Vapor bubble on a single nucleation site : Temperature and heat flux measurements

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Abstract. This work aimed at gaining a detailed understanding of heat transfer when boiling occurs on a heated substrate. More specifically, this work focuses on thermal transfers occurring at wall-fluid interfaces at the transition between natural convection and nucleate boiling regimes in pool boiling experiments. To avoid parasitic effects, the vapor bubble is created at a single artificial nucleation site. The boiling cell is instrumented with sensors for temperature measurement, pressure control, and parietal heat flux measurement. The fluid tested is Fluorinert FC-72. For providing a boiling surface and measuring heat flux, a boiling-meter consisting of a heating resistance, heat flux sensors and two thermocouples is used. This boiling-meter enables heat flux generation, the measurement of both temperature and heat flux, and can be rotated through 360°, enabling the influence of inclination to be studied. The boiling-meter is indented at its center to create a single vapor bubble. Thermal measurements are obtained and studied for different inclination angles between 0° and 180° at the saturation conditions. The results showed the nucleation site's recurrent pattern of being active and inactive for whatever is the boiling surface inclination. Preliminary results are presented and discussed.

1. Introduction

The miniaturization of electronic devices demands improvements of heat transfers. One of the passive methods of heat transfer enhancement is through boiling, since the bubbles created in the microcavities or due to roughness of heating surface modify the thermal boundary layer and result in better heat transfer. Presently the use of boiling process is encountered in several applications such as electric power generation, food industry, thermal management of space missions, ... Since the heat exchangers can be positioned in different orientations within the system, numerous studies have been done on the impact of heating surface orientation on different thermal parameters. Flat copper plate for 0° to 175° inclination was tested and the effects on heat transfer coefficient (h) were studied by [1]. Similarly, the effect of uncoated and coated microporous surfaces on incipience superheat was done by [2]. The results showed that micro-porous coated surfaces reduced incipience superheat by 80% and enhanced h by 330%. Similar experiments with two dielectric fluids FC-72 and HFE were investigated by [3], and the effects on heat transfer coefficient (h) and critical heat flux (CHF) were noted. The h and CHF for HFE were found to be 25% and 40% higher than the FC-72.

Furthermore, investigation on the changing surface inclination (ϴ) effect on onset of nucleate boiling (ONB) for single and multiple nucleation sites for sub-atmospheric nucleate pool boiling with FC-72 fluid was done by [4]. The inclination angles tested were 0° and 180°. Nucleate boiling was observed to begin quickly at ϴ=180° with a superheat of 5 °C, while for ϴ =0°, 25.5 °C of superheat was needed. Later, this study was continued by [5], to investigate the heater orientation effect on the onset of natural convection (ONC) and nucleate boiling (ONB) regime. It was observed that heat flux increased with increasing ϴ for the low superheat nucleate boiling regime and decreased with increasing ϴ approaching 180° for the high superheat nucleate boiling regime. Recently, scientists have focused on the better precise prediction of phase change and heat transfer in boiling regime. This necessitates researching bubble dynamics and variables such as bubble departure diameter, frequency, and density of nucleation sites [6]. Single bubble growth study for water and 2-butanol mixtures was done by [7]. It was found that self-rewetting fluids provided smaller bubble sizes and higher nucleation site density than water at ONB. This short review highlights the wide variety of phenomena involved in boiling processes, and a great deal of research is still needed to gain a better understanding of the phenomena that trigger boiling and the associated heat transfer.

In the present work, preliminary results on studying the heat transfer at the onset of nucleate boiling on a single nucleation site are investigated. More precisely experiments are carried out on these phenomena for several inclination angles of the boiling wall angles between 0° and 180°. Alternative active and inactive nucleation site are highlighted for all the inclination angle investigated. These experimental results are discussed through the heat flux and wall temperature measurements.

2. Experimental set up and protocol

The experimental set up aims to obtain thermodynamic and thermally controlled conditions throughout the boiling process. The experimental setup used is shown in figure 1(a) and its specifications are provided in [4], [5]. The test fluid used is FC-72. Furthermore, to create boiling with varying surface inclination, a specially designed boiling meter is used. Its specificities are given in figure 1(b) and (c), its fabrication and calibration are detailed in [4], [5]. To measure the intensity of the heat flux, two heat flux sensors having a sensitivity of 2.82 $\mu V/(W/m^2)$ are placed on both sides. For obtaining wall temperature, a thermocouple (accuracy = ±0.2 °C) placed just under the top copper layer of each fluxmeter allows the local wall temperature measurement. An artificial nucleation site of an average diameter 200 μm and depth of 150 μm is created on the center of the boiling surface to obtain a single bubble [4], [5].

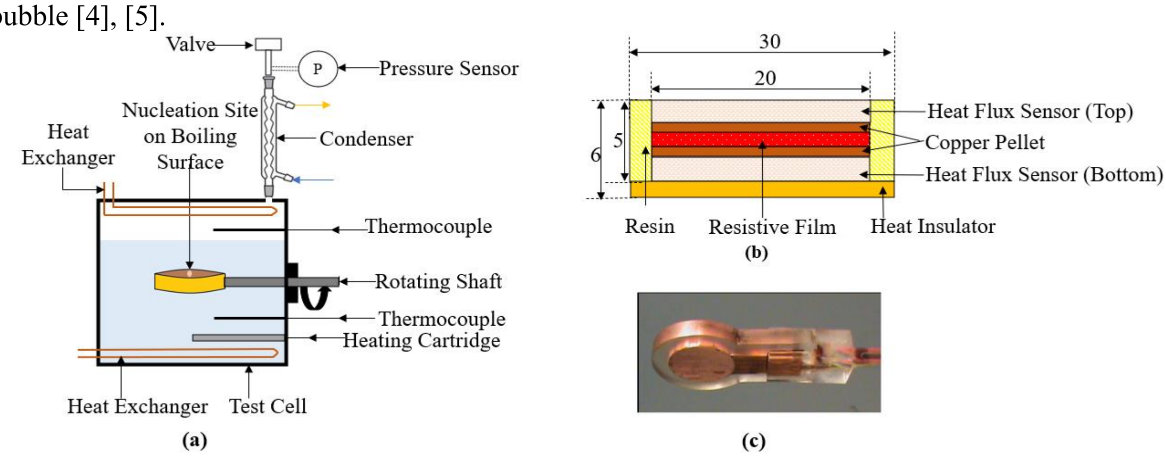

Figure 1. (a) Schematic illustration of the experimental cell, (b) Schematic representation of boiling meter (all units are in mm), (c) Pictorial representation of boiling meter [4], [5]

To begin with the experiments the cell is first partially filled with the test fluid FC-72. Before starting a series of experiments, a dedicated procedure is adapted for the removal of non-condensable gases present in the cell [4], [5]. After a steady state regime is reached, measurements are taken for wall temperature, heat flux, fluid temperature and pressure.

3. Results

In this work, one saturation condition has been investigated to ascertain how surface inclination influences the phenomenon of heat transmission. Based on the reduction of heat loss and the safety of the boiling meter, the saturation conditions Tsat = 34.3°C, Psat = 0.46 bar are selected. The power imposed in the heater of the boiling meter is 0.46 W. Further the surface inclination angles studied are 0°, 30°, 60°, 90°, 120°, 135°, 150°, 175°, 179° and 180°. An inclination of 0° indicates a boiling face upward, and 180° indicates a boiling face below. The values of the heat flux are given by the heat flux sensor and are average values over the sensor surface (3.14 x 10^{-4} m^2); wall temperature measurements are local and are provided by the thermocouple located underneath the nucleation site.

3.1. Description of the results for the reference case

In this section, a description of the heat flux and wall temperature is given for a reference case. Figure 2 shows the variation of heat flux along the time for ϴ= 60°. The results indicate that there are two different regimes highlighted for both heat flux (q) and wall temperature measurements (T_w). A first regime in which the heat flux, like the temperature, is at an almost constant average value for several seconds. This is followed by a phase in which heat flux and temperature fall or rise, inversely with each other, then stabilize around an average value for a few seconds.

Thanks to video camera visualization, we can observe phenomena associated with these two regimes. The first regime corresponds to a continuous emission of vapor bubbles at the nucleation site. In the second regime, the nucleation site becomes inactive. These observations enable us to highlight changes in transfer rates as we move from one regime to another (convective to nucleate boiling).

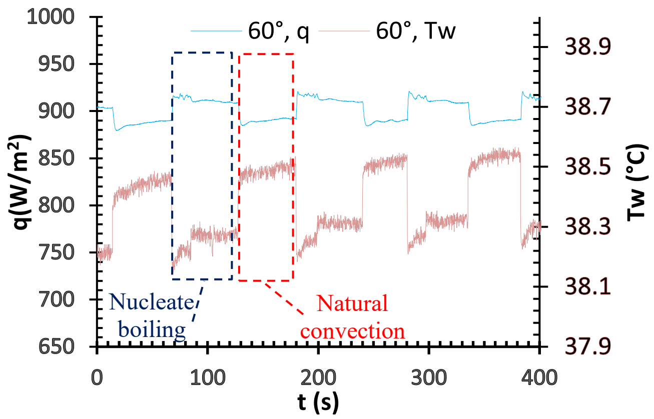

Figure 2. Variation of heat flux (q) and wall temperature (T_w) with time (t) at ϴ = 60°

The variation in heat flux for the bubble emission region (nucleate boiling) is between 910 to 920 W/m^2; while for no bubble emission region (natural convection) it is 880 to 890 W/m^2. These variations can also be observed from the wall temperature plot. When the nucleation site emits bubbles, temperature of the wall lowers to nearly 38.18 °C and further, after some instants when the site becomes inactive, wall temperature increases to nearly 38.56 °C. The alternations between regimes 1 and 2 are clearly visible using heat transfer and temperature measurements. These regimes are also observed with a BW camera. This point will be addressed in the next section.

3.2. Influence of the wall inclination

Different angles from 0° to 180° were tested to investigate the alternative phenomena highlighted for the reference case. It was observed that, as the surface inclination increases, the repetitions of site activation and deactivation amplify more periodically. This can be observed by the heat flux and wall temperature curves given in figure 3-7. These figures show that the phenomenon is almost “periodic” with small noticeable fluctuations.

Furthermore, by observing the activation and deactivation periods for each angle, we can see that in most cases, these periods are almost constant and depend on the surface inclination, ϴ. The variation of these active and inactive time period (T) with ϴ is plotted in figure 8. It can be observed that the duration of the active phase is comparatively higher than the inactive phase and it can be highlighted with the two parameters heat flux and wall temperature. In few cases (60°, 90°, 120° and 135°), the time period for each cycle of bubble emission and deactivation remains nearly constant for a given value of inclination. It is noteworthy that when surface inclination exceeds 60°, the duration for both activation and deactivation reduce; and close to 180°, the deactivation time period tends to small values. More precisely, at 180°, the nucleation site remains active throughout the time series (with an emission frequency close to 1 Hz) and few cases of nucleation site deactivation have been observed with much lower frequency than other cases of ϴ. On the other hand, when the nucleation site is activated, the emission period varies and is not repeatable: the phenomenon is highly unstable at this angle. However, with each cycle of bubble formation-growth-emission, fluctuation in the heat flux value can be noted. The conditions for minimum and maximum heat flux can be clearly seen for each bubble cycle. For explanation- when the bubble is emitted heat flux jumps to its maximum value, and further another bubble forms and it grows on the boiling surface. Since the size of the bubble is comparatively larger in this case, it covers more boiling surface area. As a result of this bubble's contact, heat transfer reduces and eventually reaches the minimum value, until the bubble separates from the surface.

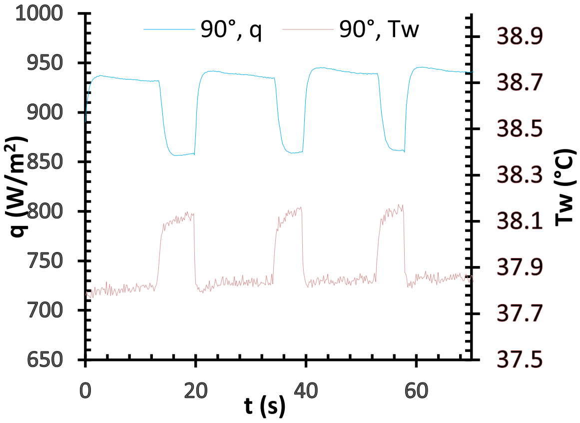

Figure 3. Variation of heat flux (q) and wall temperature (T_w) with time (t) at ϴ = 90°

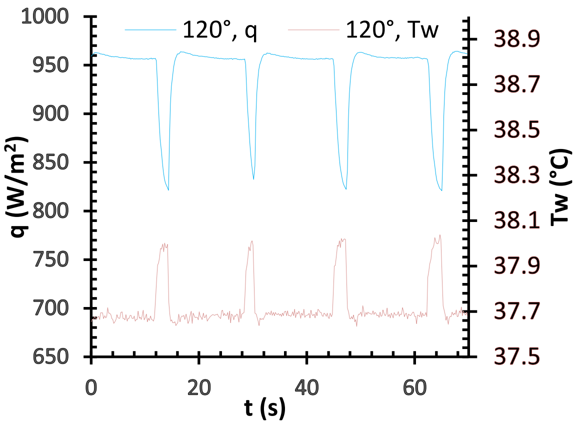

Figure 4. Variation of heat flux (q) and wall temperature (T_w) with time (t) at ϴ = 120°

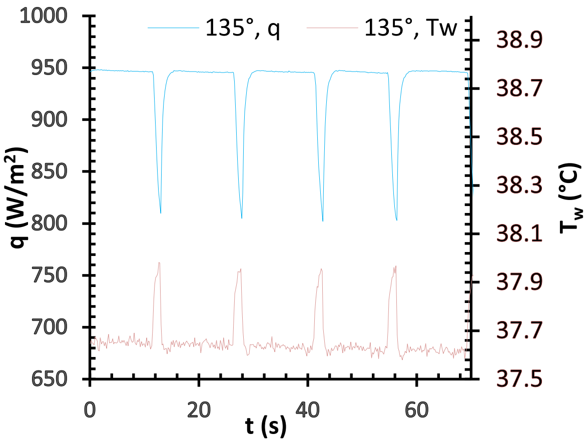

Figure 5. Variation of heat flux (q) and wall temperature (T_w) with time (t) at ϴ = 135°

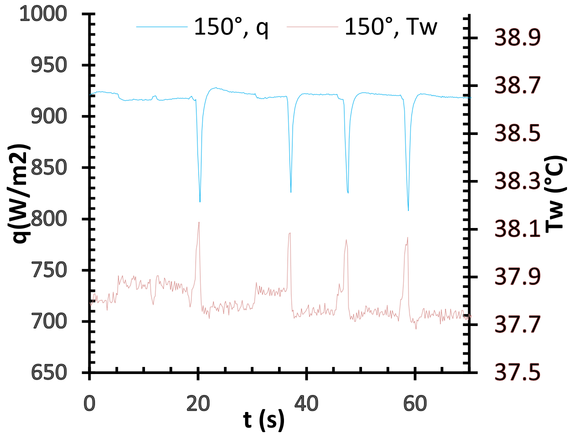

Figure 6. Variation of heat flux (q) and wall temperature (T_w) with time (t) at ϴ = 150

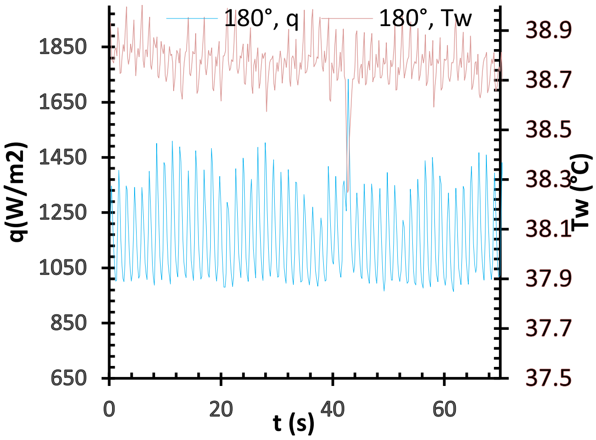

Figure7. Variation of heat flux (q) and wall temperature (T_w) with time (t) at ϴ = 180°

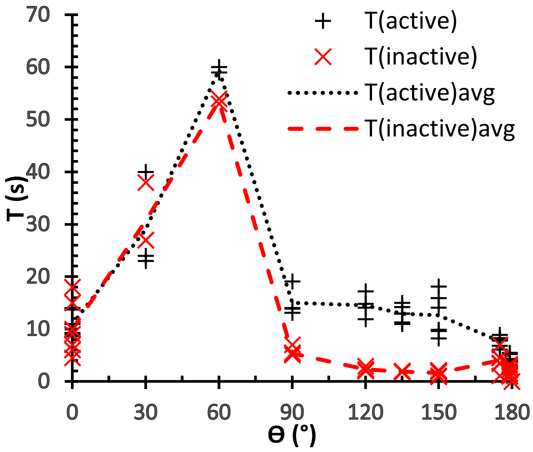

Figure 8. Variation of active and inactive time period (T) plotted for each cycle and surface inclination (ϴ)

4. Discussion

The present study on the nucleation of single bubbles reveals a transition between an active and a non-active site. This phenomenon of continuous deactivation and reactivation of the bubble nucleation site is evident for most of the inclination angles. The duration of the active period and inactive period differs in each case; however, it is seen (figure 8) that for 60° ≤ ϴ ≤150°, both the active and inactive site time periods decrease as a function of surface inclination, ϴ. According to these observations, a possible interpretation of bubble nucleation might be given. The activation and deactivation of the nucleation site could be related to the number of vapor molecules existing in the site and close to it. As soon as the deactivation regime starts, the wall temperature increases, and so does the number of vapor molecules. When the number of molecules is sufficiently high, bubbles can form. Under the effect of buoyancy forces, when the bubble reaches a given size dictated by the competition between the buoyancy and surface forces, it detaches from the surface. During a while, the quantity of vapor molecules in the site decreases. As soon as the number of molecules becomes insufficient, the site deactivates and a new cycle begins. The heat flux decreases at the wall, and the wall temperature rises. The latency time could therefore correspond to the time during which the site is supplied with vapor molecules. When the number of vapor molecules is sufficiently high, the site is reactivated, and new bubbles form and detach.

The data presented need to be further analysed to better interpret the nucleation phenomena highlighted in these experiments. The heat flux sensor enables us to follow the cycle of a single vapour bubble as it grows at high angles. At angles below 90°, the bubbles are too small and the phenomenon is too rapid to be detected in detail with the commercial heat flux sensor. So, to carry out further investigations to analyse heat transfer, a faster and more sensitive sensor should be developed.

5. Conclusion and future work

In the present work new experiments on bubble nucleation from single site are carried out. The repeating behaviour of bubble nucleation at the onset of nucleate boiling is highlighted. This phenomenon leads to give a possible interpretation of the activation and deactivation of bubble nucleation. Further investigations are needed to make a better interpretation of the bubble nucleation phenomenon on a single artificial site.

For future investigations, to reach higher sensitivity and fast response of heat flux sensor we are currently developing a miniature normal heat flux sensor NHF for a new boiling meter thanks to microfabrication techniques [8]. This sensor is composed of wafers separated by an insulating layer and possess a deep reactive ion etched (DRIE) cylindrical cavity in the center. In the future work, new investigations with these DRIE etched cylindrical shaped cavity will be tested for different saturation conditions.

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References

[1] N. Kaneyasu, F. Yasunobu, U. Satoru, and O. Haruhiko, "Effect of surface configuration on nucleate boiling heat transfer," *Int J Heat Mass Transf*, vol. 27, no. 9, pp. 1559–1571, 1984.

[2] J. Y. Chang and S. M. You, "Heater Orientation Effects on Pool Boiling of Micro-Porous-Enhanced Surfaces in Saturated FC-72," *J Heat Transfer*, vol. 118, no. 4, pp. 937–943, Nov. 1996, doi: 10.1115/1.2822592.

[3] A. Priarone, "Effect of surface orientation on nucleate boiling and critical heat flux of dielectric fluids," *International Journal of Thermal Sciences*, vol. 44, no. 9, pp. 822–831, Sep. 2005, doi: 10.1016/j.ijthermalsci.2005.02.014.

[4] M. Zamoum, L. Tadrist, H. Combeau, and M. Kessal, "Experimental Study of Boiling Heat Transfer on Multiple and Single Nucleation Sites Using a Boiling-Meter," *Heat Transfer Engineering*, vol. 35, no. 5, pp. 508–516, Mar. 2014, doi: 10.1080/01457632.2013.833052.

[5] L. Tadrist, H. Combeau, M. Zamoum, and M. Kessal, "Experimental study of heat transfer at the transition regime between the natural convection and nucleate boiling: Influence of the heated wall tilt angle on the onset of nucleate boiling (ONB) and natural convection (ONC)," *Int J Heat Mass Transf*, vol. 151, p. 119388, Apr. 2020, doi: 10.1016/J.IJHEATMASSTRANSFER.2020.119388.

[6] Y. Zhao, Y. C. Lin, K. Tang, M. Ishii, and J. R. Buchanan-Jr, "Investigation of nucleate boiling and bubble dynamics at multiple nucleation sites in subcooled boiling flow," *Int J Heat Mass Transf*, vol. 219, p. 124886, Feb. 2024, doi: 10.1016/J.IJHEATMASSTRANSFER.2023.124886.

[7] M. Zupančič, P. Zakšek, and I. Golobič, "Experimental investigation of single-bubble growth during the saturated pool boiling of water and self-rewetting aqueous n-butanol mixtures," *Case Studies in Thermal Engineering*, vol. 28, p. 101513, Dec. 2021, doi: 10.1016/J.CSITE.2021.101513.

[8] A. Zribi, M. Barthès, S. Bégot, F. Lanzetta, J. Y. Rauch, and V. Moutarlier, "Design, fabrication and characterization of thin film resistances for heat flux sensing application," *Sens Actuators A Phys*, vol. 245, pp. 26–39, Jul. 2016, doi: 10.1016/J.SNA.2016.04.040.