Onset of nucleate boiling (ONB) experiment on a smooth heating surface free from trapped vapor

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1. Introduction

Boiling is a general phenomenon widely observed in daily life and several industry fields. Particularly, due to the good boiling heat transfer performance compared to the single phase heat transfer, boiling is accepted to nuclear power plants for transferring heat. The current stage of nucleation theory is based on the vapor trapped theory, which states that micro scale cavities or defects on a commercial heating surface trapped vapor and then act as a nucleus[1]. The criteria for trapping vapor on a heating surface was suggested by Bankoff[2]. For trapped vapor, a heating surface should have micron scale surface cavities. Based on that, previous researchers predicted the nucleation sites of the trapped vapors in boiling[3-5]. Recently, however, bubble nucleation on a smooth heating surface free from trapped vapor was reported by several researchers. Benjamin and Balakrishnan[6] observed the activated nucleation site densities on heating surfaces, even if when the roughness of the heating surface is less than a certain nanoscale. Theofanous[7] conducted pool boiling experiment on a heating surface with nanoscale roughness. And they suggested the possibility of bubble nucleation on a nanoscale roughness surface. These results are not explained by the vapor trapped theory. In this study, we conducted experimental approach for the bubble nucleation on a smooth heating surface free from trapped vapor and discussed how bubble could be nucleated on a smooth surface.

2. Methods and Results

To investigate bubble nucleation on a smooth heating surface without micro cavities, we conducted onset of nucleate boiling (ONB) experiment on chemically treated silicon wafer surface, which guarantees the atomic scale roughness. And we tried to describe ONBs on different heating surfaces with the potential gradient nucleation model.

2.1 Boiling facility

A rectangular aluminium bath is used as a main pool and ONB experiments were conducted under atmospheric saturated condition with distilled water as working fluid. An immersion heater controlled by PID (Proportional Integral Derivative) controller and a reflux condenser were used to maintain saturated condition. The size of used silicon specimen was 25 x 20 mm^2 and there was 15 x 10 mm^2 effective heating area. Joule heating method is applied for generating heat. The both side of silicon wafer was fabricated: one side was made for heating part and the other side was treated as heating surface. Platinum thin layer was deposited by E-beam evaporator and used as main heating material. It is important to know the exact voltage and current during actual operation, so calibration tests were conducted for temperatures between 100 ℃ and 150 ℃ at intervals of 10 ℃. Based on this calibration procedure, wall temperature could be evaluated. The supplied heat flux was calculated by the measured voltage at the sample and reference resistance which is known resistance to get current in the circuit. After that, the heat loss was additionally considered by numerical calculation. Before main experiment, degassing procedure was conducted to expel dissolved gas by pre-heating to maintain the saturated condition for 2 hours. Main experiments were conducted by increasing the electrical load in small steps until almost reaching the ONB point. Data were recorded every second for 100s while the sample was in this quasi-steady state, then the power level was steadily increased until the ONB occur.

2.2 Surface characteristics

We used three kinds of chemically treated heating surface including bare silicon oxidized surface for investigating bubble nucleation on a smooth heating surface. For different wetting characteristics, plasma exposure and Teflon coating methods were used. The heating surface exposed under plasma had hydrophilic characteristic, and Teflon coating realized hydrophobic characteristic. The measured contact angles of plasma treated, silicon oxidized and Teflon coated specimens were 29, 54 and 123°, respectively. The absence of any micron structures was confirmed by measuring surface roughness and AFM data. There were only nano scale roughness.

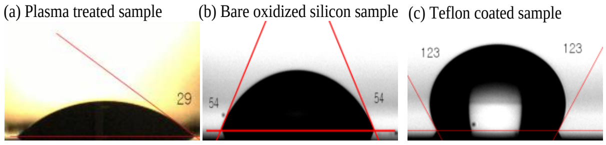

Fig. 1. Measured contact angles on chemically treated silicon samples.

2.3 ONB experimental results

Figure 2 shows the result of ONB experiment on different chemically treated heating surfaces. Most of all, it is confirmed that bubble nucleation occurs on a smooth heating surface, even if the heating surface could not entrap vapor on micro cavities or defects. It is suggested that new bubble nucleation model to describe bubble nucleation on a smooth heating surface is required. And, according to the results, more larger contact angle of the heating surface required lower superheats for bubble nucleation.

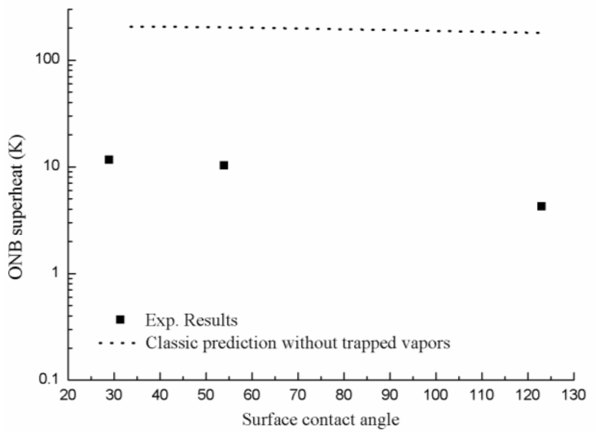

Fig. 2. ONB experimental results and classically predicted bubble nucleation superheats without trapped vapors on different wetting surfaces.

Due to the absence of micro-cavities, we compared the ONB experimental results to the predicted superheats by classic heterogeneous nucleation models[8]. However, the experimentally confirmed superheats for the heating surfaces were definitely lower than the predicted superheats.

In this study, the occurrences of bubble on a smooth heating surface could be described by the potential gradient nucleation model[9]. The potential gradient nucleation model adopted energy gradient within the thermal boundary layer on a heating surface to evaluate the kinetic nucleation rates. As a consequence of that, the nucleation rates induced by 100 μm thermal boundary layer was enough to initiate bubble nucleation, although the superheat of the heating surface was just 10 K. Also, the potential gradient model considered the thermodynamics stability. For the thermodynamics stability, the temperature of nucleated bubble top in critical state for nucleation should be higher than the temperature evaluated from Clausius-Clapeyron relation. In this process, larger contact angle of the nucleated bubble has shorter bubble height. It means that the top of the nucleated bubble on a hydrophobic surface would close to heating surface, therefore the thermodynamics stability would be satisfied at lower superheat condition. This prediction corresponds to the result of ONB experimental results conducted in this study.

3. Conclusions

To understand bubble nucleation on a smooth heating surface free from trapped vapors, ONB experiments were conducted with different wetting surfaces. In this study, it is confirmed that the bubble nucleation on a smooth surface occurs, although the heating surface does not trap any vapors on micro-cavities or defects. Furthermore, ONB depended on the contact angle of the heating surface; higher contact angle surface required lower superheat for nucleation. We discussed the bubble nucleation on a smooth heating surface and the dependency of ONB on surface wettability with the potential gradient nucleation model.

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