Bubble dynamics and mechanistic boiling heat transfer prediction on a scored copper surface

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Abstract. In this study, pool boiling heat transfer of de-ionized water was experimentally studied on a scored copper surface at a heat-flux range of 0 - 60 W/cm². Bubble dynamics in an isolated bubble region were carefully investigated, including bubble departure diameters, bubble departure frequencies, and active nucleation site densities. The bubble dynamics were compared with available models, indicating the suitable models regarding the present experimental results. Then, based on the bubble dynamics, a mechanistic heat transfer model, developed in our previous studies, was employed to predict the present boiling curve. In the mechanistic model, heat fluxes from natural convection, transient heat conduction, and microlayer evaporation were incorporated.

1. Introduction
Boiling heat transfer is an important mode for energy conversion and transport, which extensively appears in many industrial processes, e.g., power plants, electronics cooling, and refrigeration systems. It is significant to have a good understanding of its physical essence but which is quite complex because of its multi-phase and multi-physics characteristics. As one of the pioneers who dedicated to the boiling heat transfer, Nukiyama [1] reported a classical boiling curve of water on a Nichrome wire in 1934, finding that the quantity of heat transmitted increases with the increasing temperature difference, but after a certain temperature difference, the heat quantity decreases with further increase in the temperature difference. This threshold value of heat quantity is well-known as critical heat flux. Through several-decade investigations, now it is a common conscious that boiling performance depends on surface characteristics and liquid properties because liquid-surface combinations greatly affect bubble dynamics, e.g., bubble nucleation, bubble departure, bubble interactions, and even vapor-liquid dynamics. Therefore, to reveal the bubble dynamics is essential to clarify the boiling heat transfer performance, which in turn guides to manipulate the performance in practical applications.

Up to date, numerous studies have been conducted to study the bubble dynamics, and for example, many models have been proposed to predict the bubble departure diameters and frequencies, as well as bubble growth characteristics, which were reviewed in [2]. For instance, Fritz [3] proposed a bubble departure diameter correlation for pure liquids and liquid mixtures, considering the force balance between buoyancy force and surface tension force. Many other correlations were also developed subsequently, e.g., by Cole [4], Jensen and Memmel [3], Stephan [5], Kim et al. [6], and Phan et al. [7]. Regarding the bubble departure frequency which relies on wall superheat, surface-liquid combinations, and interactions between bubbles, many correlations have been proposed as well which generally combine the bubble departure diameter and liquid properties, i.e., Cole [4], Jakob [8], McFadden and Grassman [9], Zuber [10], Ivey [11] and Hatton and Hall [12]. Even though the bubble dynamics have been studied so extensively theoretically or semi-theoretically, it is still not well understood because the bubble dynamics are easily affected by random surface defects, bubble-bubble/liquid interactions which make the physical characteristics complex. Therefore, more experimental results are required to further understand the complex bubble dynamics, validate and improve existing models.
2. Methodology
This study investigated pool boiling heat transfer of de-ionized water on a scored copper surface (SS), specializing in bubble dynamics and mechanistic heat transfer prediction. The copper surface was prepared by polishing a copper surface with sandpaper of 600 grits and Figure 1 indicates its SEM images. The averaged roughness ($R_a$) was measured to be 558 nm, and the static contact angle was measured as 110°.

Figure 1. SEM images of the scored copper surface.

Figure 2 shows the schematics of the pool boiling setup. A copper rod was insulated by PTFE. The rod was heated up by five cartridge heaters (BACKER) which were powered by a transformer (KIEA 8, Tufvassons Transformer) in parallel. Two auxiliary heaters (100 W each) were used to degas and guarantee a saturated state. A high-speed camera (Phantom v611) was used to capture bubble behavior. All temperature data were collected by an Agilent 34970A. Heat fluxes were calculated by Fourier’s law, using temperatures measured by three K-type thermocouples ($T_1$, $T_2$, $T_3$) on the copper rod, with a distance of 15 mm ($y_1$) between two neighboring thermocouples. The test copper samples with a diameter and a height of 12 mm and 10 mm, respectively, were soldered on the copper rod, while a T-type thermocouple ($T_4$) was inserted to evaluate the surface temperature, with a distance of 8 mm ($y_2$) to the boiling surface.

Before experiments, around 1L of deionized water was poured into the boiling chamber, with a liquid height of 100 mm. A degassing operation was carried out firstly by boiling deionized water vigorously for around 30 mins. Boiling curves were measured in two ways in this study, i.e., first decreasing heat fluxes and then increasing heat fluxes. Bubble dynamics were captured with 2000 fps at a steady state when $T_4$ and ($T_1$-$T_3$) deviated within 0.5 °C in 2 minutes.

Figure 2. Schematic diagram of the setup.

Figure 3. Pool boiling curves on the scored surface.
3. Results and discussion
Details of data reduction and validation of the experimental setup can be found in [13]. Figure 3 compares the boiling curve of increasing and decreasing heat fluxes. It is seen that at a heat flux lower than 20 W/cm², the boiling curve repeats well, but above which, deviations occur, and the deviation seems to be enlarged with increasing heat fluxes. It is conjectured that at a high heat flux, bubble interactions become violent and dominate the heat transfer, while the interactions happen randomly. Probably, the interactions e.g., bubble coalescence and merged bubble behavior are not the same in the two heating modes, which results in the deviation.

Bubble dynamics in an isolated bubble region (q < 10 W/cm²) are quantitatively studied. In this region, the heating mode does not affect the heat transfer since the boiling curve repeats very well. Therefore, the bubble dynamics of the two heating modes can be used together. Figure 4 compares the present bubble departure diameter and several models, in which the bubble nucleates from a specific site and the departure diameter is an averaged value of 10 bubbles. It is found that the departure diameter tends to be a constant, independent of the superheat, but the model cannot give a very good prediction. Furthermore, the relationship between the bubble departure diameter and frequency is investigated, as shown in Fig. 5. The bubble departure diameter and frequency in Fig. 5 are not averaged values, but one bubble and its counterpart frequency. It is found that the relationship is roughly consistent with the trend given by Cole[4] and Jakob [8] who both provide an inverse proportion relationship for the departure diameter and frequency.

Another important fact that determines the heat transfer performance is active nucleation site density which is also carefully studied. The active nucleation site density is obtained experimentally and also compared with several correlations, i.e., Benjamin and Balakrishnan [14], Hibiki and Ishii [15], and Wang and Dhir [16]. Figure 6 compares the measured active nucleation site density versus the superheat with the correlations. It is seen that the correlation proposed by Wang and Dhir [16] well predicted the present results.

In the end, based on the discussion about the bubble departure diameter, the bubble departure frequency, and the active nucleation site density, a mechanistic model is attempted to predict the present boiling curve, considering contributions from the natural convection, the transient conduction, and the microlayer evaporation [17]. Figure 7 shows the comparison, finding that the mechanistic model can give a relatively good prediction, especially when the heat flux is lower than 10 W/cm² above which the model underpredicts the results. This is because the model only relies on isolated bubble dynamics and the bubble interactions are not involved.
4. Conclusion

The present paper provides a comprehensive study on bubble dynamics on a scored copper surface. Based on the bubble dynamics, the boiling curve is predicted with a mechanistic model. Several findings are summarized as follows:

- Regarding a specific nucleation site, the isolate bubble departure diameter tends to be a constant.
- The bubble departure frequency is roughly reverse proportional to the bubble departure diameter.
- The present active nucleation site density is well predicted by the correlation in [16].
- The mechanistic model indicates a good prediction, especially in the isolated bubble region.

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Figure 6. Comparison of measured active nucleation site density and correlations.

Figure 7. Comparison of the measured boiling curve and modeled boiling curve.
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