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EXPERIMENTAL INVESTIGATION OF VAPOUR BUBBLES NUCLEATING IN BULK LIQUID

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ABSTRACT

A new experimental setup has been built in the IKE laboratory to investigate bulk boiling of water at ambient pressure. Its main component is a high, slender, column-like container with a rectangular cross-section, which is filled with demineralised water. The water is heated from the bottom via an electrically heated copper block. In order to observe the evaporation and re-condensation phenomena of bubbles, which occur within large portions of the water column, the container's front and back sides are made of glass. Due to buoyancy hot water plumes rise upwards almost periodically into regions of reduced static pressure, where bubble growth and nucleation may occur due to local superheated conditions. These processes are analyzed using a video camera, shielded thermocouples, resistance thermometers as well as pressure transducers, which are applied to measure the local temperature in the bulk fluid and the pressure along the water column vertical wall. Heterogeneous nucleation is observed, defined here as the growth of small (< 1 mm) discrete bubbles (the 'nuclei'), which stem from the subcooled nucleate boiling at the bottom wall. Bubble detection, counting and characterization are realized by digital image processing. The focus of the present paper is on the macroscopic properties and the behaviour of relatively large bubbles (> 5 mm), which have grown from the small nuclei, and the resulting integral bulk boiling process. From these measurements the long term behaviour of the steam generation, bubble sizes, as well as geometrical shape factors are determined. Our ongoing work will later be extended towards smaller sized bubbles and details of the nuclei. The data can then be used to validate assumptions of the classical nucleation theory or new computational models.

NOMENCLATURE

A	[m^2]/[-]	Area/Empirical correlation factor
B	[-]	Empirical correlation factor
C	[-]	Empirical correlation factor
l	[pixel]	Length
p	[bar]	Pressure
R	[-]	Roundness
T	[°C]	Temperature
Special Characters		
σ	[N/m]	Surface Tension
Subscripts		
sat	[-]	Saturation
P	[-]	Perimeter

1. INTRODUCTION

1.1 MOTIVATION

In nuclear technology and safety bulk boiling processes are often of interest for the investigation of accident scenarios e.g. a pressure loss of the primary circuit or low heat input after shutdown. In the first case hot water in a pressurized circuit becomes superheated due to reduction of the system pressure. The associated bulk boiling may reduce coolability or, due to instabilities, may cause damage to the system. The fundamentals and the prediction of such scenarios is of great interest in reactor safety as well in other disciplines.

Multiphase simulations using CFD (Computational Fluid Dynamics) still lack a usable model for steam nucleation within the bulk of a flow. In the framework of the 'two-fluid model' [1], sometimes denoted as the 'inhomogeneous model', CFD methods use non-equilibrium thermodynamics in the source/sink term of the transport equations to determine the mass transfer between the phases liquid and vapour. In these models the number density (number of bubbles per unit volume) appears as a parameter, which is still unknown in many cases. Accordingly, such results depend strongly on the specified value of the number density or average bubble size and therefore on user expertise to determine forces on bubbles, turbulence and mixing parameters, as well as heat and mass transfer coefficients. Further insight into nucleation and bubble growth mechanisms is necessary and quantitative data must be provided to validate assumptions of the classical nucleation theory, new computational models or other theories for the determination of the number and the behaviour of nuclei or bubbles.

1.2 LITERATURE STATUS

Thermally driven phase change or boiling is usually observed at heated surfaces or in the liquid bulk volume e.g. due to a pressure drop. Bulk boiling occurs due to the decrease in the saturation temperature associated with a pressure decrease. A very small bubble, in the following denoted a 'nucleus', is instantaneously exposed to superheated conditions, i.e. the temperature of the surrounding fluid is higher than the temperature of the interface of the nucleus. Therefore, evaporation and growth of such nuclei will occur. There are several effects caused by this phase change, which are especially of interest in nuclear technology, e.g. bulk boiling, thermal cavitation and instabilities such as flashing, geysering and the boiling crisis. In order to describe these phenomena a model for heterogeneous nucleation is necessary.

There are various studies considering the above mentioned two-phase flow phenomena. Thermal cavitation in the gravity-driven saturated pipe flow through a complex pipe has been investigated experimentally and theoretically [2, 3]. In the accident scenario water from an assumed leak in the upper reactor chamber is drained into the containment sump through a complex pipe. Due to pressure losses along the pipe as well as various bends causing local pressure minima partly evaporation causes nucleation and two-phase flow with increased flow resistance of the pipe, causing less flow throughput than for single-phase flow.

In general, there are two alternatives to determine the number density n (number of nuclei or bubbles per unit volume) in bulk boiling. The first is a direct specification or estimation of n, the second is a indirect method by specifying the bubble radius, which is related to n. Not only the initial flow state in the nucleation region but also the further flow development depend on the model choice [4].

Instabilities like geysering have been experimentally investigated in a larger experimental setup [5] than used in the present study. This study concludes there exists a geysering frequency depending on column height and width as well as on heat input. For water columns below 3m height, it is indicated that the instability mode changes.

For determination of the nucleation rate classical nucleation theory, see e.g. [6], can be used . Starting point is at constant temperature to find the minimum work needed to create a nucleus of vapour in a liquid phase. For cavity creation the work of surface tension equal to Aσ is necessary. The maximum possible work that the gas molecules can provide is along the reversible path. Since the process is reversible and at constant temperature the molecules vaporize at vapour pressure. The classical theory is attractive because it predicts nucleation rates in terms of measureable macroscopic quantities. However this theory applies to 'homogeneous' nucleation processes on a sub-micro scale, which are not expected to be relevant for the conditions of the present experiment.

Models for heterogeneous nucleation, i.e. prediction or determination of the number density of growing bubbles ('active nuclei') on the basis of measurable quantities have not been developed. In the frame of other applications, however, interesting work about cavitation in automotive brake fluids introduced a model for prediction of bubble nucleation and subsequently a probabilistic approach for changing bubbles sizes. The size changes, or mass transfer over the bubble interface, are dependant on Gibbs free energy and the nucleation barrier [7].

1.3 AIM OF THIS STUDY

This study aims for a basic contribution in the field of thermal fluid dynamics by development of a model for transient description of nucleation processes feasible for CFD methods. In order to establish a data base for the understanding of heterogeneous bubble nucleation and growth processes and for model development experiments are performed in the experimental setup described below.

2. THEORY

The basic idea of the experimental setup is the dependence of saturation temperature on pressure. Therefore, by building a high container the pressure will rise by approximately 0.1 bar each meter. This rise in saturation temperature is given by Antoine's Equation

$$T_{sat} = \frac{B}{A - \log(1000 \cdot p)} - C \qquad (1)$$

with the pressure p given in bars and the factors A = 8.196, B = 1730.63 and C = 233.426, T_{sat} results in degrees Celsius (Fig. 1). Due to increased saturation temperature at the bottom of the container the water can be superheated in respect of a higher position inside the container.

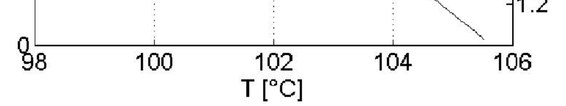

Fig. 1: Rising saturation temperature

Since heating from below creates an unstable temperature layering natural convection transports these hotter portion of water upwards into such regions. There bubble nucleation, growth and decay is observed using cameras as described in the following section.

3. EXPERIMENTAL SETUP

The test container (Fig. 2) consists of a 2.75m high column of water with a rectangular horizontal cross section of 0.38m x 0.097m. Its main frame is made of stainless steel; it holds two panes of borosilicate glass as the front and back walls. The edges of the glass plates are surrounded by a silicone-profile, which acts as a seal and avoids direct contact between the glass and metal components. All materials are chemically resistant to avoid changing experimental conditions.

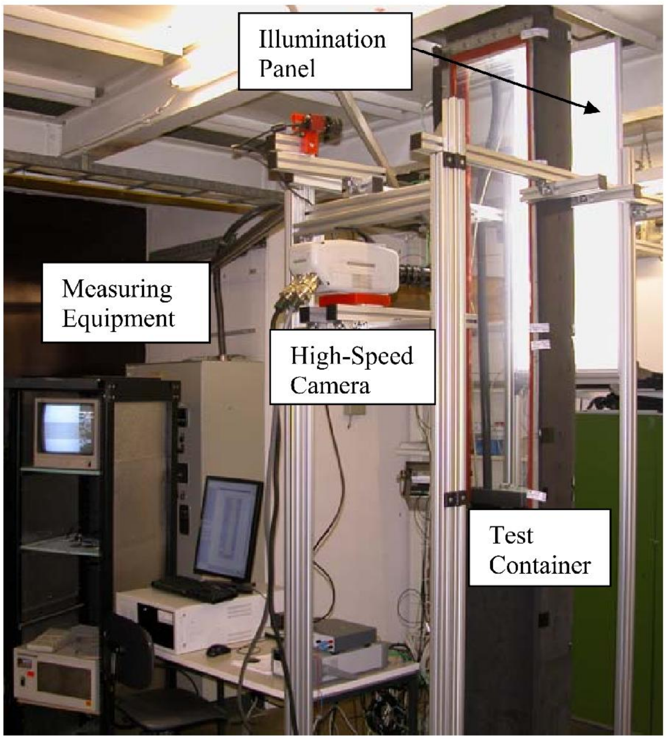

Fig. 2: Experimental setup

The bottom of the container is closed by a copper block, in which heating cartridges are installed. Altogether nine cartridges each with a maximum power of 1110 W are used, which results in a maximum heat flux of 27 W/cm²

Temperature is controlled by a PID Controller acting on a phase-controlled modulator. The temperature of the heating surface is constant with high accuracy. During a long time run the mean temperature of the copper block was 118.1 °C with a maximum deviation of ± 0.1 °C and a standard deviation of 0.025 °C (Fig. 3), which is below measuring accuracy.

The copper surface has been polished to minimize nucleate boiling, but boiling was observed in all experiments. A 19mm layer of a closed-cell elastomer is glued to the side parts as a thermal insulation. During heatup the entire glass walls are also covered with a 13 mm layer of closed cell elastomer insulation, but during experiments only those parts of the glass, which were investigated, are opened.

To reduce water losses during operation above the container a heat exchanger is used to recondense the generated vapour, hence recirculate the water. The temperatures at the inlet and the outlet, as well as the mass flow are measured.

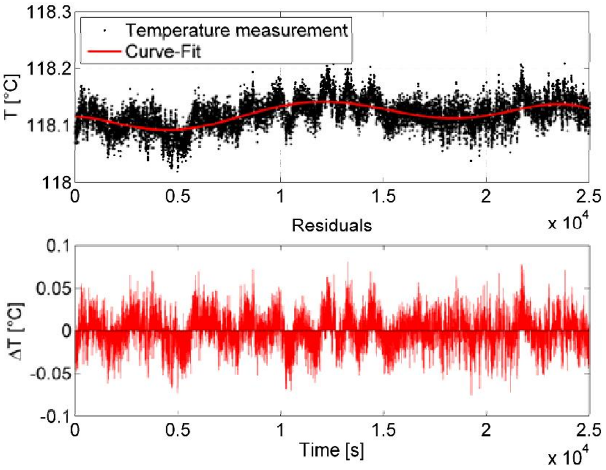

Fig. 3: Temperature controlled heating

In the test setup temperatures are measured at several positions in the bulk volume. Shielded thermo-sensors are inserted from the sides of the container as depicted in Fig. 4. Calibration of the measurement chain of the temperature sensors was performed with a metal-block calibrator system using the reference thermometer (Pt 1000) with a systematic uncertainty of 0.011 K. However, the data acquisition system has a resolution of 0.1 K, which therefore is considered to be the achieved accuracy. The used temperature sensors T1-T9 are four-wire resistance temperature detectors, the remaining sensors T10-T14 are thermocouples of type K. Pressures are measured using absolute pressure transducers with floating piezoresistive elements at the positions P1-P3. Additionally a fourth sensor (P4) of the same type is installed in the test container's chimney. An integrated microprocessor compensates temperature changes and non-linearities, resulting in 0.1% of the total pressure range. Therefore, the absolute error is 30 Pa. The measured value is

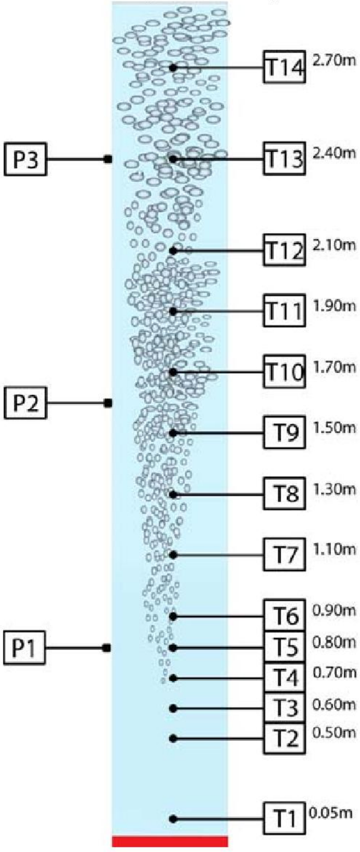

Fig. 4: Measuring positions

directly sent via an RS485 interface so that no additional error from analogue measurement needs to be accounted for.

For bubble observation the boiling process is recorded by two different video cameras. The first camera has a maximum resolution of 1292x964 Pixel @ 30 frames per second (fps). It is used with only 1200x500 pixels at 52 fps, because bubble tracking is facilitated if the image-to-image difference is small. Using this camera the overall process is recorded continuously within a relatively large image section. The second camera has a resolution of 256x256 pixels @ 4500 fps. Due to the relatively coarse resolution only a small section of the container can be investigated. The memory of the high speed camera is limited to 64 MB and can therefore store 1024 frames of each recording, resulting in 0.22 s recording time. By a reduction of the frame rate the recording time can be extended in future work. Lighting is provided by a white LED backlight, which generates a luminous flux of 5400 lumens on an area of 1.2x0.45 m^2.

The maximum temperatures in the system can be used to predict the onset of boiling. The temperature distribution in the container generates an unstable stratification, which causes single and two-phase natural convection. Large rising plumes of high-temperature low-density liquid are observed, which form streaks rising into the lower pressure regions above, where bubbles grow and slight eruptions occur. These eruptions are associated with significant vapour production. To prevent damage to the glass plates a hatch is installed in the chimney to act as a relief pressure valve. During such eruptions many bubbles are created which grow rapidly so that problems with detection, especially separation, arise. The eruptions can become more violent if the heat input is increased.

4. RESULTS

4.1 FLOW VISUALIZATION AND EVALUATION

The main tools for bubble analysis are video recordings of the bubbles nucleating. These are evaluated using MATLAB® Image Processing Toolbox for counting and measuring size and geometry. By measuring the bubble area and geometry an approximation of the bubble volume is possible at least for 'two dimensional', circular bubbles. To measure and count vapour bubbles several techniques for evaluation are necessary. The bubbles need to be separated from the background which is done by illumination differences, since bubbles are dark and the background is bright. There are several operations necessary to improve the image, e.g. increasing contrast, cropping of unneeded image parts, filling of holes, removal of small objects and objects in contact to the border (Fig. 5). Therefore, some issues in detection arise, since objects passing a temperature measuring element may not be detected due to their momentary connection to the border. It is additionally necessary to remove objects, which are in contact with the border of the picture, since bubbles are cut off at the border and therefore the geometry is tampered. This image operation is also useful in removing entire plumes, which are encountered, when eruption takes place, since they are often connected to the border. This is why a second method is used, which is separation of moving objects from the static background. This is done by creating an averaged background picture and by subsequent subtraction of each frame from this background. Averaging of the background picture is performed by construction of an image with the mean illumination value assigned to each image pixel.

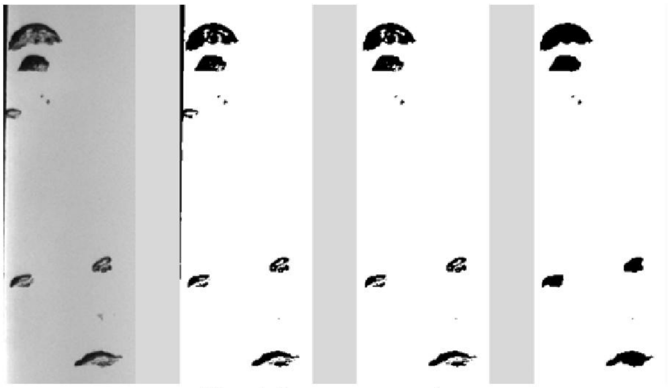

Fig. 5: Image processing

This way only pixels, that changed their value result in a new image, hence an image of only moving objects is created. In fact, both techniques are used simultaneously and their respective results are combined. Thereafter the results are converted into binary images, which then make it possible to separate object from each other and determine their position, shape and number. Evaluation needs to be done by tracking of individual detected bubbles. Problems may arise if very small bubbles are detected or not detected from frame to frame. Small objects are not detected flawlessly, so the same object may be detected in various positions, yet disappear in the mean time. This can be compensated with bubble tracking by omitting objects only detected into few frames. To follow shape changes and velocities it is necessary to track an individual bubble. Without tracking it is possible to determine integral properties like size distributions and bubble roundness depending on size, which is presented in the following section.

4.2 MEASUREMENTS

To reach temperatures above the saturation point a minimum heat input is necessary. Due to the polished heating surface, the heat transmission resistance is high and strong superheat at the heated surface is necessary to input the necessary energy. Therefore, subcooled boiling occurs at the heated surface. Some modifications were made to avoid wall boiling, but were not successful. In particular, tests without insulation were performed, which resulted in not achieving the necessary temperatures for any bubble activity inside the bulk volume. The difference in temperature between the copper block and the first temperature sensor (T1) above the copper block is about 17 K when the system is still in a single-phase state and insulated. If the test setup is not insulated this temperature difference is even higher mainly induced by the heat losses through the large glass areas needed for optical access.

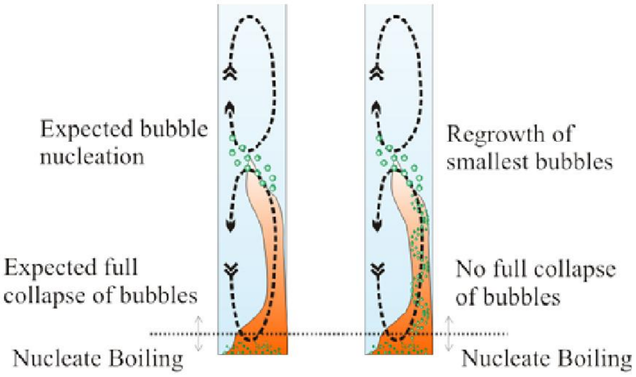

Fig. 6: Observed bubble regime

When nucleate boiling begins at the heated surface the temperature difference is slightly lower (approx. 15 K) that later during the experiments, probably due to improved mixing. Since the temperature T1 is below saturation temperature many bubbles do not collapse completely (Fig. 6). Instead they penetrate deep into lower pressure regions, where they eventually grow again.

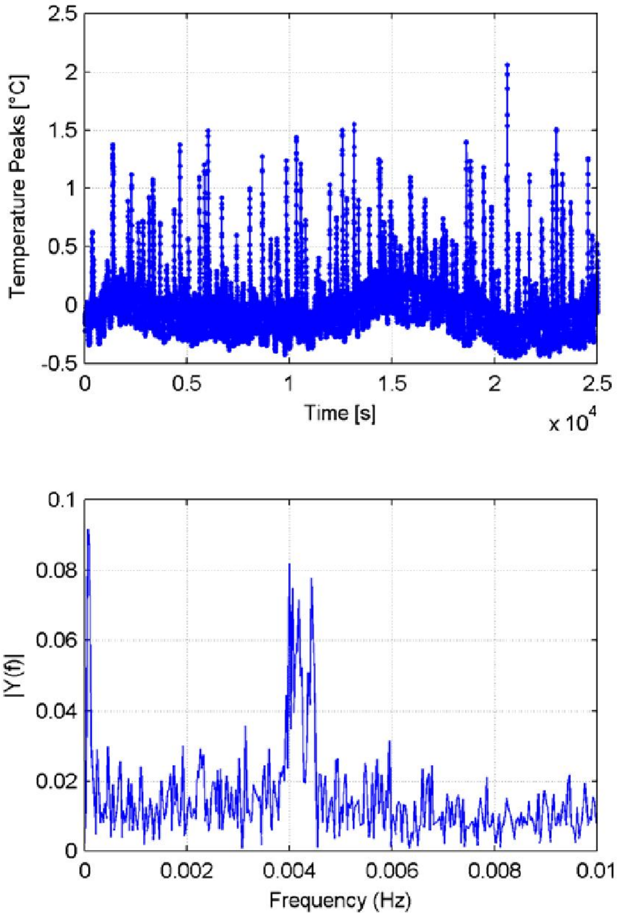

Fig. 7 : Amplitude spectrum of temperature data

This indicates, that the mass transfer of the smallest bubbles is significantly reduced, leading to their stability. At the same time, to become superheated when transported to lower saturation regions, they most probably retain the temperature of the region where they originally shrunk.

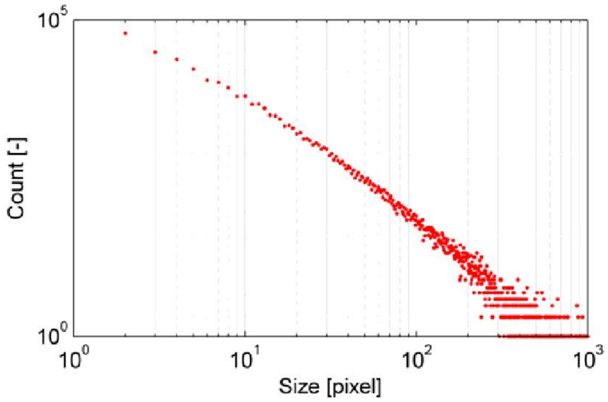

Fig. 8: Bubble size distribution

Concerning the eruption frequency two measurements can be used for evaluation. The pressure signals (P1-P4) show eruptions due an increase in system pressure as well as input temperature of the heat exchanger rises because of the increase of steam volume to be recondensed. Thus, the measurement data of pressure and heat exchanger temperatures where analyzed by Fast Fourier transformation for visualization of dominant frequencies of eruption (Fig. 7). So far there is no clear dependency visible in any of the signals. Only the input temperature of the heat exchanger (T15) show an increase at 0.004 Hz associated with an eruption every 250 seconds.

A large number of detected bubbles deliver information about bubble size distribution. The histogram (Fig. 8) shows no dominant bubble size. However, there are always more smaller sized bubbles then bigger ones.

From the determination of the bubble shapes an estimation of the roundness is performed (Fig. 9).

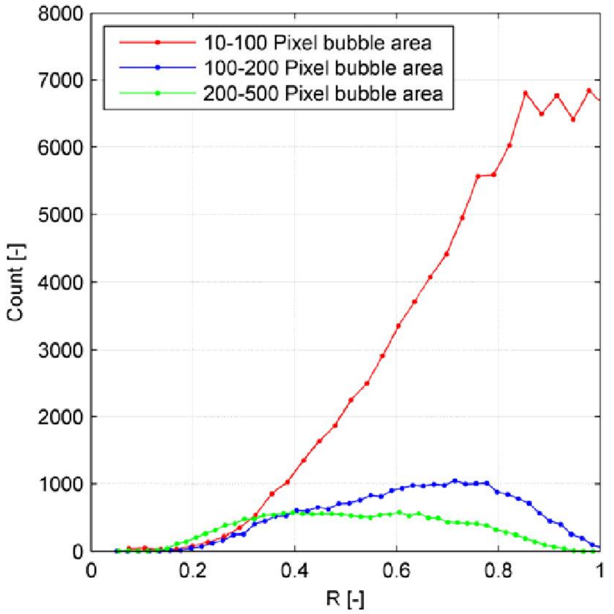

Fig. 9: Bubble roundness depending on size

Bubble roundness R follows from a calculation of area to perimeter ratio, which is normalized for a value between 1 for a perfect circle and 0 for a line. It follows

$$R = \frac{4\pi A}{l_P^2} \quad . \qquad (2)$$

Since camera pixels are quadratic, its values cannot reach 1. For detected bubbles below 10 pixels (1 pixel corresponds approximately to 1 mm) the accuracy is low as well. Therefore, areas below 10 pixel size are obliterated. This situation can be improved by reduction of the size of observed image area, thus increasing the image resolution.

Although there is a trend that bubbles are deviating from roundness when they are getting bigger, there is also a strong variation in shape in smaller sized bubbles as well. For confirmation this needs further investigation of smaller bubbles with higher image resolution, but shows that simply using spherical shape as a criterion might be inappropriate.

5. CONCLUSION

For investigation of vapour bubbles nucleating in bulk liquid a 2.75m high test container filled with water has been used. In first experiments growth and decay of vapour bubbles from pre-existing smallest bubbles have been clearly observed by means of flow visualization with video cameras and digital image processing. Additional temperature measurements indicate that in pre-existence of bubbles any superheat directly causes bubble growth. Furthermore, Fourier spectrum analyses of pressure and temperature data indicate a slight frequency peak in the spectrum, which can be correlated to periodic eruption of vapour inside the liquid volume. The bubble sizes distribution shows that bubble number diminishes with increasing bubble size. The evaluation of bubble roundness indicates that even smaller bubbles are often not perfectly shaped spheres. Since the smaller bubbles are only few image pixels in size, further investigation with smaller visualization area needs to be done to increase the image resolution and respective measuring accuracy.

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