Generation, Growth and Collapse of a Bubble in Conductive Liquid Heated Directly by Electric Current*

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Bubbles generated in conductive ink heated directly by electric current pulses can be used in an ink-jet printer to eject ink-droplets. Such parameters as the time required for bubble nucleation, growth rate of the bubble, maximum radius of the bubble and electric power input required for bubble generation, which depend strongly on the shape and size of electrodes immersed in the ink, influence the performance of the printer. A method of numerical analysis was developed to investigate the temperature distribution of the ink and dynamics of the bubble, and was confirmed to give values of the above parameters which were in good agreement with those of experiment. An optimum configuration of the electrodes was suggested, based on the comparison of results calculated for different shapes and dimensions of the electrodes.

Key Words: Bubble, Boiling, Heat Conduction, Numerical Analysis, Ink-Jet Printer, Conductive Liquid, Direct Heating, Pulse Current

1. Introduction

When a voltage is applied to a pair of electrodes immersed in conductive liquid, the electric current flows through the liquid and then the liquid is rapidly heated. When the maximum of local temperature of the liquid reaches the temperature for nucleation, a boiling bubble generates and grows rapidly by absorbing heat from the superheated liquid surrounding it. By applying this principle to ink-jet printing, a new type of ink-jet printer⁽¹⁾, in which bubbles generated in conductive ink heated directly by electric current pulses serve as a pressure source to eject ink-droplets, can be developed. From the viewpoint of utilizing boiling bubbles as the pressure source, this method is the same as the bubble-jet printing technology devel-

oped by Canon Inc.⁽²⁾⁻⁽⁴⁾. However, compared with the Canon's method, in which the bubbles are generated on thin-film resistor-heaters, the present method of direct liquid-heating may consume less electric energy.

Successful implementation of the present ink-jet printing technology requires both experimental study and theoretical analysis on the whole process of the electric heating, and the generation, growth and collapse of a microscopic bubble in the conductive ink. As the first stage of study on this subject, a method was developed to simulate numerically the generation, growth and collapse of a bubble in the conductive ink. The validity of this method was confirmed by the comparison with the results of a basic experiment. And then, based on the comparison of the results calculated for different shapes and dimensions of the electrodes, the effects of the electrode configuration were discussed to suggest how to design the optimum electrode for this new type of ink-jet printer.

Nomenclature

a : thermal diffusivity m^2/s
 c : specific heat $\text{J}/(\text{kg}\cdot\text{K})$

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- Δh_v : latent heat of vaporization J/kg
 J : electric current density A/m²
 k : thermal conductivity W/(m · K)
 k_e : electric conductivity (Ω·m)⁻¹
 L : electrode spacing m
 P : pressure Pa
 Q : electric power consumption J
 q : heat flux W/m²
 R : bubble radius m
 $\dot{R}$: bubble growth rate m/s
 r : radial coordinate originated from bubble center m
 S : heat generation rate per unit volume W/m³
 T : temperature °C or K
 t : time s
 t_n : time required for bubble nucleation s
 W : electrode width m
 μ : viscosity Pa·s
 ρ : density kg/m³
 σ : surface tension N/m
 φ : electric potential V

Subscripts

- i : liquid-vapor interface
 l : liquid
 sat : state of saturation

2. Experimental Method and Observation

Figure 1 shows a test print-head equipped with a pair of electrodes used in the present experiment for bubble generation. Each electrode attached on the glass substrate is made of thin metal film, and has a width of 20 μm and a semicircular front edge. Resin covers the root part of each electrode for insulation. The electrode spacing is 10 μm. From the points of easy processing and durability, the thickness of the electrode is taken as 1 μm. In the experiment, this test print-head is set in a tank filled with conductive ink to immerse the electrodes in the ink.

A nozzle for ink ejection, which should be installed on a practical print-head, is not installed on the test print-head, because it prevents observation of bubble behavior. In a practical printer, a number of print-heads should be integrated, and the bubble generation and subsequent ink ejection would take place in each print-head at a frequency of several kHz. In the present study, bubble generation in a single print-head with a sufficiently long period of time between bubble nucleations was investigated.

The coordinate system x - y - z shown in Fig. 1 will be used in the following description and numerical analysis.

Figure 2 shows a schematic drawing (not to scale) of the experimental apparatus used for photographing the bubble behavior in the conductive ink. A test print-

head ① was set in a transparent tank ④ filled with the conductive ink, and the positioning was adjusted for the picture of the electrodes including their surroundings to be clearly shown on a TV monitor ⑦, and then the experiment was started. A bubble was generated

(a) Coordinate system

(b) Geometry and dimensions in μm
(calculation region is shadowed)

Fig. 1 Electrodes for current pulse heating

Fig. 2 Experimental apparatus

by applying a pulse of voltage from a power amplifier ⑧ to the pair of electrodes, and its pictures were taken with a high speed camera ③ which was synchronized with a flash light ⑤. At the same time, the waveforms of the electric current flowing between the electrodes were projected onto an oscilloscope ⑨ with the help of a current probe ⑥. As the electric conductivity of the ink increases with an increase in temperature, the current flowing between the electrodes increases with time. Once a vapor bubble is generated, the current decreases rapidly due to the low conductivity of the vapor. Consequently, the period from the commencement of application of the voltage to the electrodes to the generation of a bubble, i.e. the time required for bubble nucleation, can be determined from the variation of the current waveforms shown on the oscilloscope. In the experiment, the electric power supply was stopped immediately after the current began to decrease.

Figure 3 shows a series of photographs of the growth and collapse of a bubble, which were taken under an operating ac voltage of 30.0 V and an initial ink temperature of 25°C. The photographs on a x - y plane in Fig. 3 were taken from the direction A in Fig. 1(a), while the photographs on a y - z plane from the direction of B in Fig. 1(a). A bubble initially generates close to the tip of either electrode and immediately moves to the center point between the both electrodes. Then, the bubble grows rapidly and collapses while keeping almost hemispherical in shape.

The bubble diameters were measured from these photographs at different operating conditions. The results of the measurement will be described later in

Fig. 3 Photographs of a process of bubble growth and collapse

comparison with the results of numerical analysis.

3. Theoretical Model and Computational Method

The whole process from the application of a voltage to the electrodes up to the disappearance of a collapsing bubble can be divided into two stages; one is the stage of direct heating of the conductive ink until the bubble nucleation, and the other is the stage of bubble growth after the nucleation and bubble collapse. At the first stage, the temperature distribution of the ink at a time immediately before the nucleation can be calculated from equations of three-dimensional electric conduction and three-dimensional transient heat conduction. At the next stage, by using this temperature distribution as the initial temperature distribution of the ink, a system of governing equations for bubble growth and collapse, which includes the equation of motion of the bubble, equation of energy of the liquid surrounding the bubble and equation of heat balance at the liquid-vapor interface, can be solved.

3.1 Distribution of ink temperature before bubble generation

For the electric heating until the bubble nucleation, it is assumed that the ink remains stationary, and that the heating current is a dc current while an ac current was used in the experiment. Under these assumptions, the distribution of ink temperature can be calculated as a function of time from the beginning of voltage application to the electrodes up to the time immediately before the bubble nucleation. The governing equations are:

$$\nabla \cdot \mathbf{J} = \nabla \cdot (-k_e \nabla \varphi) = 0 \quad (1)$$

$$\text{Equation of three-dimensional transient heat conduction}$$

$$\rho c \frac{\partial T}{\partial t} = -\nabla \cdot \mathbf{q} + S = \nabla \cdot (k \nabla T) + S \quad (2)$$

S is a rate at which heat is generated per unit volume of the ink, which can be evaluated from

$$S = \frac{1}{k_e} (J_x^2 + J_y^2 + J_z^2) \quad (3)$$

where J_x , J_y and J_z are the components of electric current $\mathbf{J}$ in the directions of x , y and z , respectively.

The calculation should be performed in a rectangular region, as shown in Fig. 1(a), which consists of the pair of electrodes, the conductive ink, the glass substrate and the insulators. Because of geometrical symmetry, however, only the shadowed portion in Fig. 1(b), including one electrode on the right, can be taken as the calculation region. For calculation of the three-dimensional transient heat conduction, the initial temperature is assumed to be uniform at a given value of T_{int} in the whole region. It is assumed for the

boundary condition that there is no heat transfer across the boundaries of the calculation region. Only the portion of the conductive ink is considered for calculation of the three-dimensional electric conduction. Due to symmetry, the electrical potentials on the plane of $x=0$ and on the surface of the electrode are given as $\varphi_0/2$ and φ_0 , respectively, while electric insulation is assumed on the other boundaries.

Equations (1) and (2) are discretized by a control volume method with a fully implicit scheme. By solving the derived linear discretization equations with an iterative method, the distributions of the current density, heat generation rate and temperature in the ink can be evaluated at each time step. When the maximum of the local ink temperature reaches the temperature for bubble nucleation, a bubble is assumed to start generation and the calculated time up to this moment is defined as the time required for bubble nucleation.

3.2 Model of bubble growth and collapse

Figure 4 shows a model developed for the calculation of the bubble growth and collapse in a pool of ink. The bubble is assumed to remain spherical in shape and the liquid surrounding the bubble is assumed to possess spherical symmetry in state, i.e., except for time t , this is a one-dimensional model in which any variables of the liquid can be expressed as a function only of the radial coordinate r . In practice, the bubble remains approximately hemispherical in shape during a process of bubble growth and collapse, as observed in the experiment described previously. The present model corresponds to a model of a hemispherical bubble the bottom of which is thermally insulated. In addition, it is assumed that the temperature and pressure of the vapor in the bubble are uniform at each time step and that the vapor is at the saturation temperature. The temperature jump at the liquid-vapor interface is neglected.

Under these assumptions, the governing equations can be written as follows:

Equation of motion of the bubble

$$R\ddot{R} + \left(2 - \frac{\varepsilon}{2}\right)\dot{R}^2 = \frac{P_v - P_\infty}{\rho_l \varepsilon} - \frac{2\sigma}{\rho_l \varepsilon R} - \frac{4\mu_l}{\rho_l} \frac{\dot{R}}{R} \quad (4)$$

where,

Fig. 4 Model of bubble growth and collapse

$$\varepsilon = 1 - \rho_v / \rho_l \quad (5)$$

Equation of energy of the liquid surrounding the bubble

$$\frac{\partial T}{\partial t} + \varepsilon \frac{R^2}{r^2} \dot{R} \frac{\partial T}{\partial r} = \alpha_l \left(\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \frac{\partial T}{\partial r} \right) \quad (6)$$

Equation of heat balance at the liquid-vapor interface

$$\dot{R} = \frac{dR}{dt} = - \frac{k_l}{\Delta h_v \rho_v} \frac{\partial T}{\partial r} \bigg|_{r=R} \quad (7)$$

Equation of state of the saturated vapor inside the bubble

$$P_v = P_{sat}(T_v) \quad (8)$$

The initial conditions are:

$$R(0) = R_0, \dot{R}(0) = 0, T(r, 0) = T_0(r) \quad (9)$$

The boundary conditions are:

$$T(R, t) = T_i = T_v, T(\infty, t) = T_\infty \quad (10)$$

Although the accurate value of the initial bubble radius R_0 is not known, a sufficiently small radius of $1 \mu\text{m}$ is used in the present calculation. No significant differences could be recognized among the results of calculation when using the values of R_0 of 0.5 – $2.0 \mu\text{m}$.

The initial one-dimensional temperature distribution $T_0(r)$ is also required for the calculation. This temperature distribution can be estimated by transforming the three-dimensional temperature distribution of the ink at the time immediately before the bubble nucleation, which was calculated from the electric and heat conduction equations as described before. Because a bubble is considered to be generated from the point where the local ink temperature takes a maximum, the origin of the Cartesian coordinate system (x, y, z) should be shifted onto the point of the maximum temperature to transform the calculated temperature distribution $T(x, y, z)$ into a temperature distribution $T(x', y', z')$ in a coordinate system (x', y', z') with the origin at the point of the maximum temperature. This temperature distribution should be subsequently transformed into a temperature distribution $T(r, \theta, \varphi)$ in a spherical coordinate system, and then the distribution $T_0(r)$ can be evaluated as the averaged temperature on a spherical surface of any radius r .

$$T_0(r) = \bar{T}(r) = \frac{1}{2\pi} \int_0^{\pi/2} \left\{ \int_0^{2\pi} T(r, \theta, \varphi) \sin \theta d\varphi \right\} d\theta \quad (11)$$

Equation (4) is discretized by using a forth-order Runge-Kutta method. When solving the energy equation, Eq. (6) and the heat balance equation, Eq. (7), it is convenient to fix the position of the moving liquid-vapor interface in calculation. This can be done by the following transformation:

$$\eta = 1 - R(t)/r \quad (12)$$

In the numerical calculation, this transformation has a merit to give smaller grid spacings as closer to the interface so that the temperature gradient at the

interface can be accurately evaluated. When applying this transformation, Eqs. (6) and (7) become

$$\frac{\partial T}{\partial t} = \frac{\dot{R}(1-\eta)}{R} \{1 - \varepsilon(1-\eta)^3\} \frac{\partial T}{\partial \eta} + \frac{a_l(1-\eta)^4}{R^2} \frac{\partial^2 T}{\partial \eta^2} \quad (13)$$

$$\dot{R} = \frac{k_l}{R \Delta h_v \rho_v} \left. \frac{\partial T}{\partial \eta} \right|_{\eta=0} \quad (14)$$

For the discretization of Eq. (13), an implicit method is employed in which the convection term (the first term of R. H. S) is approximated by a first-order upwind differencing scheme and the heat conduction term (the second term of R. H. S) is approximated by a second-order central differencing scheme. Equation (14) is discretized by using a third-order differencing scheme. Finally, the resulting system of discretization equations is solved in the following way. After computing the pressure P_v in the bubble by Eq. (8), the bubble growth rate $\dot{R}$ and the bubble radius R can be computed by Eq. (4) at each time step. Then, the temperature distribution of the ink can be computed at the new time step by Eqs. (13) and (14).

In order to confirm the validity of the present method for calculation of bubble growth, it was applied to the bubble growth in uniformly superheated water, and the results were compared with theoretical solutions by Plesset-Zwick⁽⁵⁾ and Mikic et al.⁽⁶⁾ Figure 5 shows such an example at a superheat of 10 K. The values calculated by the present method agree well with the theoretical solutions.

4. Results of Calculation and Discussions

Calculations were performed for a pair of electrodes shown in Fig. 1, which was used for the experiment described previously, at different initial temperatures of the ink. The pressure of the ink at infinity was assumed as $P_\infty = 0.1$ MPa. The applied dc voltage was 26.1 V, which is equal to the effective value of the experimental ac voltage of 30.0 V. For the electric conductivity of the ink, which increases with increas-

ing temperature, an empirical linear equation obtained from measurement was used. For the other properties, those of water were used instead, because the ink was water-based. The properties of water at local temperatures (for temperature above 100°C, the properties of saturated water) were used for the calculation of the ink temperature distribution, and the properties of saturated water and steam at the temperature of the liquid-vapor interface were used for the calculation of the bubble growth and collapse.

Figure 6 shows the comparison of the times required for bubble nucleation obtained by calculation and measurement at different initial temperatures of the ink. The calculated values indicated by a solid line were obtained under the assumption that the nucleation temperature in the ink was 250°C, and these agree well with measured values indicated by open circles. Consequently, the nucleation temperature is taken to be 250°C in further calculations. It should be noted that this temperature is lower than the theoretical value of the homogeneous nucleation temperature that is approximately 305°C for pure water at atmospheric pressure. The maximum bubble radius shown in Fig. 6 will be discussed later.

A bird's view of the temperature distribution on the x - y plane at $z = 1.4$ μm , which includes the point of the maximum temperature, at a time immediately before the bubble nucleation is shown in Fig. 7. This is the result of calculation at an initial ink temperature of 25°C. Figure 8 shows isotherms near the edge of electrode on each plane where the point of the maximum temperature exists. The isotherms are illustrated by solid and broken lines with a temperature difference of 20°C and the temperatures for those by solid lines are shown by figures. The shadowed portion designates the electrode. The electric current density takes a maximum (shown as J_{max} in Fig. 8) at the tip of electrode, and hence the heat generation rate takes a maximum at the same point. However, the

Fig. 5 Comparison of the present numerical result with theoretical solutions for bubble growth in uniformly superheated water

Fig. 6 Time required for bubble nucleation t_n and maximum bubble radius R_{max} at different initial ink temperatures T_{int}

temperature takes a maximum of 250°C at a short distance from the tip, because the thermal diffusivity of the electrode is larger than that of the ink. For a pair of electrodes, there exist two points of the maximum temperature near the tips of respective electrodes. In practice, a bubble generates at either of these two points, as observed in the experiment, because there might be slight differences in shape or other factors between the two electrodes.

Figure 9 shows the variations of the bubble radius R , bubble growth rate $\dot{R}$ and the pressure P_v and temperature T_v inside the bubble with time t when the initial ink temperature is 25°C, and Fig. 10 shows the radial temperature distribution of the liquid surrounding the bubble at different time steps. At the initial stage of bubble growth, because the pressure inside

Fig. 7 Temperature distribution on the x - y plane of $z=1.4\ \mu\text{m}$ at a time immediately before bubble nucleation

Fig. 8 Isotherms at a time immediately before bubble nucleation

the bubble is very high (for example, saturation pressure at 250°C is 3.98 MPa), the bubble grows rapidly due to the large pressure difference between the bubble and the surrounding liquid. As the bubble grows, it absorbs heat from the surrounding liquid, and the pressure and temperature inside the bubble and also the temperature gradient at the liquid-vapor interface decrease gradually. Once the temperature gradient at the interface changes to the negative ($t=3.26\ \mu\text{s}$ in the example shown in Figs. 9 and 10), the bubble begins to collapse. Because the pressure in the bubble at this time is much lower than the atmospheric pressure, the bubble collapse rate increases with time and finally the bubble disappears.

The results of calculation are compared with the measurements for the variation of the bubble radius with time in Fig. 11 and for the maximum bubble radius in Fig. 6 shown previously at different initial ink temperatures. At each initial ink temperature, a process of the bubble growth is well reproduced by the present calculation, and agreement of the maximum bubble radius between the calculation and measurement is satisfactorily good, though the calculated bubble collapse rate is generally larger than the

Fig. 9 Variations of bubble radius R , bubble growth rate $\dot{R}$, pressure P_v and temperature T_v inside bubble with time t

Fig. 10 Temperature distribution of liquid surrounding a bubble at different time steps

Fig. 11 Comparison of the results of calculation with measurements for bubble radius

measured one.

As demonstrated above, the present method of numerical analysis is applicable to predicting the time required for bubble nucleation, growth rate of the bubble and maximum radius of the bubble when the bubble is generated in conductive liquid heated directly by electric current pulses.

5. Optimization of Electrode Configurations

The electrode configurations, i.e., the shape, dimensions and spacing of the electrodes have significant effects on the time required for bubble nucleation and on the maximum bubble radius. For the purpose of the bubble generation that suits the ink-jet printer, the following conditions should be considered: (1) Reducing the time required for bubble nucleation t_n to obtain a quick response. (2) Minimizing the electric power consumption Q for energy saving. (3) Under these two conditions, increasing the maximum radius R_{max} of bubble generated. (4) Having only one possible bubble nucleation site, i.e., having only one well-defined maximum temperature point in the ink. In order to find an optimum electrode configuration that satisfies these four conditions, the developed method of numerical analysis for estimating the temperature distribution of the ink and predicting bubble dynamics was applied to the cases of electrode pairs of different spacings, widths and shapes. All of these calculations were performed under the conditions of the applied dc voltage of 26.1 V and the initial ink temperature of 25°C.

It should be noted that the electric power consumption Q can be expressed as

$$Q = E \int_0^{t_n} I(t) dt \quad (15)$$

where E is an applied voltage and $I(t)$ is the current flowing from one electrode to the other.

5.1 Effects of electrode spacing and width

Figure 12 shows the results of calculation of the time required for bubble nucleation t_n , the electric

Fig. 12 Effects of electrode spacing L on time required for bubble nucleation t_n , maximum bubble radius R_{max} and electric power consumption Q

Fig. 13 Effects of electrode width W on time required for bubble nucleation t_n , maximum bubble radius R_{max} and electric power consumption Q

power consumption Q and the maximum bubble radius R_{max} for the electrode pairs with a width of 20 μm , a semicircular front edge of a radius of 10 μm and different electrode spacings from 6 to 14 μm . Also the results for the electrode pairs with a spacing of 10 μm , a semicircular front edge of radius $W/2$ and different electrode widths W from 10 to 40 μm are shown in Fig. 13.

Figures 12 and 13 indicate that the electrode width has almost no effect on the time required for bubble nucleation, and that this time is decreased by reducing the electrode spacing, which causes an increase in current. In the latter case, the electric power consumption is also decreased because the decrease in the time required for bubble nucleation overcomes the increase in the current. The figures indicate also that the maximum bubble radius becomes larger, as either of the electrode width or spacing is increased, because of an increase in volume of the superheated ink between the two electrodes. From the viewpoint of reducing the time required for bubble nucleation while ensuring a sufficiently large value of the maximum bubble radius, it is considered better to reduce the electrode spacing and compensatively to increase the electrode width.

5.2 Effects of shape of electrode front edge and optimization of electrode configurations

The calculations were performed for five types of

Table 1 Geometric parameters of electrode pairs and results of calculation

No.	W μm	L μm	Shape of edge	t_n μs	$R_{\max}$ μm	Q μJ	Temperature distribution
1	20	10	Semicircle (R10)	27.2	27.7	2.72	Fig.14(a)
2	20	8	Semicircle (R10)	17.2	23.1	1.77	Fig.14(b)
3	30	10	Semicircle (R15)	26.9	30.3	3.21	Fig.14(c)
4	30	10	Rectangle	25.6	37.8	4.22	Fig.14(d)
5	30	10	Rectangle with corners rounded (R10)	25.6	34.5	3.48	Fig.14(e)
6	40	6	Semiellipse (R20&5)	9.8	27.3	1.64	Fig.14(f)

electrode pair shown in Table 1 to investigate the effects of the shape of electrode front edge and the dimensions of electrode pair. The electrode pairs 1, 2 and 3 are used for investigating the effects of the electrode spacing and electrode width, as described above. They all have semicircular front edges, whose radius is 10 μm for the electrodes 1 and 2 and 15 μm for the electrode 3. The electrode pair 1 was used for the experiment and calculation mentioned previously. The electrodes pairs 3, 4 and 5 are used for investigating the effects of the shape of electrode front edge. The electrode 4 has a rectangular front edge and the electrode 5 has the same front edge as the electrode 4 but with rounded corners of a radius of 10 μm . For each electrode pair, the results of calculation of the time required for bubble nucleation t_n , the maximum bubble radius $R_{\max}$ and the electric power consumption Q are also shown in Table 1. The calculated isotherms on the x - y plane where the maximum temperature point exists are shown in Fig. 14(a)-(e) in the same manner as in Fig. 8.

For the electrodes 1, 2 and 3 which have the semicircular front edge, there exists only one, well-defined maximum temperature point close to the tip of each electrode of a pair, as shown in Fig. 14(a)-(c). In the experiment using the electrode pair 1, a bubble was observed to generate close to the tip of either electrode and immediately to move to the center point between the both electrodes. For the electrode pair 4 which have the rectangular front edge, there are two maximum temperature points near the front edge of each electrode, as shown in Fig. 14(d), and, along a straight line connecting these two points, there exists an elongated region where the temperature is very close to the maximum temperature. In this case, a single site of bubble nucleation is not determined (it was actually observed in the experiment using a pair of electrodes similar to the electrode pair 4 that the site where a bubble was generated was not fixed). Figure 14(e) is for the electrode 5 which has rounded corners to avoid the concentration of the electric

Fig. 14 Isotherms for electrodes of different configurations at a time immediately before bubble nucleation

current density at sharp corners as the electrode 4 has. There are two maximum temperature points near the front edge of each electrode also for this electrode pair. Thus it can be said that the electrodes 4 and 5 are not suitable because they fail to satisfy the condition (4) stated previously. However, an electrode with a front edge that is rectilinear in part has an advantage of generating a larger bubble, because the volume of superheated ink is increased due to the increase in electric current.

From the above discussions on the shape of the electrode front edge, the following two points become obvious. First, in order to fix a single site for bubble generation, the electrode should have a convex front edge. Second, in order to increase the maximum bubble radius, the electrode should have a front edge that is as rectilinear as possible. To meet these conditions, the electrode with a slightly convex or semielliptic front edge is considered to be suitable.

Based on the above consideration and the previous discussion on the effects of the electrode spacing and width, a pair of electrodes with a semielliptic front edge (major axis of 20 μm and minor axis of 5 μm), 6 μm in spacing and 40 μm in width was chosen.

The results of calculation for this pair of electrodes are presented in Table 1 and Fig. 14(f) as the electrode pair 6. When using this electrode pair, as is obvious from Table 1, in comparison with the electrode pair 1 which was the one tested first, the time required for bubble nucleation is reduced approximately to one third and the electric power consumption can be decreased approximately to 60 percent, while the maximum radius of bubble is almost the same.

6. Conclusions

Experimental study and numerical analysis were performed for the development of a new type of ink-jet printer in which bubbles generated in conductive ink heated directly by electric current pulses are used as a pressure source to eject ink-droplets.

A single print-head equipped with a pair of electrodes was used in the experiment to measure the time required for bubble nucleation and the variation of bubble radius with time. It was found from photographic observation that a bubble initially generated close to the tip of either electrode and immediately moved to the center point between the both electrodes. Then, the bubble grew rapidly and collapsed while keeping almost hemispherical in shape.

A method of numerical analysis was developed to investigate the whole process of the electric heating of

the ink, and the generation, growth and collapse of a bubble in the ink, and the validity of this method was confirmed by the comparison with the above measurements. From the results of calculation for different shapes and dimensions of the electrodes, the effects of the electrode configuration on the time required for bubble nucleation, the maximum bubble radius and the electric power consumption became clear, and finally a suggestion was made on the optimum electrode pair for this new type of ink-jet printer.

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