Abstract

Numerical predictions on the entire process of droplet ejection by the growth/collapse of an explosive micro-thermal bubble are achieved by first principle equation coupled with extended Rayleigh equations and Asai’s pressure model. Supporting experiments such as the bubble size/shape image histories by high speed camera and bubble-induced flowfield by micro-Particle-Image-Velocimetry are conducted for the process. Excellent agreements between measurements and computations are obtained. Thirdly, the parameter studies on droplet ejections are conducted to seek the optimal designs for the ejection nozzle size, ink refilling chamber height, supplied heat flux, and the operating temperature.

1 Introduction

Inkjet printer technology has been rapid expanded in the recent years and the so-called drop-on-demand printers can be categorized by piezoelectric driven [1] and thermally actuated [2]. Thermal bubble jet printer is preferred due to the fact of low manufacturing costs at comparable print quality. In the inkjet process, the ink is highly superheated by a heating pulse in micro-seconds to generate vapor bubble suddenly, the rapid growth of the bubble ejects a small drop of ink out of a nozzle, and the ink reservoir is refilled after the bubble is collapsed. In order to achieve best print frequency, resolution and quality of ejected droplets, bubble nucleation as well as designs of heater, nozzle, ink chamber, heating pulse duration etc., are important parameters for optimization.

Reliable simulation is an effective and economic approach for optimization purpose and Computational Fluid Dynamic (CFD) approach has been demonstrated [3,4] the reliability by the use of first principle equations. Inkjet process is usually divided into three subsystems: bubble nucleation, bubble growth and collapse, and droplet ejection. In the present study, numerical simulations for the entire process are performed to understand the detailed flow characteristics and measurements of the induced flowfields are conducted by micro-Particle-Image-Velocimetry to compare with and validate the computed fields.

2 Mathematical and Numerical Models

In order to link the information of subsystems of bubble nucleation, bubble growth/collapse, and droplet ejection for the inkjet process, a flow domain of inkjet head is constructed by three subsystems: ink chamber, flow nozzle, flying channel with the growing and collapsing bubble acting as a pump source to eject droplet. The flow characteristics inside the flow domain must follow the conservation laws of mass and momentum in a two phase flow system. The mathematical models consist of continuity and momentum equations given as follows:

2.1 Continuity equation

\[ \frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m U_m) = 0 \]  

(1)

where \( U_m \) and \( \rho_m \) are the velocity and density of the mixed working fluids (air, water, or/and the interface region), and \( t \) represents time.

2.2 Momentum equation
\[
\frac{\partial \rho \vec{U}}{\partial t} + \nabla \cdot (\rho \vec{U} \otimes \vec{U}) = -\nabla P + \rho \vec{g} + \nabla \cdot (\mu \nabla \vec{U}) + \vec{F}_{sv}
\]  
(2)

where \( P \) is the pressure and \( \mu \) is the viscosity of the working fluids. This equation implies the balance of inertia, pressure, viscous forces with surface tension force (\( \vec{F}_{sv} \)) and can be represented by Continuum Surface Force model as

\[
\vec{F}_{sv} = \tilde{\tau}_s \delta_s + \tilde{\tau}_{sv} \sigma \nabla \cdot \vec{n}
\]
(3)

In the above equation, \( \tilde{\tau}_s \) is the surface tension per unit interfacial area, \( \delta_s \) is the surface area delta function, \( \sigma \) is the surface tension coefficient, \( \kappa = -\nabla \cdot \vec{n} \) is the curvature of interface, and \( \vec{n} \) is the unit normal vector. This equation indicates the importance of the curvature of interface to surface tension and smaller bubble implies the smaller curvature radius.

For this droplet ejection system, the balance of surface tension force at gas/liquid interface, inertia force, and pressure force in the flow field determine the formulation and ejection of droplet. For two phase flow systems in microscale, surface tension plays major role in the droplet formation, and robust scheme is needed to determine of the liquid/gas interface precisely. A continuum surface force (CSF) model [5] is chosen to calculate the surface force at interface for the present work. With two-phase homogenous flow model and the interface tracking technique, the Volume-of-Fluid (VOF) method in cooperation with Piecewise Linear Interface Calculation [6,7] is selected to obtain robust solutions for the interface determination. Numerical simulations are performed on the platform based on a commercial finite-volume computer code from CFD Research Corporation (CFD-ACE+). Since the energy is supplied only by a pulse lesser than 4\( \mu \)s and the bubbles are generated after the heating pulse, the energy transport is assumed negligible and energy equation is not included in the mathematical model. Working fluids consist of water, air, and their interface. The interface can be described by the combination of liquid and water.

### 2.3 Thermal Bubble as a Pump Source

The bubble nucleation and the bubble growth/collapse act as the pumping source to eject the droplet. In the present computations, the velocity at ejector inlet is calculated by the vapor volumetric flowrate and is served as the boundary condition to actuate the droplet. The vapor volumetric flowrate is related to the radius of bubble (\( R_b \)) which can be estimated by extended Rayleigh equation [8]

\[
R_b \frac{d^2 R_b}{dt^2} + 3 \left( \frac{dR_b}{dt} \right)^2 = \frac{1}{\rho} \left[ P_v - P_l - \frac{2\sigma}{R_b} + \tau_r (r = R_b) \right]
\]

Where \( P_v \) is the vapor pressure within the bubble, \( P_l \) is the ambient pressure of liquid, \( \tau_r \) is the normal stress at the vapor-liquid interface which is usually negligibly small. In present study, the vapor pulse pressure of microbubble is obtained by a simplified model for a high heat flux heating process following Asai [9]

\[
P_v = (P_{nc} - P_{sat}(T_{amb})) \times \exp\left(\frac{-t}{t_{half}}\right) + P_{sat}(T_{amb})
\]

where \( P_{nc} \) is the initial saturated pressure when bubble at nucleation; \( P_{sat}(T_{amb}) \) is the saturated pressure of ambient liquid corresponding temperature \( T_{amb} \); \( \lambda \) and \( t_{half} \) are the decay controllers of the bubble pressure and are obtained by fitting experimental data. This model is derived from a thin vapor film covered on the heater to a merged bubble and the nucleation condition in the inkjet head is highly subcooled. Therefore, the major driving force of liquid motion is the pressure impulse of the bubble to balance out the pressure difference of vapor/liquid and inertial force. Supplying the parameters of \( P_{nc}, P_{sat}, T_{amb}, t_{half}, \lambda, P_v \) is obtained from Asai’s pressure model (Eq.5) and then the bubble radius \( R_b \) can be obtained by solving extended Rayleigh equation (i.e.Eq.4) via Runge-Kutta method.

### 3 Experimental Methodologies

#### 3.1 Thermal Bubbles Generation
For present work, the micro heater chip has been manufactured by surface micro machining technology and platinum is acted as the heater material. The detailed manufacturing process is described in Ref. 11. For the study of shape factor effect, heaters of area 30 μm × 30 μm, 30 μm × 60 μm, 20 μm × 60 μm (i.e. aspect ratios of 1:1, 2:1, and 3:1) are fabricated and the heat fluxes are supplied with 1.2, 1.4 and 1.6 GW/m² by adjusting the voltages of the heating pulse with 4 μs duration.

3.2 Flowfield Measurements

Particle Image Velocimetry in micro-scale flow field (μPIV) is a very attractive tool for flowfield measurement with no disruption [10]. The measurement of the induced flowfields in spatial resolutions in tens of μm and temporal resolutions in hundreds of ns are required. Furthermore, the optical noise by high reflectivity at metal (aluminum connector) and the imperfect smoothness of the continuously changing bubble interface must be overcome. In the present study, micro particle image velocimetry technique coupled with the phase-averaged technique is applied for the flow visualization. Double pulses (separated by 0.5 μs) Nd-YAG laser with very short exposure time (30ns) is used to illuminate Polystyrene fluorescent particles (1 μm diameter) inside the flow region and the epi-fluorescent microscope Olympus BX51 coupling with the 20X long working distance objective lens is used to observe the sufficient region of interest (~300 μm for both X and Y directions and 8.45 μm for Z direction). The images at different phases with time steps of 1 μs are recorded for quantitative analysis. The recorded images pairs are analyzed by the TSI Inc.’s PIV analyzing software “INSIGHT™” to obtain the detailed flow field from the acquired images.

4 Results and Discussions

4.1 Bubble Shape/Size Histories

Predicted and measured bubble size histories for supplied heat fluxes of 1.2, 1.4, and 1.6 GW/m² for rectangular heaters of various ratios (30 μm × 30 μm, 30 μm × 60 μm, 20 μm × 60 μm) are plotted and are compared in Fig.1. Predictions using extended Rayleigh equation and Asai’s pressure model are in good agreement with measurements in terms of the maximum extents of the bubble volumes and the growth rate of the bubble volumes during bubble growth, but over-predict the collapse rates of bubble volumes especially at the end of bubble lifetime and thus under-predict the bubble lifetime (1 to 2 μs shorter than the measured lifetime). Furthermore, no success of obtaining the so-called “rebound” phenomena. In the predictions, the decay controller factor λ in Eq.(5) is ranged from 0.32 to 0.36.

In order to obtain the bubble shape/size variation during the growth/collapse process for explosive micro thermal bubbles quantitatively, the microscopic flow visualization method coupled with phase-averaged technique, and numerical simulations using first principle equations are performed to identify and provide the integrated and detailed characteristics of bubble dynamics. The second and fourth columns of Fig. 2 illustrate the top and side images of bubble from experiments while the third and fifth columns of Fig.2 illustrate the corresponding top and side views of the bubble images from numerical simulations at corresponding times respectively for three cases of heater aspect ratio of 1:2. Excellent agreements between experiments and numerical computations are obtained in terms of shape/size evolutions. The top view of bubble is an ellipsoid in growth process and evolved to a circle in collapsing process, and the side view of bubble is in the short cylinder shape with smaller base diameter and higher ratio of cylinder height/base. The observations illustrate the bubble dynamics by the bubble boundary formation in terms of the balance of surface tension force around the bubble boundary and the pressure field, which can be described clearly using first principles.

4.2 Induced Flowfields

At the moment of heat pulse shutting down (set as t=t₀), the highest velocities are located at bubble boundary points of opposite left and right ends. Local velocities decrease at points
located farther from the boundary. Measured and computed contours and vectors of velocity fields by μPIV are in very good agreements (Fig.3) and also confirm the bubble shape/size evolution images. The excellent agreement indicate the consistency and quality of measurements and predictions quantitatively in the microscale two phase flow system. Thus, the numerical computations in the associated flow system are validated and can be extended to applications, for example, droplet ejection formation in the ink-jet ejection system.

4.3 Droplet Ejection Process

Several design parameters need to be optimized to achieve stable printing quality for thermal bubble inkjet head such as the sizes of the ejection nozzle, connecting chamber, and ink supply channel/reservoir. In order to reduce the manufacturing tests/cost, numerical simulations are the reliable and effective tool for optimal design. The numerical grid system of the flow domain for thermal bubble inkjet head consists of 43652 grid nodes as shown in Fig. 4. The grid independent test has been performed using grids with 19916, 43652 and 57819 nodes respectively and less than 5% difference has been obtained for grid nodes of 43652 and 57819.

Figure 5a show that the chief droplet volume decreases with nozzle size and droplet volume size from 15μm×15μm nozzle is about half size of that from larger nozzle sizes of 30μm×30μm or 45μm×45μm. Insignificant effect from supplying heat flux is observed for injected droplet volume if the nozzle is small enough (15μm×15μm). Figure 5b shows the moving velocity of corresponding droplet and the velocity is slower for larger droplet size from larger nozzle size. Slower moving speed for larger nozzle size, lower heat flux supplied, and higher chamber height is observed. Figure 6 summaries relations of the injecting droplet velocity and the droplet size for different chamber sizes, nozzle sizes, supplied heat fluxes and operating temperature of working fluids. The linear relations between droplet velocity and the droplet size and the steeper rate of velocity for larger nozzle size are obtained, but the rate between velocity and size is insignificant changed as the working fluid temperature is increased from 27°C to 100°C, i.e the temperature effect is not a dominating factor.

5. Conclusions

Numerical simulations for the growth and collapse process of explosive bubble and for the droplet ejection actuating by these bubbles are combined to predict the full process from bubble growth to ejecting droplet. Good predictions on bubble growth histories and thus the actuating powers are obtained by extended Rayleigh equation coupled with pressure model from Asai as compared to bubble visualization. The droplet ejection simulations using first principle equation achieve excellent predictions on the velocity fields induced based on above mentioned histories of the growth/collapse of the bubble as they are compared with flowfield measurement using micro-PIV techniques for heater area of aspect ratios of 1:1, 1:2, and 1:3. Thirdly, the parameter studies on droplet ejections are conducted to seek the optimal designs for the ejection nozzle size, ink refilling chamber height, supplied heat flux, and the operating temperature.

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References


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Fig. 1 Measured and Predicted Explosive Bubble Size Histories by Heaters of Aspect Ratios with Supplied Heat Flux of (a) 1.2 GW/m² (b) 1.4 GW/m² (c) 1.6 GW/m²

Fig. 2. The Shape/Size Predictions of Bubble Growth/Collapse Process for Heater Aspect Ratio of 1:2 -Case II
Fig. 3 The Comparison of Induced Flowfields of Case II (heater aspect ratio: 1:2) Obtained by μPIV and CFD simulation

Fig. 4 Computation Grid System

Fig. 5 Chief Droplet Ejected vs Chamber Height for different Nozzle Sizes with Different Supply Heat Fluxes

Fig. 6 Chief Droplet Velocity vs Chief Droplet Diameter at Different Nozzle Sizes Operated at Different Temperatures