Performance of Fluids in a Silicon-based Continuous Inkjet Printhead Using Asymmetric Heating

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Abstract

In this paper, we study the performance of a variety of fluids in a new continuous inkjet printhead that employs asymmetrical heating of a jet of fluid to cause it to deflect. The basic design and operation of the printhead is described in a companion paper in this same conference. We focus mainly on the performance of non-aqueous fluids, with some discussion of the performance of water mixed with common humectants.

By examining the performance of a variety of fluids, we try to understand the mechanism causing the deflection. We compare our experimental results to the output of a Computational Fluid Dynamics (CFD) model of the device that is solved using finite difference Volume of Fluid (VOF) code. With our choice of fluids, we focus on the role played by the temperature dependence of the fluid viscosity on magnitude of the jet deflection.

Introduction

Continuous inkjet (CIJ) systems can supply drops of fluid at a very high rate. The selection of drops to produce a print is usually made via an electrostatic means. The pressurized stream is typically caused to break up in a regular manner via a piezoelectric transducer. The resulting drops are charged, and then deflected via an electric field so they land on the media, or they are captured in a guttering/recycling system. This requires the use of charging tunnels and deflection electrodes.[1] In the new CIJ printhead that is the subject of this paper, both the jet breakup and the resulting drop deflection are accomplished via the application of heat to the jet in an asymmetrical manner.[2]

Figure 1(a) shows a top view of a single nozzle of this new printhead. It consists of a hole in a thin nozzle plate with two semicircular heaters on either side. The region behind the nozzle plate is a relatively large chamber that holds pressurized fluid. Shown in Figure 1(b) is a section of an array of nozzles. The semicircular heaters are oriented with the gap between the semicircles parallel to the array direction. When heat is applied to one of the heaters, the fluid deflects away from the heated side, thus out of the plane formed by the array of jets.

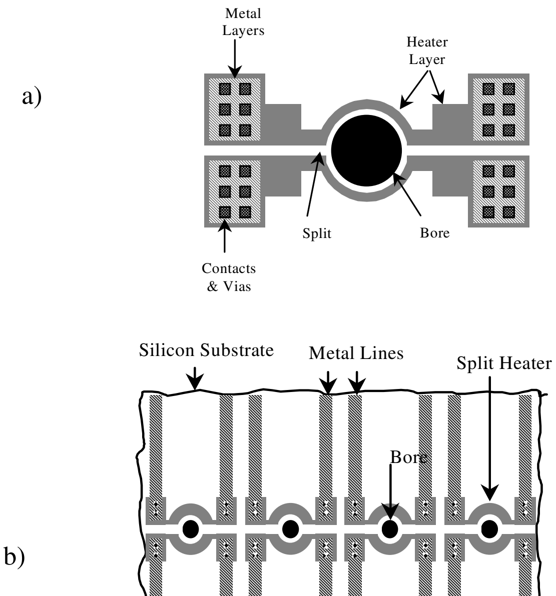

Figure 1. a) Top view of a nozzle showing split heater configuration. b) A section of an array of nozzles showing the orientation of the heaters.

In this paper, we study the performance of various fluids in this new printhead, focusing solely on the deflection angle for a stream of drops. We compare our results to a CFD model of the device that is solved using finite difference VOF code.

Experimental Details

We image the streams of fluid in a time-resolved manner using a strobe light and camera system. The video signal output of the CCD camera is captured using frame grabber in a personal computer. The fluids are filtered through a 0.45-μm pore filter in the supply line just prior to entering the printhead. Compressed nitrogen gas is used to pressurize the fluid supply container under the control of a pressure regulator. The pressurized fluid forms a cylindrical jet exiting the nozzle bore. We vary the velocity of the jets by adjusting the pressure in the fluid supply container.

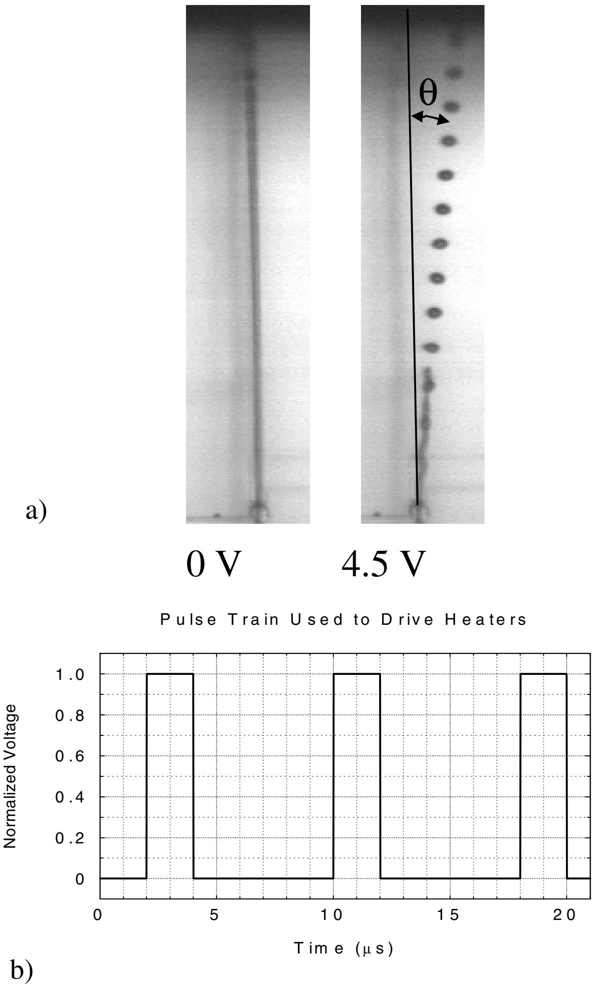

Figure 2. a) Images showing a jet of fluid being deflected. b) A portion of the waveform used to drive the heater.

The heaters are driven with voltage pulses from an arbitrary waveform generator that is subsequently amplified to provide the necessary current. For these experiments, the repetition rate for the application of a series of heat pulses was about 10 Hz (the frame rate chosen for our camera system). Shown in Figure 2(a) are images of a jet of 2-propanol with and without the application of heat pulses. The angle θ is the angle of interest in this paper. The heater on the left side of the nozzle is used and the deflection is to the right in these images. The camera is tilted at 20^{o} from the plane of the printhead. Shown in Figure 2(b) is a portion of the heater pulse sequence used. For these experiments, we used a pulse width of 2 μs with a period of 8 μs. Notice the formation of a uniform sequence of deflected drops within a short distance from the nozzle when the heat pulses are applied. Without the application of the heat pulses, the jet does not deflect and breaks up somewhat randomly at a longer distance from the nozzle.

We measure the deflection angle from such images using an image analysis program. For each image of a deflected jet, we acquire a corresponding image of the same jet without the application of heat pulses. We determine the velocity of the jet by measuring the distance between drops, knowing that the time spacing between drops is 8 μs.

To compare the performance of various fluids, we use the same voltage pulses for each fluid. This assures the same energy per pulse is being supplied to the heater, but does not mean that the same heater temperature is being achieved. The peak heater temperature will be dependent on the thermal properties of the fluids and the velocity of the fluid as it flows past the heated portions of the structure.

We measure heater temperature by monitoring the resistance of the poly-silicon heaters. The resistance of poly-silicon increases linearly with increasing temperature. By placing a small resistor (10 Ω) in series with the heater between the lower voltage contact of the heater and ground, we can monitor the current flow through the heater during the heat pulse using a digital oscilloscope. As the heater resistance increases, the current decreases because the voltage is held constant during the heat pulse. We determine the temperature coefficient of resistance (TCR), $\Delta R/R$ in $^{o}C^{-1}$, by measuring the heater resistance at room temperature and one elevated temperature, typically $130^{o}C$.

Experimental Results

Shown in Figure 3 is a comparison of the performance of various fluids, namely water and some common alcohols, in one of our experimental printheads. We also include 1-pentanol and 3-pentanol, two not-so-common alcohols. The printhead used had a nozzle bore diameter of approximately 11 μm. The width of the heater was 1 μm, and the heater resistance was 526 Ω. With the exception of water, the fluids included in Figure 3 all have low surface tension and relatively low thermal conductivity. The reference fluid we typically use is 2-propanol, or isopropyl alcohol (IPA). With the exception of 3-pentanol, IPA has the best performance of the common fluids. The behavior of water is complicated by its high surface tension. The jet of water can be biased toward one side or the other depending on where, or if, the jet pins itself on any non-uniform features of the printhead surface such as the edges of the heater. In most of the discussion that follows, we will focus on the low surface tension fluids.

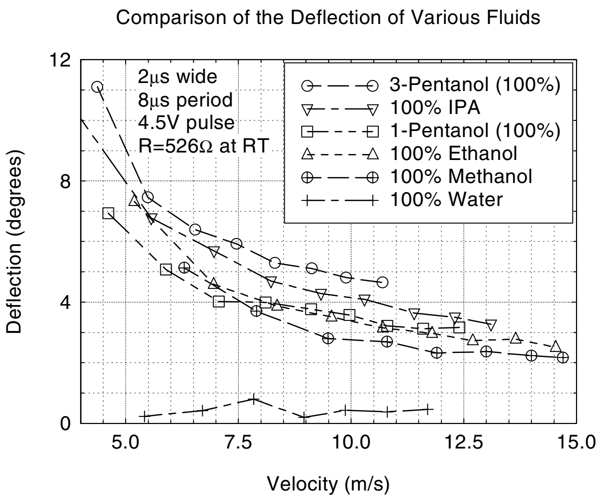

Figure 3. Comparison of the deflection of various fluids.

Using IPA in this printhead flowing at about 10 m/s from the nozzle, we measure a peak heater temperature at the end of a heat pulse in excess of 400°C. Note, this is the temperature of the poly-silicon itself, not the surfaces of the printhead in contact with the fluid. This is a very high temperature, but the fluid is never really exposed to that high of a temperature. There is a layer of oxide on top of the heater that insulates it from the fluid. The heat is also conducted into the solid structures surrounding the heater very rapidly. The energy supplied to the heater will mostly go into warming the fluid, but the fluid will not experience that extreme temperature directly.

We also studied mixtures of fluids. For some binary fluid mixtures, we found the deflection performance to scale roughly in proportion to the fraction of each fluid used. For mixtures of water with humectants, the proportionality scaling did not hold as well. However, we found that many fluids mixed with water have superior performance to that of water alone.[3] For example, a 50/50 mixture of diethylene glycol and water has about half the deflection performance of IPA in the printhead used to acquire the data shown in Figure 3, which is substantially better than 100% water. Thus, typical inks containing a mixture of water with one or more humectants are candidates for use in such a printhead.

Discussion

What could be causing the jet to deflect when heat is applied? There are two main attributes of the fluids that change significantly when heat is applied, namely viscosity and surface tension. Because we apply the heat asymmetrically, there are spatial gradients of these fluid properties. For non-uniform surface tension, there are both tangential and normal component gradients. The tangential gradients (Marangoni stresses) give rise to flows along and around the jet.

The low-surface-tension fluids such as the alcohols all have similar surface tensions and variation of surface tension with temperature, yet their deflection performance varies considerably. However, if we examine the relative variation in fluid viscosity ($\Delta\mu/\mu$) of these alcohols, we find variations consistent with their relative deflection performance. Shown in Table 1 is a comparison of the fractional viscosity change for the various fluids over the temperature range of 25-50°C. Note that for the alcohols, the ranking based on fractional viscosity change is consistent with the ranking based on deflection performance. Clearly, the ranking is not exact, especially for water. If we attempt to include the effects of the higher heat capacity and thermal conductivity for water, we predict an even lower deflection performance for water. Because of its higher heat capacity, the same amount of energy will not raise water to as high a temperature as the alcohols. Moreover, the higher thermal conductivity of water will distribute the energy in the fluid more rapidly.

Table 1. Fractional Viscosity Change Comparison.

Fluid	$\Delta\mu/\mu$ (25-50°C)
3-pentanol	0.65
IPA	0.5
1-pentanol	0.5
ethanol	0.35
methanol	0.28
water	0.38

Simulation Details

To better understand the jet deflection phenomenon, we performed a series of simulations using a CFD code (FLOW-3D). FLOW-3D is a commercially available finite difference code for solving the complete Navier-Stokes equations using the VOF method.[4,5] The capabilities of the code include three-dimensional, time-dependent, coupled fluid/structure heat transfer and free surface tracking of complex nonlinear flows. Because the jet deflection problem is cylindrical in nature (yet inherently non-symmetric with the application of heat to one side), a comprehensive model would require a full three-dimensional numerical solution. The computational cost of such a simulation is extremely high, therefore a two-dimensional planar geometry was adopted that has been shown to capture the essential features of the jet deflection phenomenon.

The computational mesh used consists of 136 cells in the cross-jet (sheet) direction (x), and 255 cells in the axial direction (z). It extends from $-15.0 < x < 15.0$ μm and $0 < z < 50.0$ μm. We uniformly apply a steady-state power to the poly-silicon heater structure in the model. Shown in Figure 4 is typical output from the simulations. Energy diffuses through the surrounding oxide/nitride layers to the fluid/structure boundary where it diffuses into and is advected away in the fluid. The physical properties of the fluid include viscosity and surface tension, which vary with temperature, as well as density, thermal conductivity, specific heat, and contact angle.

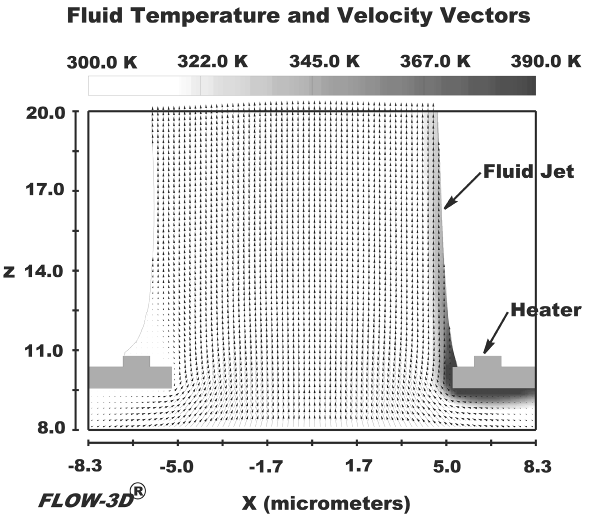

Figure 4. Typical output from the simulations. Energy has been supplied to the heater on the right.

Simulation Results Discussion

Figure 5 shows a comparison of some initial modeling results with the experimental data for water and IPA. The correspondence is very good for water, but not quite so good for IPA. However, the general trend with velocity is captured for the IPA results. Some discrepancy can be attributed to using a 2-dimensional versus a 3-dimensional model. A complete understanding of the jet deflection phenomenon is complex because of its highly coupled nature, the large number of parameters involved, and its sensitivity to geometric features. The simulations have shown that jet deflection for a given geometry is primarily controlled by the competition between three governing effects. Viscosity variation with temperature causes a momentum imbalance across the exiting jet resulting in deflection away from the heated side. Similarly, variation in surface tension with temperature and the resulting gradients cause changes in the local mean curvature and generate surface flow as a result of Marongoni stresses (tangential to the free surface). We have shown that both of these effects also play role in jet deflection.

As discussed above, the viscosity variation with temperature plays a significant role for the low surface tension fluids. Our simulations suggest that the surface tension variation with temperatures plays a somewhat larger role in higher surface tension fluids such as water mixtures. Further studies of the interplay of the various fluid properties on jet deflection are underway.

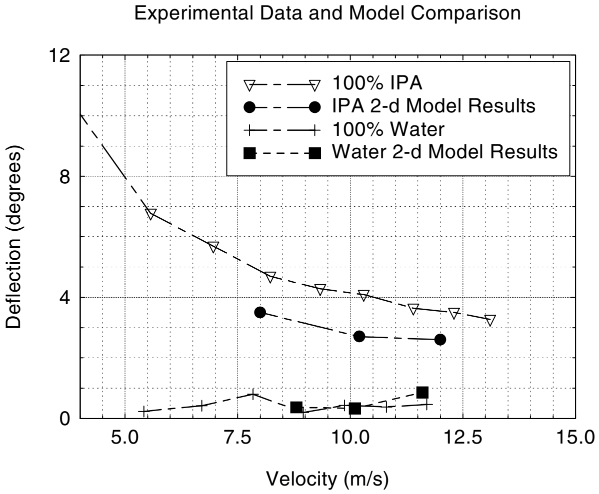

Figure 5. Comparison of experimental results with initial 2-d model results.

Conclusion

In this paper, we have described the performance of a variety of fluids in a new CIJ printhead that uses asymmetrical heating of a jet of fluid to cause it to deflect. We focused on the relative performance of some common, and not-so-common, alcohols to gain insight into one of the major components in the mechanism causing the deflection of the jet of fluid, namely the change in viscosity with temperature. We constructed a 2-dimensional model of the system and compared those results with the experimental data.

References

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Biography

David P. Trauernicht received his B.S. degree in Physics from Southern Illinois University at Edwardsville in 1980 and his Ph.D. in Physics from University of Illinois at Urbana-Champaign in 1985. Since 1985, he has worked in the Research Laboratories at Eastman Kodak Company in Rochester, NY. His current research interests are in the areas of inkjet printheads and factors affecting the image quality of printed images. He is a member of the IS&T and the American Physical Society.