Escobar Vargas, S.; Gonzalez, J.E.; Fabris, D.; Sharma, R.; Bash, C.; Ruiz, O. E.
Microbubble efficiency during fast boiling growth
Ingeniería Mecánica. Tecnología y Desarrollo, vol. 2, núm. 4, marzo, 2007, pp. 139-144
Sociedad Mexicana de Ingeniería Mecánica
Distrito Federal, México

Available in: http://www.redalyc.org/articulo.oa?id=76816763004
Microbubble efficiency during fast boiling growth

Escobar Vargas S.¹, Gonzalez J.E.¹, Fabris D.¹, Sharma R.², Bash C.², Ruiz O. E.³

¹Santa Clara University, sescobarvargas@scu.edu, jgonzalezcruz@scu.edu, dfabris@scu.edu
²Hewlett-Packard. ratsnih.sharma@hp.com, cullen.bash@hp.com
³University of Puerto Rico. oruiz@me.uprm.edu

ABSTRACT

The microboiling in confined spaces is characterized through bubble area measurements for enclosed small planar heaters (41 µm x 45 µm). A laser visualization technique is used to measure the bubble area viewed from above. The bubbles are generated in deionized water by heating pulses of power inputs (2.6-3.7 W) and total energy releases (8.6-13.9 µJ). The bubble lifecycle lasts for 10 µs - 16 µs. Direct observations of bubble area show a rapid bubble film growth followed by a volumetric growth, subsequent collapse, and bubble regrowth. The bubble vapor pressure, generated mechanical power, and bubble efficiencies at different energy and heating rate conditions were calculated using a hemispherical cap model for the bubble. The two characteristic lengths of the hemispherical cap relate the extent of the film and the volumetric growth. The effective radius of the bubble as viewed from above was fitted with a linear growth rate during the film growth phase. As the bubble reached the maximum area, the effective radius of the volume was approximated by either a linear radial growth rate, \( r \), or a square root growth rate, \( \sqrt{t} \). Using this model pressure calculations result in values up to 400x10³ Pa and conversion efficiency to mechanical work up to 0.20%

INTRODUCTION

Fast boiling in enclosed microheaters has been widely used in thermal inkjet (TIJ) (Le, 1998; Bash et al., 2003) and micro-electromechanical systems (Lin, 2003) i.e. mechanical actuators, nozzle-diffuser pumps, mixers, etc. TIJ based microboiling has been widely studied in the droplet generation mode and surface characteristics (Parrado and Gonzalez, 2000; Chen et al., 1997; O’Horo et al., 1996; Andrews and O’Horo, 1995).

In microboiling the reduction in spatial and time scales, surface energy (Thomas et al., 2003; Balss et al., 2005) and non-equilibrium phenomena (Zhao, 2000) drive the dynamics of the bubble nucleation and growth. In general, boiling and phase change bubbles nucleate depending on the local fluid superheat, availability of nucleation sites, and fluid properties (Carey, 1992).

Lin et al (1994) initially formulated a numerical model to predict superheat fluid temperatures from microheaters based on energy conservation. This model was later improved by adding an electric model to estimate the microheater resistance (Lin et al., 1998) and solved numerically. The predicted temperatures for different fluids close to the superheat limit indicated homogeneous boiling. Considerable experimental work has focused on the heating rate and nucleation time indicating that local fluid nears the thermodynamic superheat limit and that surface irregularities and non-condensable gases may play a lesser role. There has been substantially less work on the following bubble dynamics including predications of bubble duration, size, and growth phenomena. Of the limited pressure work, Zhao et al. (2000) and Glod et al. (2002) measured pressure fluctuations away from the bubble and back calculated the bubble growth rate based on a spherical bubble.

Bubble pressures larger than ambient pressure result in bubble expansion. This bubble expansion produces work that is used in MEMS (Lin, 2003). The extractable mechanical power from bubbles generated by a Pt wire have been calculated by Glod et al. (2002) using the transient Euler equation for a hemispherical bubble and the Rayleigh-Plesset equation their estimated vapor pressure ranged for up to 1x10⁶ Pa for specific input conditions. The extractable mechanical work from microbubbles formed on planar heaters was calculated by Zhao et al. (2000) and the mechanical efficiencies ranged on the order of 0.23%.

Yin et al. (2004) used small planar heaters to describe through images the expansion of bubbles on FC-72. Low heat fluxes form bubbles expanding slowly and equally in all directions. On the other hand, high heat fluxes result in spherical embryos that rapidly expand in a film growth phase, followed by a short shrinking phase, and a slower volumetric expansion phase. At fast boiling two modes dominate the bubble growth; the bubble growth is inertia-controlled in the early times and thermally-controlled at later times. The inertia-controlled regime is linearly proportional to time, while the thermal-controlled regime is proportional to the square root of time (Carey, 1992).
In the current work the collected experimental data on the bubble growth have been separated in two regimes: film and volumetric. The film growth is calculated with a linear function of time. The volumetric growth is estimated by either a linear function of time, \( t \), or a square root function of time, \( t^{1/2} \).

In this study, microheaters are covered with a thin passivation layer separating the heater from the fluid with the intention of extending the heater longevity. The microheater is centered under a fluid volume that is formed by vertical walls with two microchannels that supply fluid. The microheater geometry makes this study more representative of typical MEMS devices. This work contributes to the characterization of microbubble lifecycle and the mechanical bubble efficiency by measuring the bubble size with optical bubble images. The results are compared to published work measuring the acoustic pressure pulse and calculating bubble pressure, mechanical work, and mechanical efficiency.

**EXPERIMENTAL SETUP**

The experiment uses an enclosed planar heater from an array of individual heaters in a production TIJ device. The microheaters are operated in a mode where the bubbles grow and collapse without detachment from the heated surface. The growth phases of the bubble are imaged through a short laser light pulse synchronized with the heating pulse and recorded with a microscope and digital camera. Figure 1 shows a schematic of the experimental equipment. A schematic of the TIJ is included in Fig 2a, the TIJ has an array of microheaters (Fig 2b) activated electrically. The laser time delays can be adjusted to reconstruct from a collection of images the history of the boiling event.

Microheaters are enclosed by walls forming a cube open from two lateral sides and above (Fig 2b). The volume is filled with the working fluid (deionized water). The working fluid is separated from the microheater by the passivation layer and the heater sits on an insulation layer to minimize heat losses.

The circuit driving the microheater uses a microprocessor Ubi-com, SX28AC/DP, programmed to trigger the microbubble and the laser (UT5-30G-650, World Star Tech). The microprocessor provides a trigger signal to a Darlington array that feeds a regulated voltage \( 8 \text{V} - 12 \text{V} \) to an individual microheater. Both the laser and circuit are powered by a laboratory power supply \( 72-280 \text{ TENMA} \). The laser pulse is synchronized at different time delays to the heating pulse either through the microprocessor or a digital delay/pulse generator (DG-535, SRS), and the boiling events are captured in a CCD camera (TM-7200, Pulnix). A laser pulse of 200 ns width was used to illuminate the bubble and freeze the event.

The boiling process is magnified by a microscope and two doublers (Infinitivar continuously focusable, Infinity Photo-Optical Co) and recorded through a full frame CCD camera. The overall optical magnification is 32 times and the heater occupies 1/9\(^n\) of the field of view. The laser illumination is aligned with the microscope using a 45\(^\circ\) beam splitter and the images record the backscattering off the surface. Video images are recorded to a computer through a PCI video frame grabber card (Videoh! PCI, Adaptec). Microboiling events were directly and instantaneously observed on a monitor (13" PVM-1354Q, Sony) and recorded on a computer. Image processing is carried out with a computer program to determine the bubble size.

Given the diffraction and the background shading of the microheater array, an image processing technique is used to identify the bubble size. The still images were processed by subtracting a background, filtering, thresholding, and overlaying spatial masks. The effectiveness of the image processing was tested by manually identifying the bubble area for a small subset of the data. Detailed steps of the image processing technique are listed in Escobar-Vargas et al. (2005). The automated bubble area determination method underpredicts the area by a factor of 1% for small bubble areas and by a factor of 8% when bubbles reached their maximum size.
EXPERIMENTAL RESULTS
Several bubble stills were obtained, for different input conditions of energy and power, and the mean bubble projected area was measured. The different bubble regimes present during experiments are shown in terms of the projected bubble area (Fig. 3) for a specific case heating time of 4.3 µs resulting in 13.4 µJ and 3.2 W. The microbubble life cycle is composed of nucleation, growth, maximum size, collapsing and regrowth. The image in Figure 3a shows the heater with shadows and diffraction generated from surface features on the device. The edges of the heater are outlined by the dark square in the center of the still. The early stage of bubble growth frames show bubbles nucleating near the upper left edge (3b). In our experiments, the early bubble growth phase showed very rapid expansion. Following nucleation, the bubble film growth phase is dominated by a very rapid film expansion over the heater surface shown in Figures 3c and 3d. Continued bubble expansion and higher image contrast in Frame 3e indicates a large curved upper surface which we refer to as volumetric growth. The images in Figures 3f, 3g, and 3h show different steps in the collapse process. The bubble appears smoother during the collapse. Bubble collapse near rigid surfaces tends to be highly influenced by the surroundings (Blake and Gibson, 1987).

Projected bubble area was measured using an image processing code and the equivalent radius is plotted versus time (Fig. 4). The different bubble life cycle regimes are present as evidenced by two different slopes on the growing phase. The steepest slope is due to the film growth and the later and less steep slope is due to the bubble volumetric growth. In some cases, a local maximum at the end of the film growth is present when the heating pulse energy is large enough. At later times, the bubble reaches a global maximum that is determined by the total applied energy to the heater (Escobar-Vargas et al. 2007). After the maximum bubble size the collapsing is present at a much smaller rate than the growth. In some cases after the collapse, bubble regrowth occurs.

It was determined in previous work that the maximum bubble size and the bubble lifetime correlate to the input energy (Escobar-Vargas et al. 2007). In addition, increasing heat rate (power applied) shortens the time until nucleation, Fig. 5.
Spherical bubble assumptions have been typically used in order to calculate the bubble internal pressure and efficiency. Only in specific cases actual bubbles have spherical shape; however, the spherical assumption is still useful to determine the effective trend of the pressure increase. The experimental data collected in this work show a film expansion followed by a volumetric expansion. This effect has been reported by Yin et al. (2004) who showed FC-72 bubbles formed by embryo nucleation followed by a lateral expansion and subsequent vertical expansion on bubbles nucleating near a hot surface. It is considered that a more realistic shape to represent an expanding bubble near a hot surface is a spherical cap as shown in Fig. 6. Two distances, \( r_1 \) and \( r_2 \), are calculated from the experimental data using the film growth and the volumetric growth, respectively.

Where \( r_1 \) is calculated from the linear fit of the film expansion on the experimental data. The vertical distance \( r_2 \) is calculated from the volumetric growth rate derived from experimental data. The volumetric expansion was approximated with different fits: square root and linear. The choice of the volumetric growth rate trend is based on the asymptotic growth rate limits at early times. The bubble radius during thermal-controlled expansion is function of time in the form of \( t^{1/2} \) and it occurs at later times of the bubble growth. During inertia-controlled bubble expansion the bubble radius is a linear function of time, (Carey, 1992).

The film growth is assumed to be linearly proportional to time based on empirical data. Fig. 7 shows the trend lines for the film and volumetric growth where Fig. 7a denotes the linear trend by using the experimental data of the film growth phase. The two approximations for the volumetric expansion in Fig 7b use the nucleation time determined from the linear fit of the film growth and the data points from the volumetric growth phase.

The radius of curvature of the hemispherical cap is estimated to determine the internal bubble pressure. Equation 1 gives the relationship between the curvature radius and the characteristic lengths of the hemispherical cap,

\[ R = \frac{r_1^2 + r_2^2}{2r_2}, \]  

where the radius of curvature \( R \) of the hemispherical cap was used to calculate the change of pressure on the Rayleigh-Plesset equation (Eq. 2),

\[ p_v - p_a = \rho_l R \left( \frac{dR}{dt} \right)^2 + \frac{3}{2} \rho_l \left( \frac{dR}{dt} \right) + 2 \rho_l \frac{dR}{dt} + \frac{2 \sigma}{R}, \]  

where \( \rho_l \) is the liquid density, \( \mu_l \) liquid viscosity, and \( \sigma \) liquid surface tension. Changes in pressure relate the extractable mechanical energy by the bubble change of volume. The extractable mechanical energy is defined by Eq. 3 (Glad et al., 2002)

\[ E_m = \int \left( p_v - p_a - \frac{\sigma}{R} \right) dV \]  

where \( A \) and \( V \) are the liquid-vapor surface area and volume of the hemispherical cap respectively. In terms of the cap volume and characteristic lengths the extractable mechanical energy is given by Eq. 4

\[ E_m = \int \left( p_v - p_a - \frac{2 \sigma}{r_2} \right) dV \]  

The extractable power results from the derivative of Eq 4. The mechanical efficiency is calculated for the data using Eq 5
where $E_m$ is the extractable mechanical energy from the bubble and $E_{in}$ is the input energy to the microheater.

Fig. 8 shows the experimental data (Fig. 8a) for the complete bubble lifetime and the calculated pressure change $p_v-p_0$ (Fig. 8b) using the Rayleigh-Plesset equation, for the initial 4.5 μs. During the same initial time the generated power (Fig. 8c) is calculated by taking the derivative respect to time of the extractable mechanical energy (Eq. 4), and the estimated efficiency (Fig. 8d) defined by Eq 5 using the different fitting approaches.

Large vapor pressure variations due to the fitting method are present (Fig. 8b). Maximum $\Delta P$ for different experiments predict $0.4 \times 10^6$ Pa for the square root approximation and $1 \times 10^6$ Pa for the linear approximation (see Table 1). Reported internal vapor pressures are given up to $1 \times 10^6$ Pa by Glod et al. (2002). These measurements were based on the emitted acoustical pressure and back calculated the bubble pressure.

The initial pressure estimate does not influence the efficiency since the volumetric expansion at that point is small, as noticed in Fig. 8d. The square root approximation resulted in an efficiency larger by 9% over the efficiency based on the linear approximation. The predicted maximum efficiencies ranged from 0.1 to 0.2%. Zhao et al. (2000) reported maximum efficiencies ranging 0.04-0.23%. Table 2 lists the resulting efficiencies for different experiments. For energy density of 5625 J/m², Zhao et al. (2000) reports an efficiency of approximately 0.23%. This approximates the case of 10.78 μJ for this work (Table 2) that results in 5842 J/m² energy density, and the calculated efficiency is 0.19%.

**Table 1.** Pressure difference ($\Delta p=p_v-p_0$) and initial times for different input conditions

<table>
<thead>
<tr>
<th>P [W]</th>
<th>E [μJ]</th>
<th>$\Delta p$ [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3739</td>
<td>8.69</td>
<td>4.36E+05</td>
</tr>
<tr>
<td>2.6855</td>
<td>8.86</td>
<td>4.23E+05</td>
</tr>
<tr>
<td>2.9091</td>
<td>9.89</td>
<td>3.71E+05</td>
</tr>
<tr>
<td>3.2665</td>
<td>10.78</td>
<td>3.84E+05</td>
</tr>
<tr>
<td>2.7453</td>
<td>11.81</td>
<td>5.30E+05</td>
</tr>
<tr>
<td>3.0887</td>
<td>13.28</td>
<td>3.11E+05</td>
</tr>
<tr>
<td>2.6354</td>
<td>13.97</td>
<td>3.71E+05</td>
</tr>
<tr>
<td>3.0544</td>
<td>16.19</td>
<td>3.25E+05</td>
</tr>
</tbody>
</table>

Figure 8. Data analysis. (a) bubble radius; (b) pressure change $p_v-p_0$; (c) power derived from the extractable mechanical work; (d) efficiency.
from Table 2, letter a corresponds to the square root volumetric approach and letter b corresponds to the linear volumetric approach.

Conclusions

A laser based imaging technique was used to measure bubble area as viewed from above. The water bubble evolution showed a sequence of events: fast growth, shrinking, slow growth, maximum size, slow collapse, and bubble regrowth. Similar bubble evolution was reported by Yin et al. (2004) for FC-72. The bubble lifetime shows two growth rates corresponding to the film growth and volumetric growth. Film growth is described by a linear relation with time as determined from experimental data. Volumetric growth is described according to two limiting asymptotic regimes: thermally limited the effective radius increasing as the root of time or inertially limited with the effective radius increasing linearly with time.

A hemispherical cap bubble shape assumption and the bubble images were used to calculate the internal bubble vapor pressures, extractable bubble mechanical power, and bubble mechanical efficiency. Results are compared to other works from different researchers. Using the square root approximation, the maximum calculated pressure in this work resulted in 0.4x10^6 Pa. Glod et al. (2002) reported a maximum of 1x10^6 Pa from acoustic pressure measurements. The maximum estimated bubble mechanical efficiency in this work is 0.2%, this value is comparable to the work from Zhao et al. (2000) who reported 0.23% for cases with approximate similar energy density.

Acknowledgments

This work was partially sponsored by the GOALI program of the National Science Foundation (NSF), Grant #0131994, and by Hewlett Packard Co.

References


