BBBLE BEHAVIOR AND DEPARTURE BBBLE DIAMETER OF BBLES GENERATED OVER NUCLEATING CAVITIES IN FLOW BOILING

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ABSTRACT

This paper presents the results of an experimental study of bubbles nucleating over cavities on a localized heater surface under a flow of subcooled water at low bubble frequencies. The experimental apparatus consists of a rectangular flow channel 50 wide x 3 mm high with a 10 mm square copper heating surface placed flush in the center of the bottom wall surface. A viewing window located directly above the heater surface provides a clear view of the cavities and the bubbles growing over them. A microscope equipped with a video camera is connected to a digital image grabber board and to a video cassette recorder. The maximum effective magnification attained is approximately 700X which allows a feature dimension recognition of 3 μm.

Water at atmospheric pressure is circulated through a constant temperature bath equipped with heating and cooling options. The water temperature is kept between 45 and 80°C. The flow rate through the channel is measured by a rotameter and the flow is controlled with a hand valve. Pressure drop through the channel is measured using an inverted inclined U-tube manometer filled with water.

The visual study indicates that, for the flow rates investigated, the departing bubble diameters can be as small as 5 μm over nucleating cavities which are 2-3 μm in diameter. The departure bubble diameters become larger as the flow rate is reduced. Experimental data is presented for departure bubble diameter as a function of flow velocity and cavity diameter.

Some interesting features were revealed through the visual observation. The bubbles coming from upstream sites generally do not knock out the bubbles growing at a nucleation site. Rather, the oncoming bubbles follow a streamline around the nucleating bubble if there is enough room to go around. In some cases, bubbles seem to "walk" along the surface in the flow direction. The experiments were conducted at relatively low power levels to obtain bubble frequencies less than 500-1000 per second.

INTRODUCTION

Flow boiling refers to the conversion of a flowing liquid phase into its vapor phase over a solid surface caused by heat transferred from the solid surface. When the heater surface temperature is sufficiently high, the actual phase change process occurs close to the wall surface through the nucleation of bubbles and their subsequent growth on cavities present on the surface. When the flow velocity is zero, the heat transfer by this mechanism is referred to as pool boiling.

When a liquid flows over a solid surface heated to a point below the local saturation temperature, heat is transferred by a single-phase convective mechanism. As the heater surface temperature is raised above the local saturation temperature, heat is transferred through the liquid to the vapor-liquid interface in the bulk flow where phase change takes place.

The mechanism of heat transfer in flow boiling is a combination of the above two mechanisms - nucleate boiling and single-phase convective heat transfer. The degree to which each mechanism contributes to the total heat transfer has been investigated by many researchers while developing empirical correlations for internal flow boiling in circular tubes. Some investigators have considered the heat transfer mechanisms to be divided into three regions - (i) fully developed nucleate boiling with no effect of mass velocity or quality on the heat transfer coefficient, (ii) a combined nucleate boiling and convective heat transfer region where the two mechanisms are additive, and (iii) convective boiling with complete suppression of nucleate boiling where the heat transfer coefficient is independent of the heat flux. The correlation by Shah (1982) would fall under this category. A number of investigators have assumed the presence of both mechanisms throughout the entire region during flow boiling and proposed that the heat transfer by these mechanisms is additive. The correlations by Chen (1966) and Kandlikar (1990) fall into this category.
The approaches pursued by many investigators in developing correlations were purely empirical. They were based on the observation of patterns and trends followed by a large number of experimental data for different fluids over a wide range of operating and system parameters. The assumption of fully developed nucleate boiling on one side of the spectrum to complete suppression of nucleate boiling on the other was derived from the trends seen in heat transfer coefficient versus heat flux, mass flux, and quality. This approach has served a useful purpose of providing reasonably accurate correlations for designers of flow boiling equipment. In some cases, these correlations have provided a limited insight in the underlying mechanism (Kandlikar, 1990, 1991).

The presence of nucleate boiling in the "convective boiling region" has been a subject of controversy for a long time. The evidence presented on both sides of the issue was generally derived from selected experimental data. For example, Aounallah et al. (1982) cite their own experimental data in concluding the absence of nucleate boiling in annular flow, while Beattie and Green (1983) assert the presence of nucleate boiling on the basis of the experimental data reported by Bertolotti et al. (1964). Yilmaz and Westwater (1979) measured the effect of velocity on heat transfer to boiling R-113 over a wide range of parameters and observed an increase in the heat transfer coefficient with velocity in the nucleate boiling region, an observation contrary to those made by some previous investigators (e.g. McKee and Bell, 1969, Bitter, 1972, and Lemmer and Chawla, 1977).

This paper presents the results of an experimental investigation aimed at obtaining information on (i) bubble formation and departure diameters and (ii) individual bubble behavior under flow conditions, and (iii) photographic evidence of the presence of nucleate boiling using high speed video photography.

LITERATURE REVIEW

A brief survey of existing literature on the photographic study of flow boiling is presented here. One of the early studies was conducted by Gunther (1951). He employed a rectangular channel, 4.76 mm x 12.7 mm in cross section. A metal heater strip 3.175 mm wide and 10 μm thick was suspended in a transparent channel at the mid-plane. Gunther recognized the need for high speed as well as the high resolution needed to visualize the small bubble sizes in flow boiling. A high frame rate of 20,000 frames/second with a magnification of 5X was employed. A Kerr-cell electro-optical shutter with a shutterless camera was used. The resulting magnification allowed him to visualize bubbles of diameters as small as 50 μm. However, it is suspected that Gunther could not observe bubbles of sizes smaller than about 100 μm because of the relatively low resolution of his optical system.

Gunther's work provides one of the most detailed photographic investigation on the presence of nucleation in flow boiling. Individual bubbles growing on the heater surface were detected in the photographs when they reached a size of approximately 100 μm. The bubbles reached a maximum size of 100 μm to more than 500 μm before collapsing under highly poled conditions. Figure 1 shows a plot, derived from his data, depicting the effect of velocity on the average maximum bubble radius, and average fraction of the heater surface covered by bubbles. The fraction of area covered by bubbles represents the fraction covered by bubbles which were larger than about 100 μm. It is observed from Figure 1 that both, the bubble diameter and the fraction covered, decrease as the flow velocity increases.

Jiji and Clark (1964) performed a photographic study to investigate the bubble boundary layer and temperature profiles in the boundary layer. They also employed a rectangular channel of 12.7 mm x 11.68 mm cross section with a flow of water over a thin heated plate, 12.7 mm in width and 240.8 mm long, placed on one of the sides of the channel. The plate was instrumented to obtain a temperature profile along its length in the flow direction. The channel was placed vertically with water flowing in an upward direction. A Graphex camera was employed to photograph the side view of the plate capturing the development of the bubble boundary layer growth. The camera did not have any magnification lens. It is estimated that the maximum bubble diameter that could be clearly identified is about 1 mm. Jiji and Clark observed the presence and growth of a bubble boundary layer leading to a burnout condition at high heat flux values.

Berenson and Stone (1965) obtained photographs of bubbles on the walls of a transparent glass tube. R-113 was used as the test fluid. Heat was supplied by water flowing through the annular space between the test section and an outer glass tube. A WF-3 Fastax camera with a supplementary 6" Aero Ektar lens was employed to obtain pictures at a maximum frame rate of 7000 frames per second. The smallest recognizable feature dimension was about 100 μm. Their photographs show the presence of bubbles larger than 100 μm in the bubbly region streaking out from identifiable cavities. Under annular flow conditions, although picture clarity suffered due to reflections from the vapor-liquid interface, vapor bubbles larger than 100 μm diameter could be seen clearly in some of the photographs.

A study by Lorentz, Mikic, and Rohsenow (1974) on the effect of surface conditions in pool boiling provides important information on active cavity sizes. Their theoretical work predicted nucleation on cavity sizes in the range of 2 to 5 μm. Their experimental measurements confirmed the nucleation on these small sized cavities. Similar studies by Ali and Judd (1981) and Griffith and Wallis (1959) were concerned with nucleation over cavities as small as 1 μm under pool boiling conditions.
Kandlikar (1990) postulated that the additional force acting on the bubble due to shear stress at the wall in flow boiling would reduce the departure bubble diameters as compared to pool boiling. This is in agreement with Gunther’s experiments as seen from Figure 1. Kandlikar also provided an estimate for the effect of the wall temperature gradient on the active cavity sizes under flow boiling conditions, the combined result being that the departure bubble diameters in flow boiling could be very small, as small as only a few μm.

PRESENT INVESTIGATION

The present work is aimed at exploring the nature of nucleate boiling under the high wall shear stress conditions encountered in external as well as internal flow boiling. To obtain a clear view of the growing bubbles unobstructed by the vapor-liquid interface, the experiments were conducted with flow of subcooled water over a small heater surface. A narrow rectangular channel similar to that used by Gunther (1951) was employed to provide the desired shear stress at the heater surface.

Experimental Setup

A schematic of the experimental setup is shown in Figure 2a. A rectangular channel, 3mm x 50 mm, has a 10 mm square copper heater surface flush with the inner bottom channel wall. The heater consists of a copper block with a heating element wound on its other side, as shown in Figure 2b. Three T-type thermocouples are located in the heat flow direction to act as a heat flow meter. Water from a constant temperature tank is circulated through the channel by a pump. An Omega flowmeter, Model FL-6404 (accuracy ±5 percent, calibrated between 2 to 8 liters/min water flow) measures the flow. The wall above the heater surface has a glass window for the visual observation of the bubbles generated over nucleating cavities on the heater surface. A small mirror is installed adjacent to the heater at 45° angle to provide a side view of the bubbles.

A microscope (Micromanipulators Co. Inc., Model ASDS) is placed directly over the viewing window. It has three lenses, 2.25X, 8X and 25X, and a continuous adjustment eyepiece between 1X and 2X. Depending on the speed desired, a 30 frames/second CCD camera or a high speed Kodak camera (Ektapro 1000 high speed imaging system with speeds up to 6,000 frames per second) is used to visualize the bubbles. The maximum effective magnification on a 14" monitor is 700X.

EXPERIMENTAL RESULTS

The bubbles were observed both from the top as well as from the side view. Figure 3a shows the side view of a bubble growing on a cavity. It can be seen that the bubble is attached to the cavity like a balloon and is not a spreading bubble. Figure 3b shows a top view of a bubble growing on a cavity. The top view was used to measure the cavity diameter and the departure bubble diameter.

Figure 4 shows the departure bubble diameter plotted as a function of the nucleating cavity diameter and the flow rate. It can be seen that the departure bubble diameter decreases with increasing flow velocities. Also, for higher flow velocities, nucleating cavity sizes become smaller. The experiments were conducted by gradually increasing the heat flux until nucleation started. Heat flux was then adjusted, higher as well as lower, to

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**Fig 2. Schematic and details of the present experimental investigation**

(1) Flow loop
(2) Heater
Fig 3. Photographs of bubbles growing on cavities on the heater surface under subcooled flow boiling conditions
1) Side view
2) Top view

Fig 4. Departure bubble diameter as a function of nucleating cavity diameter and flow velocity in subcooled flow boiling

capture bubble activity on smallest cavity size points. Additional data was obtained for larger sized cavities. At high fluxes, the bubble frequency exceeded the maximum frame rate of the camera due to lighting limitations. Hence, the effect of subcooling on bubble activity could not be clearly established because of limited number of data points.

This study is similar to that conducted by Gunther where he used the present system is equipped with both a higher magnification microscope. It is suspected that in the regions indicated in the separate regions described in Figure 1, where Gunther did not observe any bubbles smaller than 100 μm, there might have been bubbles present but undetected by his optical system. In the present investigation, some cavities as small as 3-5 um and the surrounding bubble activity could be clearly visualized.

An interesting phenomenon was observed with individual bubbles. At low flow rates, bubbles reached a certain size and then started moving slowly along the wall in the flow direction until they were swept away. A separate theoretical study conducted established that the bubbles are removed under the influence of either shear forces or lift forces. At low flow rates, the shear forces are primarily responsible for bubble removal, but as the flow velocity increases, the bubble frequency also increases under the influence of lift forces. Some of the small cavities were activated by bubbles sweeping past them. However, at higher heat fluxes, the bubble activity was seen only with a high speed camera, while the regular VHS camera did not indicate any activity. It was also observed that the bubble frequency with bubbles smaller than about 20 μm was very low. A reduction in heat flux generally stopped the nucleation altogether. Obtaining a low bubble frequency, say 100-500 per second was impossible with smaller sized cavities.

CONCLUSIONS

The experimental results for flow boiling of subcooled water at atmospheric pressure and a temperature of 45-80°C, presented in this paper. These results indicate that bubble nucleated over cavities smaller than 20 μm diameter under
high velocity flow. The nucleating cavity sizes become smaller as the flow velocity is increased. A high power microscope, a high speed camera, and adequate lighting are essential to visually ascertain the presence of nucleation in flow boiling. Also, as the flow velocity is increased, the departure bubble diameters become smaller. Quantitative results are presented for departure bubble diameter as a function of the cavity diameter and flow rate. The study also provides a visual information on bubble characteristics for flow under high shear stress conditions.

REFERENCES


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