conservation equations with treatment of surface tension effect. The droplet generator was a squeeze-type cylindrical microinjector with a specific corresponding temporary displacement profile of the piezo diaphragm. The results showed good agreement with related experimental work. An axisymmetric three-dimensional simulation system was developed [18] for a micro-ink squeeze-mode jet based on a solution algorithm (SOLA) scheme for the solution of velocity and pressure fields. It was coupled with volume of fluid (VOF) and piecewise-linear interface construction (PLIC) simulation techniques. In addition, a continuum surface force model was used. The calculations were consistent with the experimental results. A complete physical process in the flow channel of a piezoelectric ink jet was investigated [19], and a detailed description of the pressure response and velocity variations was given by the simulations results. The simulations concentrated on the pressure wave as it propagated through the ink chamber with time. The pressure was shown to decrease and become negative. A characteristic frequency was found. The pressure was presented as a function of time at a position close to the nozzle, and an analytical function was fitted. The pressure completely attenuates after 20 μs.

A high-order numerical method based on the Navier–Stokes equation (for two-phase flow) for modeling the entire jetting process in micro-jet devices was developed [20] and the accuracy of calculations was demonstrated.

Two numerical solutions are presented for the drop formation process outside the nozzle [21] based on one-dimensional jet theories, with and without radial inertial effects. These models are for inviscid fluids with surface tension and require an axial velocity boundary condition at the external face of the nozzle plate. The generic kinematics properties of the incompressible meniscus fluid system inside a DOD ink jet orifice were explored [22], and attention was focused on the interaction between the pressure pulse and the meniscus at the fluid interface inside the orifice. The free surface drop formation problem was considered [23] using a numerical solution of the axisymmetric Navier–Stokes equation. A numerical method making use of the complete incompressible flow equations with a free surface was discussed to study an impulsive driven laminar jet. Flow behavior dependence upon fluid properties was compared for drop integrity purposes. A description of the mechanism of drop formation in a lumped mass model in a DOD system was given [24], where the actual droplet formation was shown to be very complex with moving boundaries lacking an established steady-state flow. Furthermore, fluids having identical properties as far as the Navier–Stokes equation is concerned show markedly different drop ejection geometries. The capillary refilling of the nozzle was examined [25], taking into account inertial forces, surface tension forces and viscosity. Pressure waves and delay times were neglected in this solution.

Drop shape can vary from an ideal tear-shaped sphere to a tadpole shape having a very long tail. These differences create different dot shapes on the printing media, expressed by printing inaccuracy. The drop size or volume varies under different operating conditions. For example, at high ejection frequencies, the ink chamber is not filled properly with ink due to flow problems, and a smaller drop volume is ejected. The literature [12–14,26] usually reports a relatively large drop size since the technology at that time was insufficient to produce nozzles on today's smaller scale (hundreds of micrometers then, down to tens of micrometers today).

Satellite drops are a normal consequence of liquid ink drop ejection from the nozzles of ink jet printing heads. The number, size and other characteristics of the satellite drops associated with a given primary drop typically depend on many factors associated with the printing head, including ink properties, ejection mechanism, nozzle geometries, etc. The satellite drops result from a breakup of the ligament or "tail" of ink that attaches the ejected drop to the ink in the printing head before separation. The behavior of satellite drops and the conditions under which they are created are described by several researchers [21,23,26,27–32].

Printing quality demands new approaches and a better understanding of the problem. Even if the device reported is modern and produces smaller drops [18], the ink jet type and geometry differ. It is therefore necessary to remodel the phenomena involved in order to be able to improve the product (the printing).

The work presented in this paper investigates drop generation by wide-format printing devices. The ink chambers are of a DOD piezoelectric push-mode type. Extensive work has been done on the velocity measurements of the ejected drops and their distribution on the target under different operational conditions. The drop velocities are measured by Laser Doppler Velocimetry (LDV) and Image Velocimetry (IV) in order to determine optimal working conditions for quality printing.

The results reported in this paper show a significant difference between different printing head performances checked under different operational conditions. Furthermore, a comparison of dye and pigment inks is presented, as well as an examination and comparison of two different printing head performances.

This paper also deals with a three-dimensional simulation of a piezo-DOD nozzle. The transient simulation system consists of a FLUENT 6.1 CFD package. The simulated results are compared to the experimental results.

## 2. Description of the printing head

A schematic presentation of the experimental system is shown in Fig. 1. The experimental system is divided into three sub-systems.

### 2.1. Drop formation system

The drops were generated by an ejection head. Two ejection heads were used in this work: a vertical ejection head (drops ejected in the direction of gravity) provided by "Aprion," Netanya, Israel