Scaling of nucleate boiling rates from water to liquid helium I: wetting conditions on oxidized copper surfaces*

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Copper is a frequently used stabilizer substrate for metallic superconducting composites in magnets using low transition-temperature materials. Wetting effects, quantified by contact angle measurements, have been studied in water. The water data are used as a basis for scaling of nucleate boiling transport from high temperatures to the low boiling liquid He I (4.2 K).

Keywords: copper; helium; nucleate boiling

Similarity rules are known to account for vapour removal rates at the peak (critical) heat flux of nucleate boiling. Data are in good agreement with Kutateladze–Zuber type equations all the way from high boiling to low boiling liquids1,2. Contact angles of the vapour–liquid interface do not enter explicitly.

In contrast to vapour removal, the nucleate boiling characteristics are known to be influenced by wetting phenomena. Recent quantification of contact angle effects in water3,4 has resolved unknown details of oxide layer coverage of copper surfaces during nucleate boiling. If similarity constraints do apply, there ought to be an opportunity to scale down from water to He I nucleate boiling on the same surface. This study has the purpose of investigating this issue.

Nucleate boiling of water on copper

The system Cu–water has been studied at 1 atm using a vertical surface5. The static contact angle (Figure 1) has been used as a measure of the oxide layer thickness. A temperature–time protocol of heat treatment produces a well-defined oxide layer thickness. As seen in Figure 1, the oxide layer thickness is a monotonically decreasing function of contact angle \( \theta \) (or a monotonically increasing function of the angle \( 180 - \theta \)).

Figure 2 presents the resulting nucleate boiling characteristics at 1 atm. Heat flux (\( q \)) is plotted versus the temperature difference from the copper block to bulk saturated liquid. The heating surface is the vertical face of a copper cylinder with horizontal axis. The slope \( dq/d\Delta T \) appears to be only weakly affected by the contact angle. The derivative \( d \log q/d \log \Delta T \) is about 3.3. At a large contact angle, the temperature difference at a specific heat flux is small. As the angle is decreased, upon an increase of the oxide thickness, the temperature difference is enhanced. A negligibly small temperature difference exists across the oxide layer at the relatively high temperatures of the water experiments.

A better understanding of the contact angle effect on peak flux is related to the bubble population density. At low \( \Delta T \), a relatively smooth Cu surface has a high density. This is important for the peak flux. A vapour

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Figure 2 Effect of surface wettability on nucleate boiling on a copper surface in water at 1 atm

Bubble coalescence criterion invoked for the peak of nucleate boiling predicts a low peak flux since the population density cannot be increased significantly. In contrast, at the same q, a small contact angle leads to a significantly reduced population density. The oxide layer thickness is enlarged, and peak flux attained for bubble coalescence is increased noticeably. The coalescence criterion has also been incorporated in the work of Nishio et al. After recognition of these relationships it is of interest to inspect the low boiling liquid He I in the nucleate boiling mode at Cu stabilizers.

**Nucleate boiling of He I on copper**

First, we inspect (q/qp) for the horizontal and the vertical surface. Second, we consider the metastable liquid range and its limit at the spinodal (isothermal spinodal). If q p is the reference flux for the horizontal surface with heat flow up, we note that the peak on the vertical surface is reduced. For water the reference peak is 110 W cm⁻²; for He I it is only 0.8 W cm⁻². The q p ratio for the vertical-to-horizontal surface is retained in the subsequent scaled-down plot of q(AT) for He I.

The temperature difference is constrained by the spinodal which constitutes an upper bound to the T-distance from the binodal (=vapour pressure curve of vapour–liquid equilibrium). Figure 3 is a plot of the reduced spinodal temperature Tₛpr versus the reduced pressure P/Pₐ (Pₐ is the thermodynamic critical pressure). The figure shows that water has the highest spinodal, close to that of organic liquids. The cryogenic liquids are below the organic liquid range. The van der Waals spinodal is quite near the hydrogen data model. This agreement has to be considered fortuitous. It does not extend to other thermodynamic properties in general.

Figure 4 displays the q(ΔT) curves for He II as deduced from Figure 1 in the q-ratio scaling. As to the He I temperature difference, we note several constraints: dynamic data are given by Schmidt–Lin type equations. The case of relatively slow q-increase is exemplified by the Cu data of Bewilogua et al., Cummings and others (see Bald et al. comparison). The scaled-down temperature difference is shifted to reach the decreasing curve of reference 2. This feature shows important differences between He I and water: the slope d log q/d log ΔT is reduced in He I. Further, there is additional ‘contact’ resistance at transition domains. The total resistance (=generalized Kapitza resistance) is the sum of the oxide–He I interface domain, of the oxide layer, and of the oxide–bulk Cu interfacial domain. Aside from these Kapitza

Figure 3 Liquid superheat results versus reduced pressure: reduced maximum temperatures of experiments in metastable liquids; this set of values is considered representative (in its upper boundary) of the spinodal: ○ water; •, organic fluids; +, nitrogen; x, oxygen; ▲, hydrogen; ▼, neon; ●, helium; ○, helium[3]; ———, van der Waals spinodal.
resistances, the contact angle effect is predicted qualitatively in agreement with oxidized surface data for Cu—He I.

Conclusion

The He I $q$ values, scaled down from water, are in good agreement with experimental He I values. The scaled-down temperature differences, in terms of a fraction of the spinodal—binodal distance, are larger experimentally in He I than in water. The presence of various Kapitza resistance contributions associated with the oxide layer increases the He I $\Delta T$ observed on the solid Cu in comparison to water.

References

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Note added in proof

Very recent work suggests special precautions switching from water to He I because of adsorption at atmospheric pressure (Inman, J.S. and Roth, J.A. Vanderbilt Univ Nashville TN, The water adsorption characteristics of an oxidized Cu surface, AIChE Meeting, Nov. 1991, Los Angeles, paper 231). This contrasts with early work at vacuum conditions (Sharma, S. P. J Vac Sci Technol 1979 16 1557. A well defined protocol appears to be needed to obtain reproducible He I results for nucleate boiling on oxidized copper.