Operating Voltage Effects on Bubble Growth Dynamics of Thermal Inkjet Printheads

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Abstract

The ejection performance and printing quality of a thermal inkjet printhead are significantly affected by bubble growth dynamics. This study investigated bubble growth dynamics and the ink ejection process under various heating conditions that are controlled by driving voltages. Numerical predictions are presented for bubble generating time, volume, temperature and pressure. The numerical computations suggest that a three-step voltage control method results in a larger ink-ejection velocity than a one-step voltage control method, even though the former generates less thermal energy. Through simulation, it can be shown that the three-step voltage control method actually has a larger heat flux rate from the printhead heater to the ink chamber when the ink is nucleated. Therefore a larger bubble pressure and a faster ink ejection are generated. This prediction is verified by the experimental results.

Introduction

The printing quality of a thermal inkjet printhead is significantly affected by droplet ejection performance. Therefore, factors affecting the droplet ejection process should be carefully investigated. Asai et al. (1987) conducted both numerical simulation and experimental measurements to obtain the temporal variation of the ejected droplet length. Chen et al. (1997) used a one-dimensional model to describe the unsteady heat conduction problem, bubble growth, and ink motion of the top-shooter thermal inkjet printhead. Their results show that the threshold operating voltage for ink ejection decreases with the heat pulse width increasing. In addition, increasing the operating voltage causes a little volume change of the ejected droplet at a fixed heating pulse width. Therefore, the droplet volume is only slightly affected by the variation of heating pulse if the operating voltage is kept at a constant value. The aim of the present study is to investigate the bubble growth dynamics and ink ejection process under various heating conditions (i.e. operating voltage control methods).

Ink droplet with larger ejection velocity from an inkjet printhead will be less affected by the surrounded air disturbance and keep a good directionality. The present study with numerical predictions on printhead HP51626A reveal that a three-step voltage heating condition (with less thermal energy input) results in a larger ink-ejection velocity than a one-step voltage heating method. The larger heat flux rate from the printhead heater to the ink chamber results in larger bubble pressure and ink-ejection velocity. Numerical predictions are also presented for bubble generating time, volume, temperature and pressure under various heating conditions. The experimental results show conclusions in agreement with numerical simulation predictions.

Theoretical Model and Numerical Scheme

The printhead considered has nozzles with a radius of 32.5μm. Below the nozzle, there is a 60 μm × 60 μm rectangular chamber. The density of the water-based ink is 1.02 g/cm^3 and has a dynamic viscosity of 1.28 cps. After the heating pulse is applied, the unsteady heat conduction problem can be modeled with the following one-dimensional heat-diffusion equation:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\left(\frac{E}{R_{all}}\right)^2\left(\frac{R_h}{V_h}\right)=\rho c\frac{\partial T}{\partial t} \qquad (1)$$

where k , ρ, and c denote the thermal conductivity, density, and specific heat of the material, respectively, at the vertical location of x. In Eq.(1), E is the operating voltage, V_h is the resistor volume, R_h denotes the electrical resistance of the resistor, and R_{all} denotes the total electrical resistance of the resistor with extended electrodes, In this study, the values of R_h and R_{all} are 35 and 46 Ω, respectively, and are assumed to be constant in the range of operation. The above unsteady heat conduction problem is subject to the following initial and boundary conditions.

$$T = T_{amb} \quad at \quad t = 0 \quad for \quad 0 \le x \le x_e$$
$$T = T_{amb} \quad at \quad x = 0 \text{ and } x = x_e \quad for \quad t > 0 \qquad (2)$$

An implicit finite-difference numerical scheme was employed to solve Eqs. (1) and (2). Since the thermal conductivity of the ink is relatively low, the sharp thermal gradient is expected in the heater-ink interface region. Thus, a non-uniform grid was used. The time increment of 0.01 μs and 341 grids were used throughout the present simulation.

With the high heat flux conducted into the ink, an empirical correlation was used to predict the threshold temperature T_t, given by (Runge, 1992):

$$T_t(^oC) = 230^oC + 1.6\cdot 10^{-7}\left(\frac{\partial T}{\partial x}\right)_{hi} \qquad (3)$$

where $(\partial T/\partial x)_{hi}$ denotes the temperature gradient in the ink at the heater-ink interface. Once the temperature at the ink-heater interface is greater than T_t, homogeneous nucleation following the film boiling immediately takes place. The induced vapor bubble quickly covers the upper surface of the heater and the height of vapor bubble is assumed to be uniform all over the heater.

The ink in the nozzle is assumed to be incompressible and its surface tension is neglected in this case. We also assumed the vapor to be an ideal gas with the uniform vapor temperature and pressure. The vapor pressure in the bubble initially ranges from 1 to 10 MPa, and then, within a few microseconds, decreases to the saturated water vapor pressure at ambient temperature. To predict the vapor pressure, Asai (1991) classified the process of bubble growth into two stages. In the early stage, the Clausius-Clapeyron equation is adequate to describe the pressure in the vapor bubble, P_v, for the water-ink ink, given by

$$P_v = P_{atm}\, exp\left[\frac{wh_{fg}}{K}\left(\frac{1}{273+T_{bp}} - \frac{1}{273+T_v}\right)\right] \qquad (4)$$

Here, K is the gas constant, w denotes the molecular weight of the water vapor in the bubble, and h_{fg} and T_{bp} denote the heat of vaporization and boiling point temperature of water at 1 atm, respectively. However, Eq. (4) is only valid when the vapor bubble height is thin and the ink flow velocity is small.

An exponential decay formula suggested by Asai (1991) to describe the sharp drop in the vapor pressure in the later stage of the bubble growth process was given by

$$P_v = (P_t(T_t) - P_s(T_{atm}))\, exp\left[-\left(\frac{t-t_b}{\tau}\right)^{\lambda}\right] + P_s(T_{amb}) \qquad (5)$$

where t_b denotes the onset time of homogeneous nucleation in the ink, τ is the time constant, and P_t and P_s are the values for saturated vapor pressure at T_t and T_{amb}, respectively. The λ value is carefully selected by matching the time histories between the measured and predicted ejected ink lengths. In this study, a λ value of 0.5 was used.

Results and Discussion

Rembe et al. (2000) presented a cinematographic measuring technique for the visualization of droplet ejection with a Hewlett-Packard DeskJet 500 printhead (HP51626A). The bubble nucleation for the standard heating pulse with a length of 3 μs and an amplitude of 6.5W as shown in Fig. 1. The nucleation process in the ink chamber starts 3.1 μs after the beginning of heating. Figure 2 shows the bubble pressure and temperature after nucleation with the same condition of Rembe et al. (2000) for HP51626A. With the high heat flux into the ink, homogeneous bubble nucleation results in a rapid growth of the vapor bubble and, consequently, a high pressure rises in the ink chamber. Such a high pressure pushes the ink out of the nozzle. After the short electrical heating pulse width, no heat energy is generated and conducted from the resistor to the vapor bubble. The bubble pressure and temperature quickly decrease and the bubble collapse. The nucleation start at 3.016 μs after the beginning of heating by the numerical simulation is almost the same with the investigation of Rembe et al. (2000).

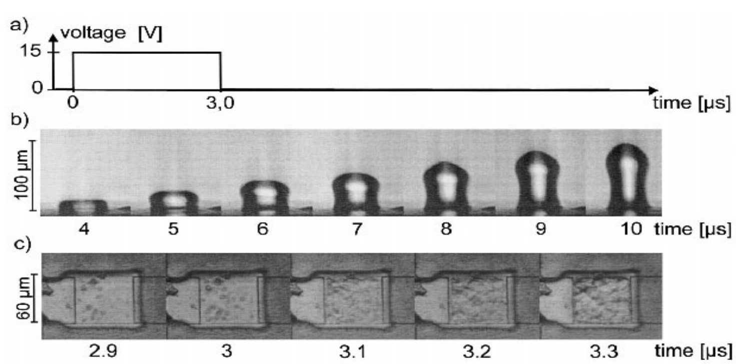

Figure 1. (a) input pulse, (b) Visualization of droplet ejection, and (c) nucleation for the standard heating pulse with an amplitude of 6.5W (Rembe et al., 2000)

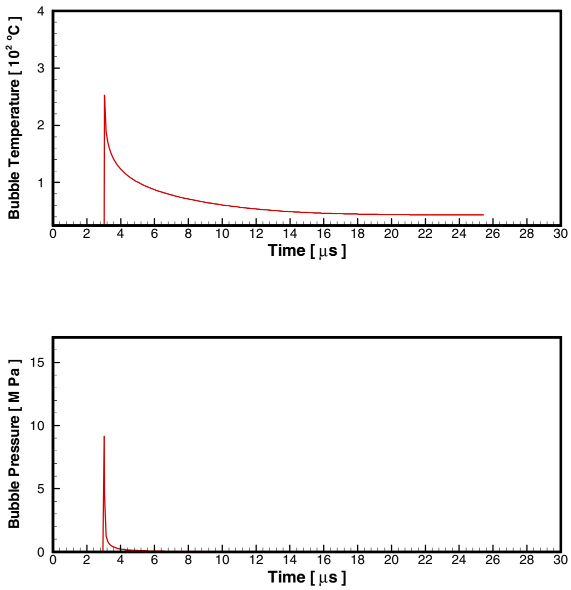

Figure 2. Numerical results of printhead HP51626A (a) bubble temperature, and (b) bubble pressure for the standard heating pulse with an amplitude of 6.5W

Numerical predictions on printhead HP51626A, as shown in Fig. 3, reveal that a three-step voltage heating condition (with less thermal energy input) results in a larger ink-ejection velocity than the one-step voltage heating method. However, the larger ejection velocity results in the longer ink droplet tail. Figure 4 reveals that the larger heat flux rate (a three-step voltage heating condition) from the printhead heater to the ink chamber results in the larger bubble pressure and ink-ejection velocity.

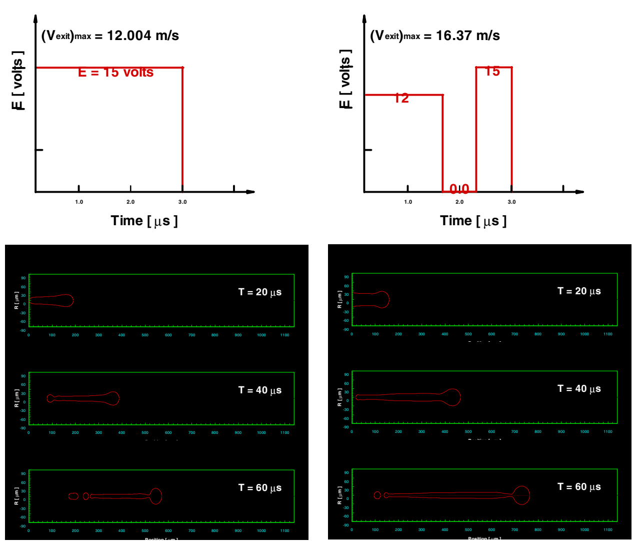

Figure 3. Numerical predictions on mean inkjet nozzle exit velocity for (a) one-step voltage heating method, and (b) three-step voltage heating condition

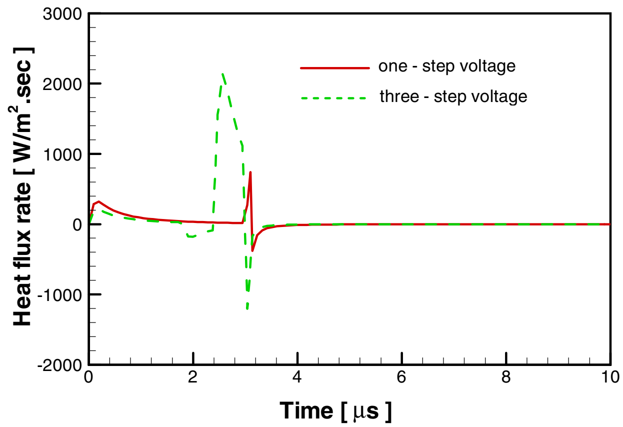

Figure 4. Heat flux rate for (a) one-step voltage heating condition, and (b) three-step voltage heating condition

Figure 5 shows the experimental results of printhead HP51641A, which has the same mechanism as HP51626A, at 20 μs after the energy was given for one-step voltage and three-step voltage heating methods. The results show conclusions in agreement with numerical simulation predictions.

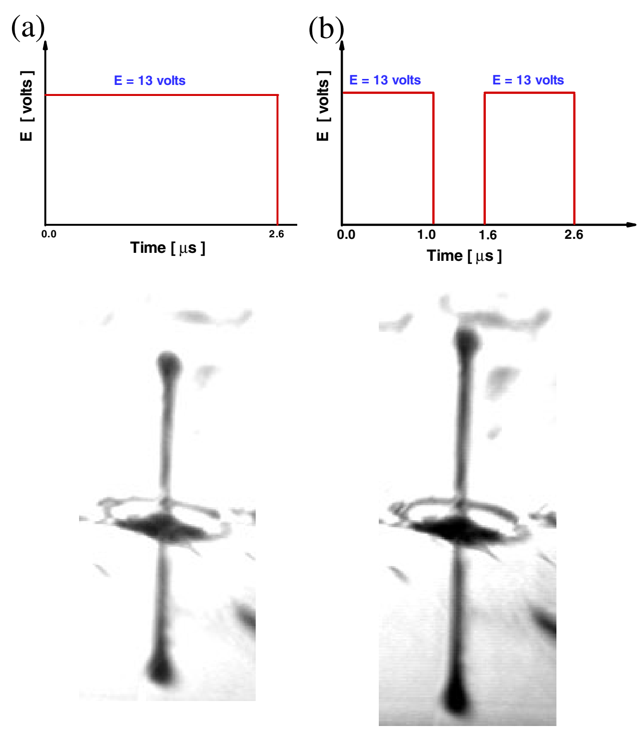

Figure 5. Experimental results of printhead HP51641A at 20 μs after energy was given for (a) one-step voltage, and (b) three-step voltage heating methods

Conclusion

Numerical predictions on printhead HP51626A reveal that a three-step voltage heating condition (with less thermal energy input) results in a larger ink-ejection velocity than the one-step voltage heating method. The larger heat flux rate from the printhead heater to the ink chamber results in larger bubble pressure and ink-ejection velocity. Numerical predictions are also presented for bubble generating time, volume, temperature and pressure under various heating conditions. The experimental results show conclusions in agreement with numerical simulation predictions.

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Biography

Jinn-Cherng Yang jointed the Print Head Testing Section of OES/ITRI in 2001. He received his M.S. and Ph.D from Institute of Aeronautical and Astronautical Engineering of National Cheng Kung University. His interest lies in the turbulent flow field of computational fluid dynamics, numerical simulation of two-phase flow.

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