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Heterogeneous nucleation on ultra smooth surfaces

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ABSTRACT

An experimental investigation is presented with heterogeneous nucleate boiling on ultra smooth metallic surfaces (30–365 nm RMS roughness), including brass, unpolished stainless steel, and electropolished stainless steel. The fluids used for the investigation are highly wetting pentane and butane. It is observed that the incipient superheat is low for all cases considered, despite the fact that no vapor trapping cavities are available for incipience at low superheat. These data provide further evidence that in addition to vapor trapping, another mechanism must be available for heterogeneous nucleation in boiling systems. The boiling curves are presented for the different surface/fluid combinations. It is found that the heat transfer rate on the brass surface is considerably better than that on the stainless steel surfaces due to the ease with which nucleation sites are formed. In contrast, nucleation site formation on stainless steel is considerably more sparse than that on brass.

1. Introduction

The observations by Corty and Foust [1] that heterogeneous boiling occurs at low superheat on surfaces with irregularities led to the hypothesis that vapor trapped in surface cavities seeds the boiling nucleation process. Griffith and Wallis [2] quantitatively identified the minimum cavity size required for bubble incipience from a surface cavity at a specified superheat. Recently, Qi and Klausner [3] manufactured artificial cylindrical cavities of varying size and tested the Griffith and Wallis theory. It was found that over the size range of cavities investigated the theory is qualitatively satisfactory, and the superheat required to initiate bubble incipience is twice that predicted by the Griffith and Wallis theory.

Many important advances in understanding the thermo-physical mechanics of the boiling process have been made over the past 25 years, including the ability to simulate bubble growth and heat transfer from a single nucleation site [4–8]. Yet a first principles predictive model for nucleate boiling heat transfer remains elusive. It is generally agreed that a robust model that predicts the location and number of nucleation sites on a boiling surface is a precursor to the development of a mechanistic boiling heat transfer model. Attempts to predict the nucleation site density on a boiling surface have typically relied on specific knowledge of the surface finish and fluid wettability; nucleation site density models assume that cavity vapor trapping is a necessary criterion for bubble incipience. Such models typically show good agreement for a specific surface/fluid combination but fail when compared to a variety of fluids and surfaces. For example, Wang and Dhir [9] used a statistical model to predict nucleation site density for water with varying degrees of wettability on a specially prepared copper surface with spherical cavities. Agreement between the measured and predicted nucleation site density was quite good, although the model was not extended to other surface/fluid combinations. Luke [10], Luke and Gorenflo [11], and Luke [12] identified several important length scales on the boiling surface that are useful for correlating nucleation site density. Qi and Klausner [13] also used a statistical model and fortuitously found very good agreement with the measured pool boiling nucleation site density for water on a brass surface. However, the same model grossly under-predicted the nucleation site density for water on a stainless steel surface.

The most surprising result from the Qi and Klausner [13] experiments is that they were successful in initiating nucleate boiling with ethanol on both brass and stainless steel surfaces at very low superheats (on the order of 10 °C) despite evidence that a high probability existed for flooding all surface cavities. These results suggested that the vapor trapping mechanism was not responsible for bubble incipience for these experiments. In order to explore this idea further, Qi and Klausner [3,13] polished both the brass and stainless steel surfaces to a mirror-like finish with an rms roughness on the order of 10 nm. It was again found that the incipient superheat for ethanol on these surfaces was on the order of 10 °C, and the nucleation site density curves were almost identical to those for the rough surfaces, thus providing very convincing evidence that another mechanism other than vapor trapping is available to initiate heterogeneous nucleate boiling for these surface/fluid combinations. In contrast, when heterogeneous nucleate pool boiling was attempted with ethanol on a silicon surface, the incipience superheat was found to be considerably higher, 60 °C. This superheat is near the homogeneous limit of ethanol, thus providing

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