Available online at www.sciencedirect.com

ScienceDirect

International Journal of Heat and Mass Transfer 51 (2008) 353–360

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Single bubble dynamics and transient pressure during subcooled nucleate pool boiling ☆

Andreas Bode *

BASF AG, Process Engineering, GCT/R-L544, D-67056 Ludwigshafen, Germany

Received 22 March 2005; received in revised form 13 September 2007
Available online 3 December 2007

To the memory of Dr.-Ing. Jens-Jürgen Schröder (30.8.1938–26.4.2004).

Abstract

This article investigates the growth and collapse of a single vapor bubble during subcooled nucleate pool boiling of water at a vertical copper surface. Two high-speed cameras and a hydrophone were used for a synchronized measurement of the bubble life cycle and the pressure transient in the surrounding liquid at a system pressure of 25 kPa. A pressure transient with the basic form of one and a half sine was expected. This expectation was basically confirmed, but additional significant minima and maxima corresponding to a frequency of approximately 60 Hz were found in the pressure transient. The comparison of the bubble volume and the pressure transient leads to the conclusion, that heat transfer effects will have to be considered to explain the deviations from the sine. Pressure wave reflections inside the evaporator are of minor importance since their wave length is much larger than the extensions of the evaporator.

Keywords: Bubble; Bubble dynamics; Heat transfer; High-speed camera; Hydrophone; Water

1. Introduction

An unexpected cracking and hissing noise surprised Schröder et al. [1] in 1996 while investigating the subcooled nucleate boiling of water. For the experiments, a vertical copper surface was used, the subcooling was higher than 25 K, and the absolute pressure was 20 kPa.

By employing a high-speed camera, Schröder et al. observed a large, rapidly growing and collapsing initial bubble invisible for the human eye followed by numerous small bubbles. They found the initial bubble to generate the cracking noise, the small bubbles to generate the hissing noise. The investigation of the different types of bubble formation revealed alternating boiling modes [2] with different heat transfer efficiency and different mechanisms of heat transfer [3].

Especially, the sound emission accompanying bubble formation and its use for the identification of boiling situations attracted Schröder's attention. Consequently, the pressure pulse generation by single bubbles and the interpretation of frequency spectra measured during the boiling process were investigated in more detail [4].

This article focusses on experimental data for pressure transients during subcooled boiling from [4]. The experimental setup was the same as for the heat transfer measurements presented earlier in [3]. The reason for this approach is that the available theoretical considerations concerning pressure transients in the surrounding of bubbles often assume infinite systems with radial symmetry and conditions without thermal effects. But, in [3] one finds evaporator walls, a free surface and thermal effects, due to the bubble growth and collapse near to the heating surface.

Previous results about pressure transients during the growth and collapse of single bubbles at a system pressure

---

☆ This article is based on research work at the Institute for Thermodynamics, Callinstr 36, University of Hannover, Germany.

* Tel.: +49 621 60 55352; fax: +49 621 60 78175.
E-mail address: andreas.bode@basf.com

0017-9310/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2007.10.008

Nomenclature

d	diameter, distance (m)
f	frequency (1/s)
p	pressure (Pa)
P	power (W)
$\dot{q}$	heat flux (W/m^2)
$\dot{Q}$	heat flow (W)
r	radial coordinate (m)
R	vapor bubble radius, surface roughness (m)
t	time, lifetime (s)
T	temperature (K)
V	volume (m^3)
x, y, z	coordinate (m)

Greek symbols

Δp	pressure change during the bubble lifetime (Pa)
ΔT_{sub}	subcooling $T_{\text{s}} - T_\infty$ (K)
ΔT_{W}	wall superheat $T_{\text{W}} - T_{\text{s}}$ (K)
ρ	density (kg/m^3)

Subscripts

a	arithmetic mean
b	bubble
B	heated area of the heating surface
c	bubble collapse
el	electric
eq	equivalent to sphere
F	non-heated fin area of heating surface/fin
g	bubble growth
h	horizontal, hydrophone
L	liquid
max	maximum height of profile
s	saturation
v	vertical
W	wall
z	mean depth of profile
∞	bulk liquid, system

of 40 kPa [5] are extended here with new and more accurate data for 25 kPa. Synchronized high speed video images filmed in normal and tangential direction and the accompanying pressure transient are presented. Refs. [4,6] contain heat transfer data, the interpretation of frequency spectra and the theoretical background.

The data presented here might be useful for the modeling of pressure fields generated in subcooled or saturated nucleate boiling. Possible application areas are the diagnosis of boiling situations in evaporators, the use of bubbles as actuators of micro pumps similar to the process in ink jet printers, or the evaporative cooling of microelectronic devices. Such a microelectronic cooling depends on pressure fluctuations since they influence the circulation of the cooling fluid and cavitation-like phenomena can cause chip damages.

2. Literature review

Reasons for and characteristics of sound emission in boiling systems were investigated intensively approximately between 1960 and 1975. The subject of the investigations was mainly nucleate boiling but also transition and film boiling. Background of these research projects was often to use the sound measurement for detecting and identifying boiling situations in nuclear reactor loops to prevent reactor burn-out, since advantages of acoustic sensors are high sensitivity and a short response time.

It is well accepted that bubble dynamics is vital for the generation and the form of pressure changes in the fluid becoming audible as sound emission. But the available experimental studies used different conditions and the measured pressure changes are normally not given in absolute values. Nevertheless, it is possible to systemize the results of these studies: Bode [4] investigates the size of the heating element, pressure and subcooling with respect to their influence on total sound emission and frequency spectrum.

To the authors knowledge only Schmidt et al. and Robinson and Schmidt [7,8] provide quantitative measurements of the pressure transient during a bubble life cycle. They performed synchronous high-speed video captures and measurements of pressure fluctuations during bubble growth and collapse for subcooled boiling on a horizontal wire at atmospheric pressure. A significant pressure pulse was found at the beginning of the bubble growth but not during the collapse. Due to the moderate subcooling of 20 K the volume decrease rate of the bubble was lower than the volume growth rate.

Schmidt et al. [8] calculated the bubble growth process in saturated liquid and the resulting pressure fluctuations through numerically solving the conservation equations for a spherical bubble growing in an infinite liquid pool. From the momentum equation in the liquid using the radial coordinate r, bubble radius R and system pressure p_∞ it is possible to determine the transient pressure with known bubble radius versus time from

$$\frac{p(r,t) - p_\infty}{\rho_{\text{L}}} = \frac{R^2}{r}\ddot{R} + 2\frac{R}{r}\dot{R}^2 - \frac{1}{2}\dot{R}^2\left(\frac{R}{r}\right)^4. \tag{1}$$

Schmidt et al. were able to calculate their experimental results by fitting a polynomial to measured radius-time data to evaluate Eq. (1).

Bessho and Nishihara [9] calculated the pressure transient generated by bubbles growing on a wire and a plate based on polynomials for the bubble radius with Eq. (1). They concluded that bubbles growing on a wire reach lower maximum radius and life time than on a plate. Therefore, more higher frequency components are present in the spectrum for nucleate boiling on small heating surfaces. Additionally, it was found that high subcooling and high flow velocity cause high frequency components in the spectrum.

The interdependence of bubble life cycle and pressure fluctuation is the subject of a review article by Dorofeev [10]. The influence of the boiling vessel on the pressure fluctuation is treated for three special cases: First, without elasticity of the liquid, the pressure changes only due to volume changes of the bubble. Second, in case of an oscillation possibility in one dimension, a planar wave develops. Third, in an infinite liquid the bubble emits spherical waves. In these three cases the same bubble life cycle results in qualitatively different pressure transients in the liquid. Dorofeev calculated the pressure-time signal and the frequency transform for different growth and collapse times based on correlations for the time-dependent bubble volume. The spectrum in the case of an infinite liquid exhibits a maximum at approx. $1.3/t_b$ if the ratio of growth and collapse time is in the range $0.5 < t_g/t_c < 2$.

Nesis [11] presented a study of the influence of subcooling on the spectrum of sound emission. Evaluation of Eq. (1) revealed that the pressure changes its algebraic sign twice during subcooled boiling (Fig. 1) whereas in saturated boiling only a positive pressure pulse occurs.

According to Nesis, the spectrum of the pressure in subcooled boiling shows a peak at the reciprocal of the bubble period of $f \approx 1/(2/3t_b) = 1.5/t_b$ since this frequency occurs in the pressure-time signal during bubble growth and collapse (Fig. 1).

On one hand, experimental results for pressure transients during bubble growth and collapse in [5,6] confirm Dorofeev's and Nesis' analysis regarding the basic frequency contained in the signal generated by the bubble period. On the other hand, deviations from the qualitative transient given in Fig. 1 occur mainly during bubble collapse. Higher frequency components generate significant minima and maxima in the pressure transient during bubble collapse.

Refs. [4,6] provide experimental data, but also a qualitative theoretical approach to check the plausibility of the measurements. A potential flow model reveals the volume acceleration of the bubble, the height of the liquid level above the nucleation site, and the free surface area as main parameters influencing the pressure transient. The model does not need to take the wave nature of the pressure changes into account, since the propagation time of the pressure disturbance is much shorter than the time-scale of the bubble movement. Therefore, infinite speed of sound can be assumed and the relevant equations can be reduced to the Bernoulli equation for unsteady conditions (cf. [12]).

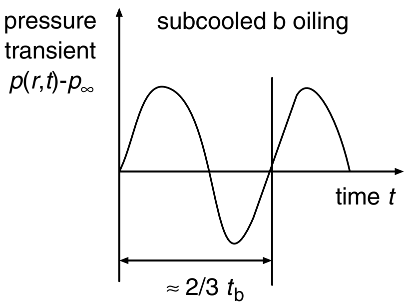

Fig. 1. Qualitative behavior of the pressure-time signal during bubble cycle in subcooled boiling according to Nesis [11].

3. Measurement description

3.1. Apparatus

3.1.1. Construction

The experimental setup used for this study is depicted in Fig. 2. The main part of the setup was an evaporator made from a stainless steel tube with an inner diameter of 300 mm and an inner depth of 173 mm. The main dimensions were identical to the dimensions of the apparatus for the investigation of nucleate boiling as it had been developed by Goetz [13].

Net vapor generated during saturated or nearly saturated boiling was condensed above the evaporator and flowed back into the evaporator by natural circulation. A pre-heater at the evaporator inlet controlled the liquid temperature.

The present study deals with subcooled liquid. Therefore, no or nearly no net vapor was generated. Heat removal was not possible with the condenser. But, a temperature controlled chamber confined the whole apparatus and temperature control was achieved by forced convection and by simultaneous operation of a heater and a cooler. Heat supplied to the evaporator was removed mainly via the evaporator walls.

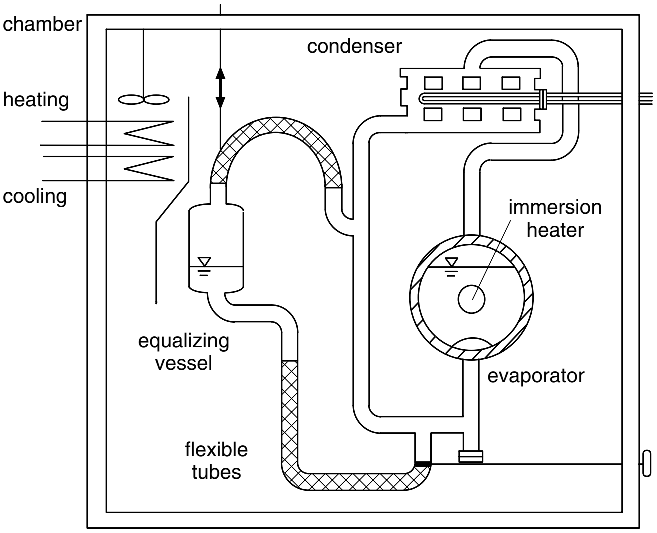

Fig. 2. Schematic of the experimental apparatus.

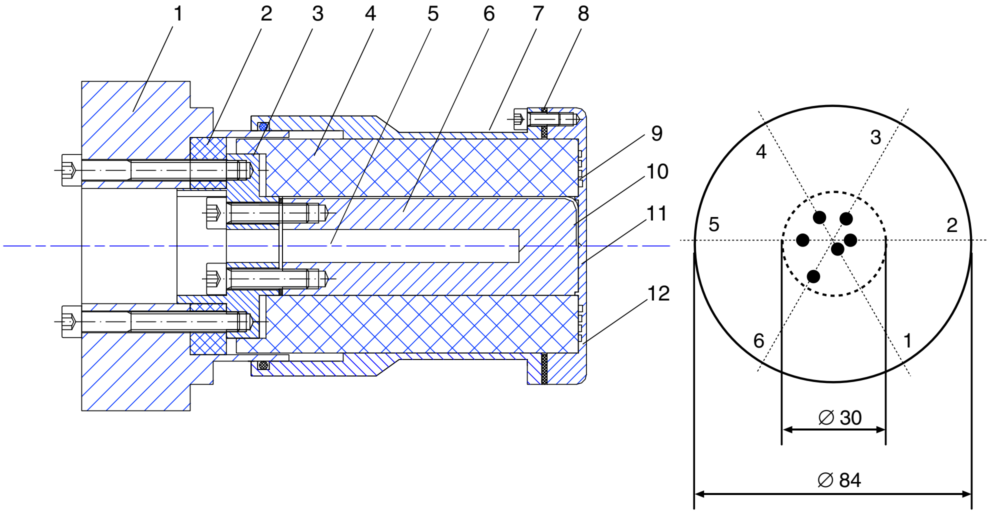

Fig. 3. Heating element with vertical copper surface and arrangement of thermocouples soldered underneath: (1) mount, (2) PTFE bushing, (3) flange, (4) mineral wool insulation, (5) drilled hole for heating element, (6) copper core, (7) stainless steel cylinder, (8) PTFE gasket, (9) concentric grooves, (10) thermocouple, (11) heating surface, thermocouple distance from center: 3, 5, 7, 10, 12 and 14 mm, (12) non-heated fin area.

Before the present study was started, Mineur [14] had modified the apparatus of Goetz essentially to investigate the influence of the contact angle on the heat transfer in nucleate boiling. First, an equalizing vessel had been installed to adjust the liquid level in the evaporator. Second, Mineur had developed the heating element depicted in Fig. 3 with a vertical copper surface that was used for the present study.

Heat was generated inside the heating element by a cartridge heater inside a copper rod. The copper rod was enclosed by mineral wool insulation. The heat flux was directed axially towards the heating surface which was soldered to the copper rod. The copper surface extended radially over the insulation to avoid joints and material changes in the heated area of the surface since they would have been favored nucleation sites. Radial heat losses were minimized by concentric grooves.

Six thermocouples soldered, spirally distributed, between copper rod and copper surface according to Fig. 3 measured the temperature below the heating surface. The heating surface was 2.0 mm thick so that the measured temperatures did not match the surface temperatures. The surface temperatures were calculated assuming one-dimensional steady state heat conduction (Section 3.2.2).

A piezoelectric miniature hydrophone measured the pressure changes during nucleate boiling. This type of hydrophone (Fig. 4) is used for example for the measurement of cavitation pressure transients or sound pressure in marine applications. Figs. 4 and 5 depict the arrangement of the hydrophone inside the evaporator.

3.1.2. Data acquisition

The data acquisition system was designed not only for the synchronized measurement of pressure transient and

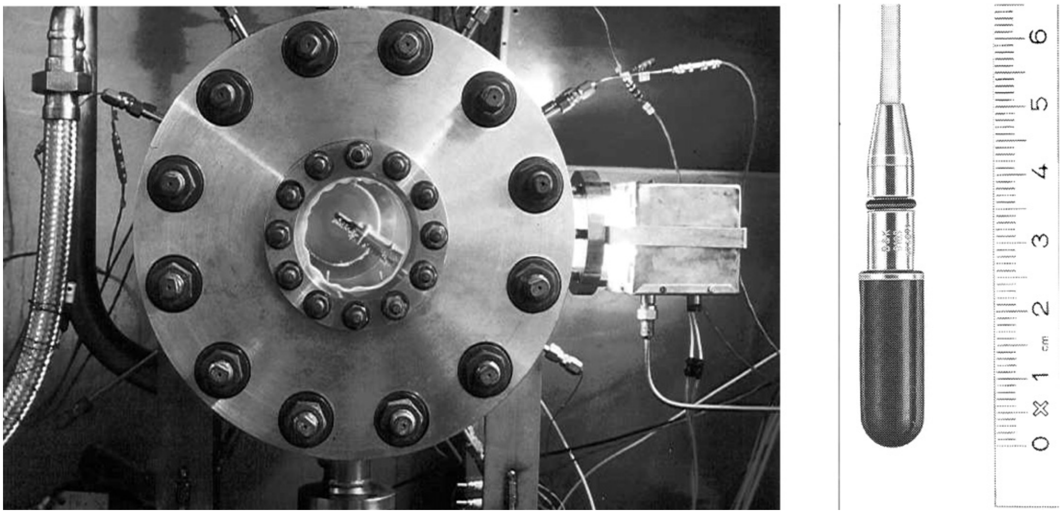

Fig. 4. Photograph of the evaporator with hydrophone and photograph of the hydrophone Brüel & Kjær type 8103.

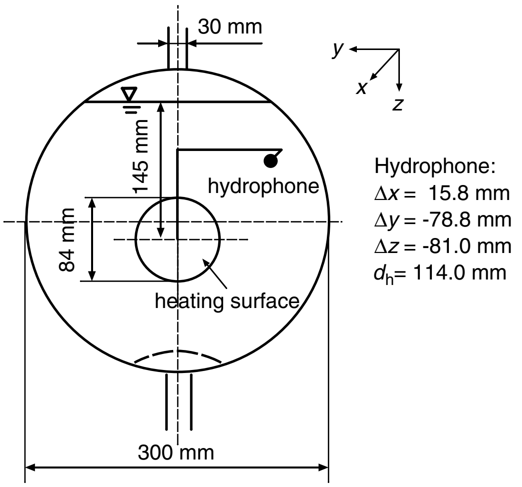

Fig. 5. Arrangement of the hydrophone in the evaporator.

high-speed video-images but also for heat transfer measurements. The assembly consisted of four groups of measured values, power, thermal data, high-speed-video and sound pressure. Ref. [4] lists all devices of the data acquisition system and their technical data.

The signal of the hydrophone was amplified and recorded by an oscilloscope and a frequency analyzer. A digital high-speed video system made by Optronis was used. The image resolution was 512 × 512 pixels at 1000 Hz and the maximum frame rate was 2500 Hz at a resolution of 512 × 128 pixels. A second camera was provided for the measurement of a bubble life cycle from two directions. The synchronization of the two cameras was achieved by a signal generator. The high-speed images were evaluated manually.

The measurement of pressure transients during bubble growth and collapse required high resolution during a measurement time of approx. 100 ms. This short-time measurement was started by a trigger from the PC which simultaneously switched a diode filmed by the high-speed camera. In this manner the video camera was synchronized with the other equipment.

3.2. Experimental

3.2.1. Measurement preparation

Measurement preparation included the treatment of water for the experiments and preparation of the heating surface. Water was treated to have low conductivity of between 1 and 5 μS/cm. The pH-value of the water was between 6 and 8. Water and air were assumed to be in vapor–liquid equilibrium inside the apparatus since operation time prior to measurements was several hours. The oxygen concentration was calculated and measured to be in the range of between 0.9 and 1.1 ppm.

Horsthemke and Schröder [15] developed a method for preparing the heating surface that was later used by Mineur [14] during his heat transfer measurements. The method guarantees reproducible roughness, structure and wetting behavior of the surface. Although the influence of wettability was not investigated in the present study, the method was employed to ensure comparability with the previous measurements. Due to the homogeneous surface roughness after preparing the surface and the temperature maximum occurring in the center of the heating surface, the incipience of boiling occurred always in or near the center of the heating surface. If off-center sites were activated, the boiling process would not be stable enough for reproducible measurements of the transient pressure during bubble growth and collapse.

The preparation method included grinding with emery paper of increasing fineness starting with 400 and proceeding up to 1000, polishing rouge, and paste. Afterwards, the surface was cleaned in a sequence with acetone, laboratory rinsing agent, ethanol and water in an ultrasound bath. Details of the procedure are given in [4].

Surface roughness of the heating surface was measured with a contact stylus instrument. Roughness values according to the German standard DIN 4777 [16] were within the ranges of $0.04 < R_a < 0.08$ μm, arithmetic mean roughness ('arithmetischer Mittenrauhwert'), $R_z < 0.8$ μm, mean depth of profile ('gemittelte Rauhtiefe'), and $R_{max} < 1.3$ μm, maximum height of surface profile('maximale Profilhöhe').

During the experiments, oxidation or scale formation occurred from time to time on the heating surface. But roughness values could be kept within the above given ranges through regularly repeating the preparation procedure.

3.2.2. Data evaluation

The area of the heating surface not heated directly via the copper rod was treated like a heat transferring fin. In the fin area, heat was transferred by single phase convection and the heat transfer coefficient was assumed to be constant, also during nucleate boiling in the central area of the heating surface. The determination of the heat transfer coefficient in the fin area required a single phase heat transfer correlation which was derived from single phase convection experiments [4].

Electrical power was assumed to be supplied to the heating element with negligible losses. The heat transfer to the fluid was via the heated area and via the fin area according to $P_{el} = \dot{Q}_B + \dot{Q}_F$.

The temperature in the heating surface was measured by averaging the signals of six thermocouples (Fig. 3). The gradient through heat conduction between measurement location and heating surface was taken into account by assuming one dimensional, steady-state heat conduction.

Heat conduction from the inner part of the surface to the outer part resulted in a temperature profile with approximately constant temperature in the heated area and steep decrease in radial direction in the fin area.

3.3. Measurement results

The measurement was performed under steady state conditions with the parameters: system pressure $p = 25\,\text{kPa}$, $\Delta T_{\text{sub}} = 10.7\,\text{K}$, $\Delta T_{\text{W}} = 22.8\,\text{K}$ and $\dot{q} = 118.7\,\text{kW/m}^2$. The liquid level in the evaporator was located 145 mm above the center of the heating surface.

Fig. 6 depicts the normal and the tangential video images for the growing and collapsing bubble. The numbers refer to Fig. 7(bottom). Fig. 7 also depicts the bubble dimensions as horizontal and vertical radii evaluated from the images filmed in the direction normal to the heating surface. With the assumption of an half ellipsoid for the bubble shape during the whole bubble cycle, the sphere-equivalent radius was calculated and is given as well as the bubble volume.

The interpretation of the images in Fig. 6 is difficult due to light reflections and blur. Therefore, the main points are listed in the following for each of the images.

Image 1: Circular bubble contour projected on the heating surface, tangential view shows the bubble shape of an half ellipsoid.
Image 2: Maximum bubble volume, cavity formation at the bottom of the bubble.
Image 3: Light reflection at the nucleation site indicates a second bubble, steam jet penetrates the bubble near to the heating surface and emerges at the bubble top.
Image 4: Jet at its upper dead center, start of wave formation in the upper interface area close to the heating surface, third bubble at the nucleation site.

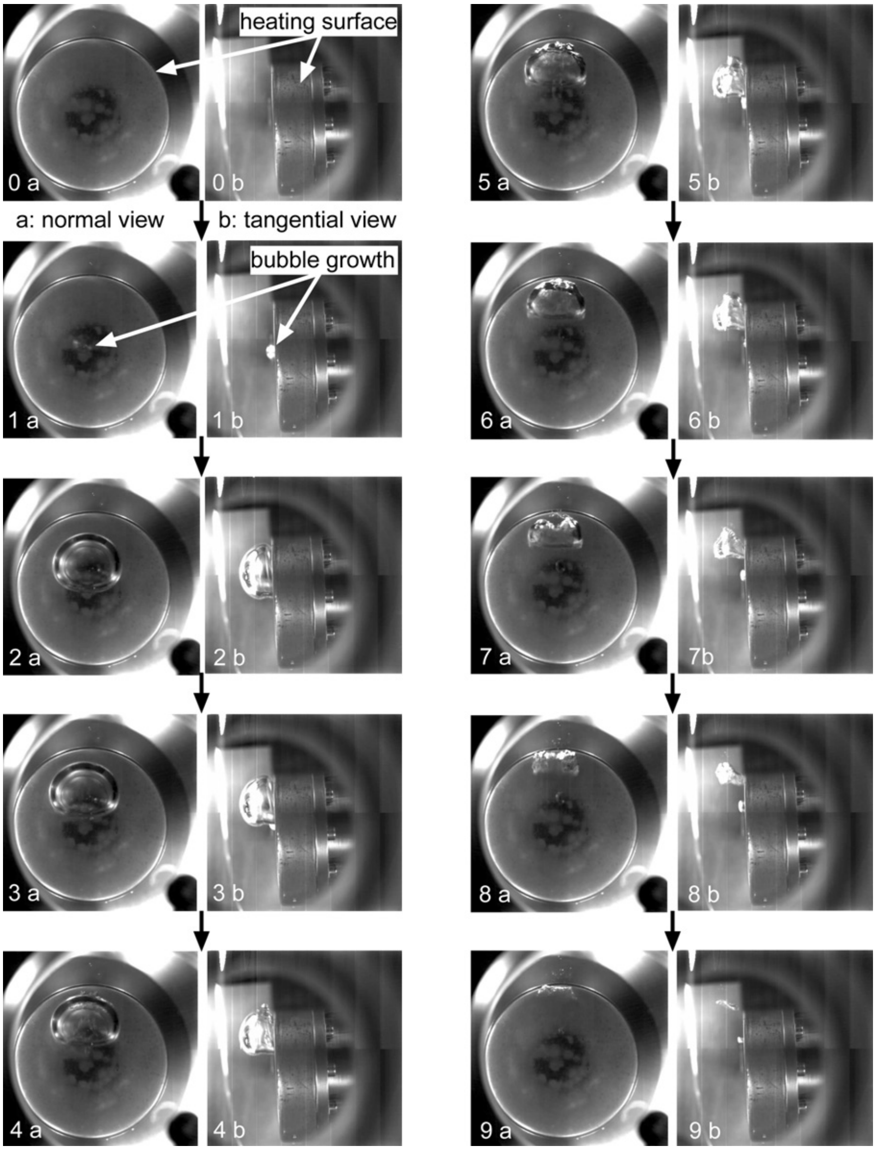

Fig. 6. Normal and tangential digital high-speed video of a single bubble at $p = 25\,\text{kPa}$, $\Delta T_{\text{sub}} = 10.7\,\text{K}$, $\Delta T_{\text{W}} = 22.8\,\text{K}$, $\dot{q} = 118.7\,\text{kW/m}^2$, diameter of the vertical copper heating surface 84 mm, numbers refer to Fig. 7.

Image 5: Instability of the bubble interface.
Image 6: Bubble interface starts to move away from the heating surface.
Image 7: Third small bubble visible at the nucleation site.
Image 8: Bubble still connected to the heating surface, bubble shape in normal view nearly rectangular, in tangential view pear shaped.
Image 9: Bubble collapse, vapor/gas fragments form a line-shaped projection shortly before they condense or get dissolved in the liquid.

The pressure transient in Fig. 7 starts with the expected pressure maximum and the following minimum due to the beginning of bubble growth and the maximum bubble volume, respectively. But during the collapse phase the pressure transient deviates significantly from the one and a half sine (see Section 2) due to additional minima and maxima. The transient pressure of −200 Pa at the end of the bubble cycle indicates the start of an oscillation of the liquid level of approximately 20 mm due to surface waves.

The maximum bubble volume is found at 1.165 s (bubble growth time 49 ms) followed by the collapse phase (bubble collapse time 73 ms) with a saddle point and slight oscillations of the bubble volume. The beginning of growth of the small bubbles does not occur synchronously with the pressure peaks 3, 5, 7 nor 9. Moreover, the volume of the small bubbles can be neglected in comparison with the volume of the large bubble. Therefore, it can be assumed that the pressure pulses generated by the growth of the small bubbles are dampened by the volume of the large bubble.

A different reason for the pressure maxima and minima during the collapse phase is more plausible: The collapse process starts through condensation of vapor at the interface reaching into the colder liquid. A pressure decrease inside the bubble is induced and accelerates the liquid. The resulting decrease of the bubble volume, the continuing evaporative mass transfer into the bubble and the released heat of condensation result in a pressure increase inside the bubble and inside the moving liquid. The collapse is controlled by the heat transfer since the heat of condensation can not be transferred quickly enough into the liquid at the relatively low subcooling. The pressure increase stops at the maximum 3 when the first succeeding bubble leads to the jet protruding through the large bubble and the saddle point is formed in the course of the bubble volume. The moving liquid is decelerated.

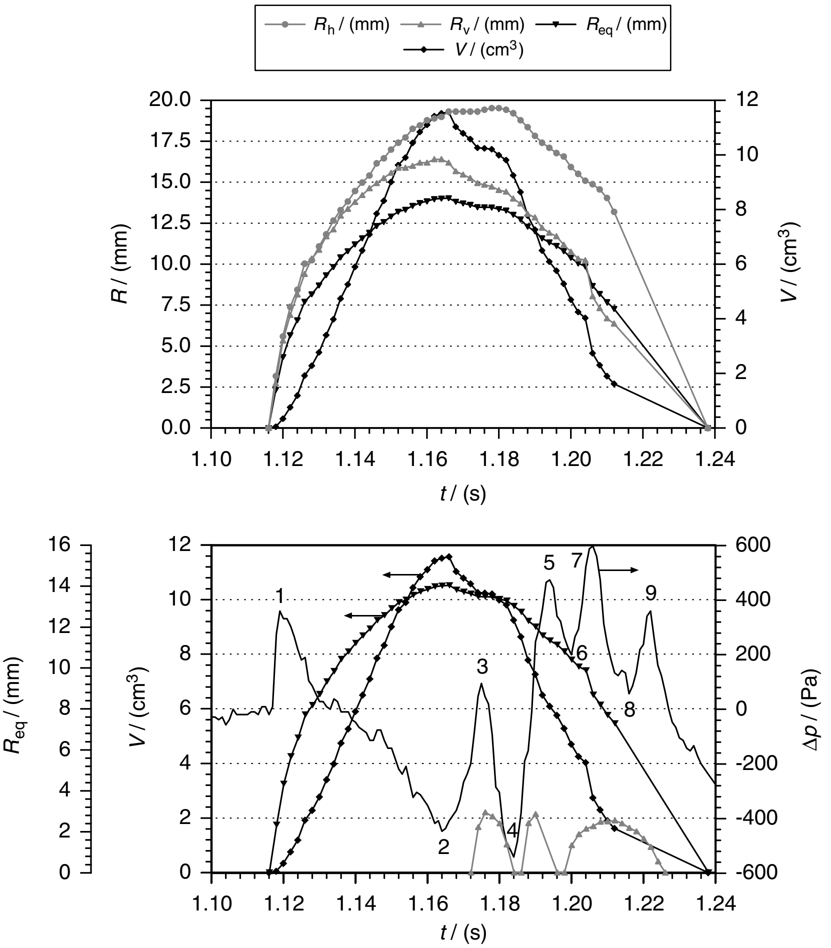

Fig. 7. Top: Bubble radius and volume for the bubble in Fig. 6 (normal view). Bottom: Comparison of bubble volume, volume of small bubbles following the first bubble acc. to Fig. 6 and pressure-time-signal (uncertainty ±21 Pa, background noise (50 Hz) ±15 Pa, hydrophone arrangement acc. to Fig. 5).

Then, heat transfer from the bubble to the liquid is increasing again and the pressure inside the bubble decreases. The liquid is accelerated so that again a pressure increase is induced due to further released heat. The instability of the interface, beginning at the pressure minimum 4, leads to a higher heat transfer to the liquid. This interaction of heat transfer and liquid inertia is also responsible for the pressure maxima 5 and 7 as is indicated by the slightly oscillating bubble volume and its equivalent radius. The pressure maximum 9 is associated with the collapse of the last vapor fragments.

Starting at pressure minimum 2, the time interval between the minima 4, 6, and 8 is approximately 16 ms corresponding to a frequency of approx 60 Hz. This frequency is superposed to the one and a half sine described by Nesis (Section 2).

A rough calculation of the corresponding wavelength yields 24 m assuming a speed of sound of 1 500 m/s (water) and even 4.8 m for 300 m/s (steam). The actual speed of sound depends on the vapor content in the liquid. But, the wave length is much larger than the dimensions of the evaporator with a diameter of 0.3 m. Therefore, the frequency of 60 Hz in the pressure transient is connected with the dynamics of the vapor bubble. Pressure wave reflections inside the evaporator are of minor importance in this situation.

4. Results and conclusions

The measured pressure transient during bubble growth and collapse in subcooled nucleate boiling shows several minima and maxima with a frequency of approximately 60 Hz corresponding to changes of the bubble volume. This frequency is superposed to the basic, theoretically derived pressure transient with one and a half sine waves [11].

The deviations from the sine can be attributed to heat transfer effects during the bubble life-cycle: Liquid is evaporated close to the heating surface and condensed in the cold liquid especially during the collapse phase of the bubble. Comparing the wave length of between 5 and 24 m for 60 Hz with the evaporator extensions of 0.3 m reveals, that reflections of pressure waves inside the evaporator are of minor importance in this situation.

Before a further quantitative analysis is performed, the bubble volume, especially during the collapse phase, should be evaluated more accurately. Then, the data presented here might be useful for the further development of computational heat transfer models for subcooled nucleate boiling.

Acknowledgements

The subject of [4] was suggested by Dr.-Ing. Jens-Jürgen Schröder, Senior Research Engineer at the Institute for Thermodynamics, University of Hannover, Germany. Dr. Schröder suddenly passed away on 26th of April 2004 shortly after his retirement. His constant intellectual and financial support made this work possible and I am greatly indebted to him for many talks and discussions.

Dr. Schröder was active in many fields of thermodynamics and heat transfer for more than 30 years. Three basic principles of his work are of great importance to me: First, thermodynamics and heat transfer are connected intrinsically. Second, basic research and industry related projects are of equal importance. Third, good experiments require many efforts and – nowadays – they are especially valuable to reach new levels of knowledge.

I will remember him as inspired researcher and inspiring teacher.

References

[1] J.J. Schröder, S. McGill, M. Dirbach, F. Podzelny, Secondary nucleation, ambivalent heat transfer, and sound emission in low pressure subcooled boiling, in: Proc. EUROTHERM Seminar Nr. 48: Pool Boiling 2, Paderborn, 1996, pp. 291–299.

[2] A. Bode, L. Panning, J.J. Schröder, Growth and collapse of vapor bubbles in the region of alternating boiling modes, in: Proc. 11th Int. Heat Transfer Conf. Kyongju, vol. 2, 23–28 August 1998, pp. 431–436.

[3] J.J. Schröder, A. Bode, The influence of subcooling on pool boiling heat transfer and its acoustic manifestation, Multiphase Science and Technology 12 (3&4) (2000) 65–83.

[4] A. Bode, Heat Transfer, Vapour Bubble Dynamics and Sound Emission in Subcooled Nucleate Pool Boiling, Shaker Verlag, Aachen, 2004.

[5] A. Bode, J.J. Schröder, Pressure pulse generation by single bubbles in subcooled pool boiling, Multiphase Science and Technology 12 (3 & 4) (2000) 85–101.

[6] A. Bode, J.J. Schröder, Bubble dynamics and acoustic phenomena in subcooled pool boiling, in: Proc. 12th Int. Heat Transfer Conf., Grenoble, 18–23 August 2002.

[7] G.E. Robinson, F.W. Schmidt, H.R. Block, G. Green, An experimental determination of isolated bubble acoustics in nucleate boiling system, in: Proc. 5th Int. Heat Transfer Conf., Tokio, 3–7 vol. 4 (B2.9), September 1974, pp. 75–79.

[8] F.W. Schmidt, G.E. Robinson, R.J. Skapura, Experimental study of noise generation in a nucleate boiling system, in: Proc. 4th Int. Heat Transfer Conf., Paris-Versailles, vol. 5, 1970, B 1.8.

[9] Y. Bessho, H. Nishihara, Boiling acoustic emission and bubble dynamics in nucleate boiling, Journal of Nuclear Science and Technology 13 (9) (1976) 520–522.

[10] B.M. Dorofeev, Acoustic phenomena in boiling, High Temperature 23 (3) (1985) 479–492.

[11] Y.I. Nesis, Growth of vapor bubbles and the acoustic noise of a boiling liquid. Part 1. First order theory, Fluid Mechanics—Soviet Research 20 (2) (1991) 108–112.

[12] A. Prosperetti, A. Lezzi, Bubble dynamics in a compressible liquid. Part 1. First order theory, Journal of Fluid Mechanics 168 (1986) 457–478.

[13] J. Goetz, Entwicklung und Erprobung einer Normapparatur zur Messung des Wärmeübergangs bei Blasensieden. Dissertation, Universität Karlsruhe (TH), 1980 (in German).

[14] M. Mineur, Der Einfluß des Randwinkels auf den Wärmeübergang beim Behälter-Blasensieden. Dissertation, Universität Hannover, 1990 (in German).

[15] A. Horsthemke, J.J. Schröder, The wettability of industrial surfaces, Chemical Engineering Fundamentals 2 (1983) 66–74.

[16] DIN 4777—Oberflächenmeßtechnik; Profilfilter zur Anwedung in elektrischen Tastschnittgeräten; Phasenkorrekte Filter, Mai 1990, Beuth Verlag, Berlin (in German).