From Ink Bottle to Ink Drop: The Flow Environment in an Inkjet Printhead

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Abstract

In any inkjet system, the ink goes through various physical and geometric constraints which influence the flow dynamics and finally the jetting characteristics. The dynamic flow behaviour in-channel, through the nozzle and in flight during printing is vital to control print quality (drop ejection characteristic, reliability) and further advances in the capability of inkjet technology.

This paper will discuss the flow behaviour at each stage of a drop-on-demand printhead. The fluid dynamics of the ink on the millimetre scale within the printhead inlet is very different to that on the micron scale within the channel and nozzle. Although they are all in the laminar flow regime they are subject to very different shear rates. In a printhead, various system components (ink, heaters, pumps, actuator and nozzle) must be designed or configured to achieve target velocity, frequency, drop size, and reliability. Both simulation and experimental results on these topics will be discussed in this paper.

Introduction

A printhead can be broken down into a series of functional components, each of which performs a specific task in taking a static bulk fluid and converting it into dynamic micro-scale drops. An ink supply, whether a gravity-fed bottle or a sophisticated pumping system serves two principal purposes; to deliver ink to the printhead inlet and to control meniscus pressure. From the inlet the manifold distributes ink to the channels, its optimised design ensuring that each channel is supplied with the same pressure and flow rate. The channels' size defines the final drop volume while its geometry can define its operation mode and ultimately the sort of ink that can be used. Activation of the channel walls dictates the type of drop that is ejected while the nozzle holds the ink in while not printing and controls the drop formation process while drops are ejected.

From ink bottle to ink drop, the ink is subject to a wide range of dynamic and thermal perturbations. In this paper, Computational Fluid Dynamics (CFD) and drop ejection modelling code are used to model flow regimes within a typical printhead system at various stages through the ink path.

Acoustic pressure pulse drop ejection

The acoustic driving mechanism for drop ejection is discussed in more detail in previous papers, see for example [1]. Briefly, the active ink channel formed by the shared wall PZT structure is connected to a supply manifold providing a source of fluid to replenish that ejected from the nozzle. A secondary manifold is positioned at the other end of the active ink channel, to collect the through-flow ink and return the excess ink back to the ink supply reservoir. Using a larger cross section than necessary in the manifolds reduces through-flow fluid pressure drops, but also promotes an impedance mismatch between active channel and supply manifold to cause partial reflection of pressure waves. Ejection of droplets can therefore proceed due to coincidence of pressure pulses arriving at the nozzle entry from a multiple of operations of the actuating element.

Acoustic operation is initiated by electrical activation of the PZT walls, causing the two longitudinal walls to move apart and to rapidly increase the volume of the active channel. The resulting rarefaction of the ink in the channels causes positive elastic waves to travel in from the two manifold regions, which superimpose at the nozzle point at the centre of the active channel. Further pressure wave pulses that are caused by reflection at the two channel / manifold interfaces are actively used to control the drop ejection process. Actuators combining this longitudinal acoustic mode and low restriction through-flow ink supply are able to operate at frequencies in excess of 200 kHz (6pl drop) since the time of flight of the acoustic wave along the length of the channel is short.

Flow regime changes within printhead

The flow regimes are evaluated at a number of distinct regions within the ink flow cycle, namely in the main ink supply tubing, within an inlet manifold and within the acoustic firing channel itself.

Fully developed laminar flow is achieved in the supply tubing linking the ink bottle to the printhead, assuming a total through-flow volumetric flow rate of 150l/min. Xaar printheads typically subdivide this input supply using an inlet manifold that splits the flow input into a series of flow paths individually supplying addressable areas of printhead channel manifold. The goal for this inlet manifold, a representation of which is shown in Figure 1, is to supply a series of smaller bore branches with nominally equal throughputs of ink, to avoid ink starvation in high duty cycle channels and to ensure the minimum through-flow for cooling and cleaning of the actuator channel.

Microfluidic design using commercial CFD code such as COMSOL Multiphysics is suitable for optimizing the flow channel geometry to equalize the flow characteristics across the printhead. In the initial realization of a manifold design shown in Figure 1, momentum derived from geometric characteristics that would not be predicted by a Bernoulli-based pipe network analysis are observed to promote increased velocity in the outlet ports nearest to the trajectory of the main inlet port.

A first attempt at optimizing the flow geometry is presented in Figure 2, where variable flow cross-section and fillets are introduced to complement the fluid momentum characteristics.

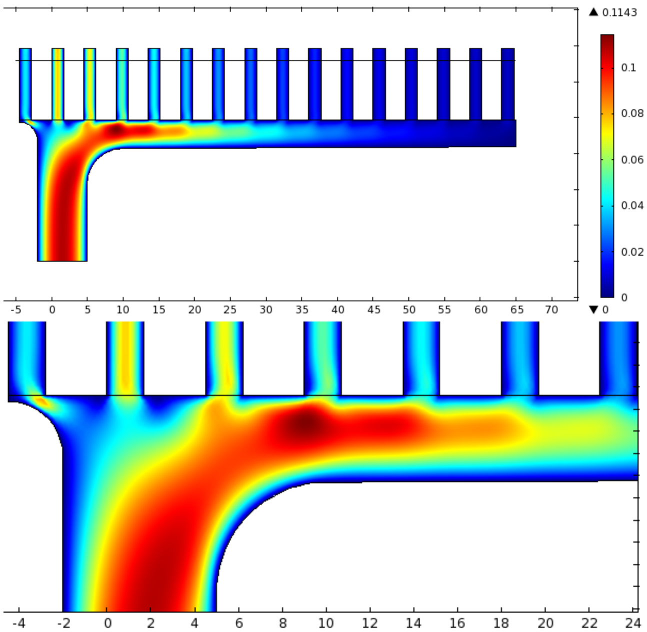

Figure 1. *Basic inlet manifold geometry, plotting CFD predicted flow velocity magnitude distribution. The top figure plots the whole geometry; the second figure zooms into the left hand end. The flow velocity magnitude varies between 0 and 0.1143m/s, represented by colour scaling.*

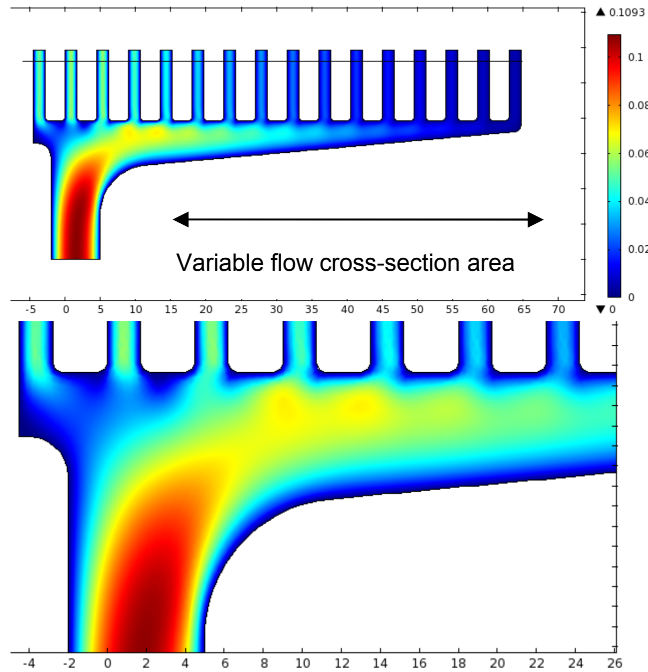

Figure 2. *Results for first optimization of inlet manifold geometry to improve fluid flow distribution.*

The relative improvement in flow equality across the inlet manifold's outlet ports through the optimization is presented in Figure 3, which plots the maximum axial velocity along the ports. An ideal manifold would distribute fluid such that the axial velocity is equal across all outlet ports. The partially optimized manifold design results in a more equal distribution, although it is clear from this analysis that additional work is required to further improve the quality of this network component.

Whilst the simulation work to this point has modeled flow regimes using stationary analysis, simulating the flow regime in a drop on demand inkjet channel requires transient analysis, as the acoustic pressure pulse causing the drop ejection is a transient effect.

The channel consists of parallel-sided PZT walls that deflect along their length to cause a pressure wave that originates from a pair of manifolds at each end of the channel. To eject a 6pl drop from the nozzle design used in the Xaar actuator requires a nozzle inlet velocity field pulse period of approximately 7µs, consisting of an initial negative draw on the nozzle, followed by a large positive pulse used to eject the droplet, and a small amplitude negative pulse to pull the ligature back to the nozzle away from the droplet.

The solver routine used in this work initially used a stationary solver to predict the steady state through-flow fluid flow, and a subsequent transient solver routine to model the time-varying flow field resulting from droplet output from the nozzle region. The method used to apply the time-varying velocity field in the nozzle region was to define the nozzle outlet as an outlet boundary with time varying volumetric flow rate, whose integrated magnitude matched the drop volume.

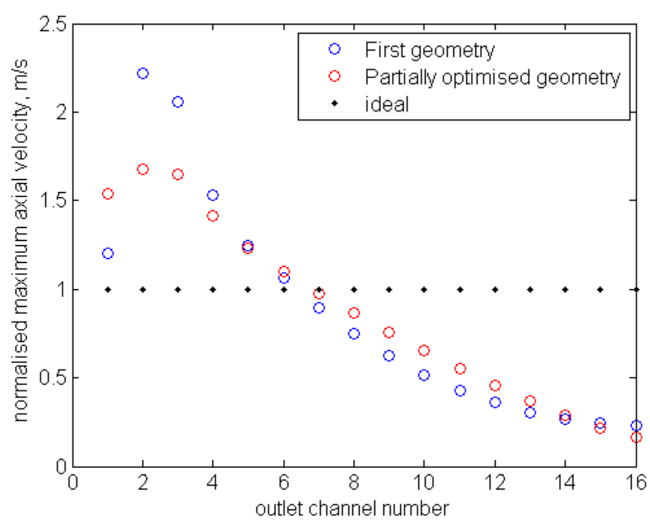

Figure 3. *Normalised maximum axial velocity for 16 output ports, for first geometry design, subsequent partial optimization and the optimum desired flow velocity distribution. The optimisation procedure has achieved a more consistent flow pattern across the 16 channels, although further work is required to achieve higher correlation across all channels.*

The modelled velocity in the direction axially through the nozzle is plotted in Figure 4 for the temporal point coinciding with the peak nozzle ejection flow rate point, with a predicted maximum fluid velocity magnitude of 9.1m/s.

Referring to Figure 5 which plots the time history of the boundary integrated outlet flow, an important result from this analysis is that a modeled drop ejection has a significant effect on the stationary through-flow flow regime, with a short duration reverse flow in the down-stream end of the channel. The short time step used in the CFD resolved this unexpected result, whose implication is a high shear rate for the channel caused by the short duration transient.

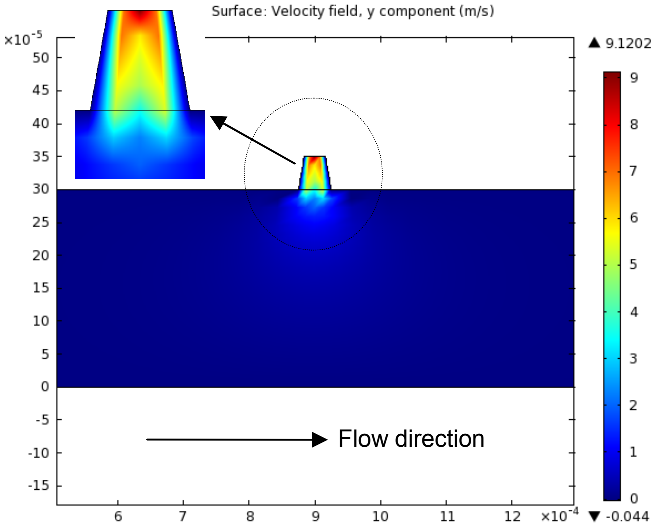

Figure 4. 'Y' axis velocity distribution in active ink channel, at the midpoint of the transient drop ejection pulse.

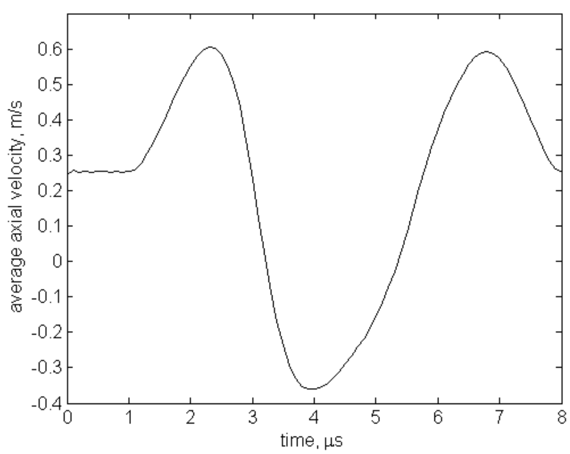

Figure 5. Output axial flow velocity, measured at the output boundary. Integrating the flow through the boundary in the stationary context results in a steady state volumetric flow rate of $5x10^{-9}m^3/s$. The axial flow velocity returns to the steady state value after a few µs (not shown)

Fluidic parameters at various points in the supply

Table 1 summarises the modelled results from the computational approaches used to model the ink supply system. The system is entirely laminar, with speeds in the main through-flow regions typically less than 1m/s. During the ejection process, the transient flow speed in the main channel increased significantly, and the flow magnitude in the nozzle for a 6pl drop.

The main pressure drop contribution occurs within the active channel, due to the constraints of the flow cross-section. Shear rate for the fluid increases dramatically in the active channel, which has profound implications on the ink rheology properties and jetting behavior [3-4]. A fluid under consideration for use in the printhead must be capable of maintaining performance under these wide variations of shear rates, and to sustain pressure fluctuation frequencies up to 200kHz with no degradation in properties.

Table 1: Peak flow regime parameters evaluated at various points within ink supply system

Region and flow area	Flow area mm^2	Flow rate l/min	Speed m/s	Reynolds No -	Shear rate 1/s
Ink tube	12.6	150	0.156	0.9	95
Inlet manifold	31.5	150	0.109	1.4	120
Channel (steady state)	0.02	0.3	0.280	0.2	12157
Nozzle (transient)	$5x10^{-4}$	$5x10^{-5}$	9.1	2.5	558770

Jetting

The simulation of drop formation and ejection was calculated using a drop-on-demand simulation tool developed by Morrison and Harlen [5]. The simulator sets up a two-dimensional grid within a region defined between a hemispherical boundary that caps the entrance to the nozzle and a curved (or flat) fluid-air interface at the nozzle exit. A velocity profile is imposed perpendicular to the hemispherical boundary (Figure. 6) and, using full fluid dynamical equations, the displacement at each of the grid vertices is followed over time as the jet issuing from the nozzle evolves and breaks up into drops.

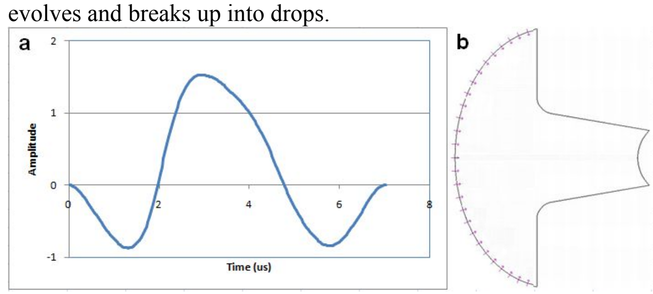

Figure 6. Representation of velocity profile (a) imposed on hemispherical boundary which caps the nozzle inlet (b).

The jetting behaviour of two types of fluid is briefly described. The first is that for a Newtonian fluid and the second is that for a viscoelastic fluid. For a Newtonian fluid the principal fluid parameters used are the density, viscosity and surface tension. Typical values for an oil based ink were used. For a viscoelastic fluid, the FENE (Finite Extensible Nonlinear Elastic) model was used and further parameters were incorporated to describe the fluid in terms of a suspension of dumbbell molecules. These parameters are the viscosity of the carrier solvent, the concentration of dumbbells (0.03 in dimensionless units), the dumbbell extensibility (10.0 in units of unstretched molecule length) and a relaxation time term (0.0001s).

To start with both fluids appear to jet in a similar manner (step 1, in Figure 7). As the jet extends the elasticity of the second fluid begin to dominate over its viscosity properties. The ligature is now shorter compared to that of the purely Newtonian fluid (step 2). The velocity of the jet is similarly lower for the viscoelastic fluid and a higher drive voltage in a printhead would be required for it to jet with the same velocity as the purely Newtonian fluid. At a later time (step 3) the Newtonian fluid has detached into drops while the viscoelastic fluid is still connected by its ligature. The distance and velocity of the drops at each of these time steps are indicated in Figures 8 and 9 respectively.

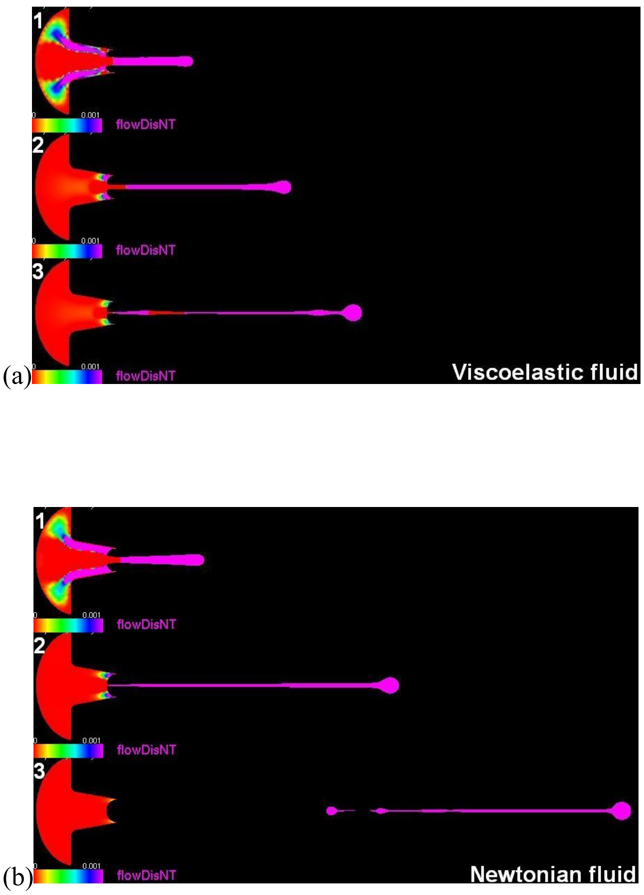

Figure 7 *Simulated jet evolution for (a) Newtonian and (b) viscoelastic fluids. Colour represent fluid velocity. Time steps 1, 2 and 3 taken at 7.5µs, 25µs and 48µs respectively from the start of the velocity profile.*

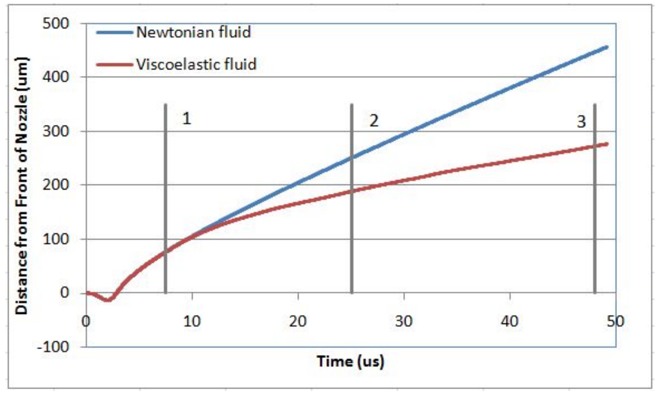

Figure 8. *Distance from nozzle of the jets of Newtonian and viscoelasctic fluids when driven with the same velocity profile at the time intervals shown in Figure 7.*

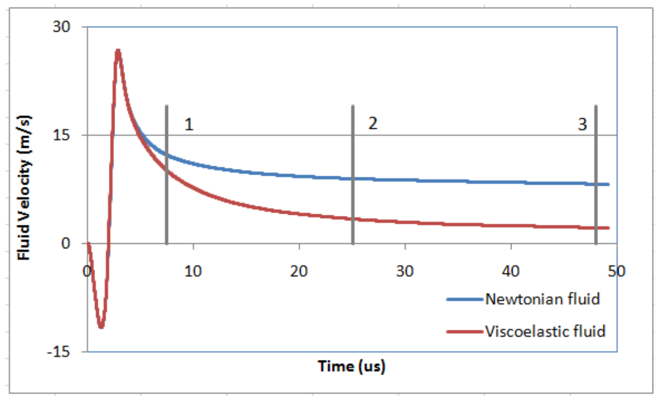

Figure 9 *Velocity of the jets of Newtonian and viscoelastic fluids when driven with the same velocity profile at the time intervals shown in Figure 7.*

Conclusions

The ink fluidic regimes of drop-on-demand printers are shown to vary widely as the ink is pumped through the system. The constituent component parts must be designed to promote efficient flow through the system, with minimal variation between adjacent supply channels to avoid ink starvation in high duty cycle regions of the printhead. Computational approaches to microfluidic design using CFD has been shown to be powerful for optimising flow geometries, and for providing insight into the sensitivity of the flow regime to fluid parameters, volumetric flow rates and geometric features.

The acoustic operation of Xaar's printhead has been discussed, and the drop ejection procedure has an influence on the flow regime of the whole active ink channel.

References

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Author Biography

Mario Massucci has a BSc in chemistry and PhD in physical chemistry from University of Bristol. He has many years experience in developing instruments in R&D in both academia and industry. He joined Xaar in 2007 as a research technologist and currently works on visualisation and measurement techniques along with simulation tools for current and future printhead designs.