

Augmented boiling on copper-graphite composite surface

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Abstract—An experimental study is conducted to determine the nucleate pool boiling heat transfer performance of a copper-graphite (Cu-Gr) composite surface in Freon 113. The composite medium consists of ultra-high thermal conductivity graphite fibers of 0.0008–0.010 mm diameter being consolidated in a copper matrix (50% area fraction). It has high thermal conductivity along the fiber directions, several times those in the other two directions. The heating surface is constructed with a Gr-Cu composite plate of 25 mm diameter and 10 mm thick. The boiling heat flux in the nucleate regime is compared to isotropic pure copper used as the heating surface. It is disclosed that the boiling heat transfer coefficients on the composite surface are higher than those on the copper surface by a factor of over 6 to 3, respectively at lower and higher values of superheating. Hence, the composite surface may serve as a high heat flux boiling surface with the merits of no extra pressure drop, no fouling and low cost.

1. INTRODUCTION

THE DEVELOPMENT of high performance heat transfer surfaces is an important mission of heat transfer research. The immediate advantages of high performance surfaces are numerous: for example, more energy extraction or utilization from an energy source (especially low energy-density sources), more energy recovery from waste heat, efficient cooling of electronic components, compact and light weight which are important in vehicular applications, etc. It is well known that the practical use of the Sterling engine in automobiles is hinged on the size of heat exchangers and that the feasibility of an OTEC (ocean thermal energy conversion) plant for power generation is hampered by the size of its boiler and condenser.

The application for highly effective high heat flux surfaces for electronic chips (very large-scale integration, VLSI) cooling is required to keep pace with the evolving chip technology. Higher computer speeds require more circuit power packaged in smaller volumes. This will require improved heat transfer surfaces to deal with the higher heat flux requirements. Figure 1 [1] shows the trend of the heat flux at the module level in several computer systems. The success of nucleate boiling in these applications will be dependent on (1) how to initiate boiling, and (2) how to extend the burnout points. Bergles and Chyu [2] conducted research to assess boiling enhancement using various surfaces. Other researchers evaluated direct

applications of electronic chip cooling by attaching the high heat flux surface to the structure of the chip. For example, Nakayama *et al.* [3] investigated the boiling performance of heat sink studs with enhanced surfaces and Oktay *et al.* [4] reported high heat flux capability using a tunnel heat sink.

Rapid advances were made in the development of special nucleate boiling geometries since the early 1960s [5, 6]. Many potential measures have been suggested [7]. Today, six nucleate boiling geometries are commercially available [5]. Two basic approaches are

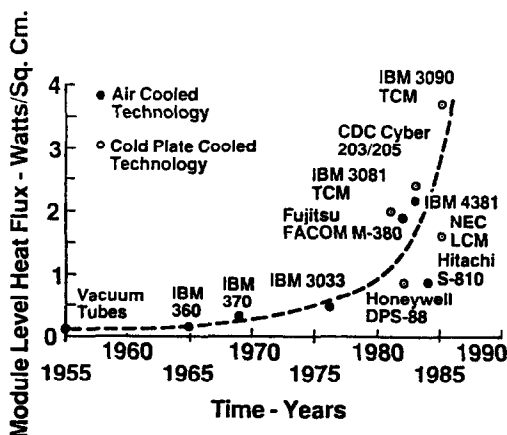


FIG. 1. The trend in heat flux at the module level [1].

NOMENCLATURE

<p>A heat transfer area [m²]</p> <p>h_b boiling heat transfer coefficient [W m⁻² K⁻¹]</p> <p>k thermal conductivity of Gr-Cu [W m⁻¹ K⁻¹]</p> <p>L distance between thermocouples [m]</p> <p>q rate of heat transfer [W]</p> <p>T temperature [°C]: T_l, of liquid; T_s, of heating surface; T_{sat}, saturate temperature</p>	<p>ΔT temperature difference [°C]: ΔT_x, between two locations at a distance of L; ΔT_s, $T_s - T_{sat}$.</p> <p>Subscripts</p> <p>f liquid</p> <p>s heating surface</p> <p>sat saturate liquid</p> <p>x local.</p>
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employed to form a high area density of nucleation sites: porous boiling surfaces (PBS) and integral 'roughness' surface (IRS). PBS consists of a sintered, porous, metallic matrix bonded to a base surface. The sintered porous coating is approximately 0.25 mm thick, with a 50–65% void fraction. The average pore radius ranges from 0.01 to 0.1 mm which functions as sites for generation of vapor bubbles. Union Carbide, Linde Division has developed such a PBS, called UC high flux surface [8]. In the case of integral roughness, the metal is cold worked to form re-entrant nucleation sites which are interconnected below the surface. The groove opening at the surface is a critical dimension, 0.0038–0.0089 mm for Refrigerant 11 [9]. The performance is sharply diminished for a gap width outside of this range. The preferred gap spacing is expected to be higher for high surface tension fluids. Thermoexel developed by Hitachi [10] is a surface formed from an integral-fin tube, which has small spaced contours at the fin tips. These 'saw tooth' fins are bent to a horizontal position to form tunnels with spaced pores at their top. The liquid in the tunnels is heated rapidly and changes to vapor which leaves through openings as bubbles. Part of the vapor always remains in the tunnels and thus, boiling occurs continuously. Another nucleate boiling roughness geometry by Weiland Werke A.G. is formed from standard 7.5 fins cm⁻¹ integral-fin-tubing [11]. However, the special surface geometries employed for enhancement of nucleate pool boiling generally cannot be applied to forced convection vaporization inside tubes, with the exception of the Linde PBS.

Similar to PBS, porous condensing surfaces (PCS) formed by attached metal particles have been developed for condensation of vertical tubes [12] and forced condensation inside tubes [13]. An array of small metal particles, 0.25–1.0 mm high, covers 20–60% of the surface [12]. In the case of condensation on vertical tubes, condensation occurs on the particle array (i.e. convex surfaces of the particles) and drains along the smooth base surface. In the case of forced condensation inside tubes, the spaced metal particles provide an extended surface at high vapor qualities and turbulence of the film at lower vapor qualities.

The use of PBS (and PCS in condensation) and IRS

suffers from the pressure drop (although relatively small), the loss of enhancement efficiency due to fouling (to plug up pores and re-entrant cavities) and, most important of all, the cost of fabrication and maintenance.

Several investigations have been conducted to evaluate the effect of isotropic surface thermal properties on boiling and condensation [14–18]. Recently, Wright and Gebhart [19] performed pool boiling experiments on vertical, smooth and regularly micro-configured etched silicon surfaces in saturated water at 1 atm. All specimens were 1.27 cm square and approximately 300 μ m thick. In the nucleate boiling regime, the hexagonally dimpled and trenched specimens had a heat transfer increase of a factor of 4.2 and 3.1, respectively, over that of the smooth specimens. However, the localized effect of an isotropic high thermal conductivity perpendicular to the surface has not been evaluated. The aim of this paper is to experimentally investigate nucleate pool boiling performance of advanced copper-graphite (Cu-Gr) composite surfaces. The boiling heat flux in the nucleate boiling regime is compared to isotropic pure copper used as the heating surface. In comparison with the conventional high heat flux boiling surfaces, the Cu-Gr surface causes no extra pressure drop, is free from fouling and benefits from low primary and maintenance costs.

2. FEATURE OF COPPER-GRAPHITE COMPOSITE

The graphite fiber reinforced copper (Gr-Cu) produced by SPARTA consists of graphite fiber of 0.008–0.010 mm diameter imbedded uniaxially within a copper matrix (50% area fraction). Figure 2 illustrates the photomicrographs of the surface. The higher fiber thermal conductivity is three times larger than the adjacent matrix conductivity. The fibers act as highly efficient pin fins that penetrate into the heat transfer surface. The effect of the local high conductivity fibers may be to enhance the conduction path into or away from the surface fluid and increase the surface nucleation site activity. The effect would be a thermal enhancement that is provided by tailored thermal

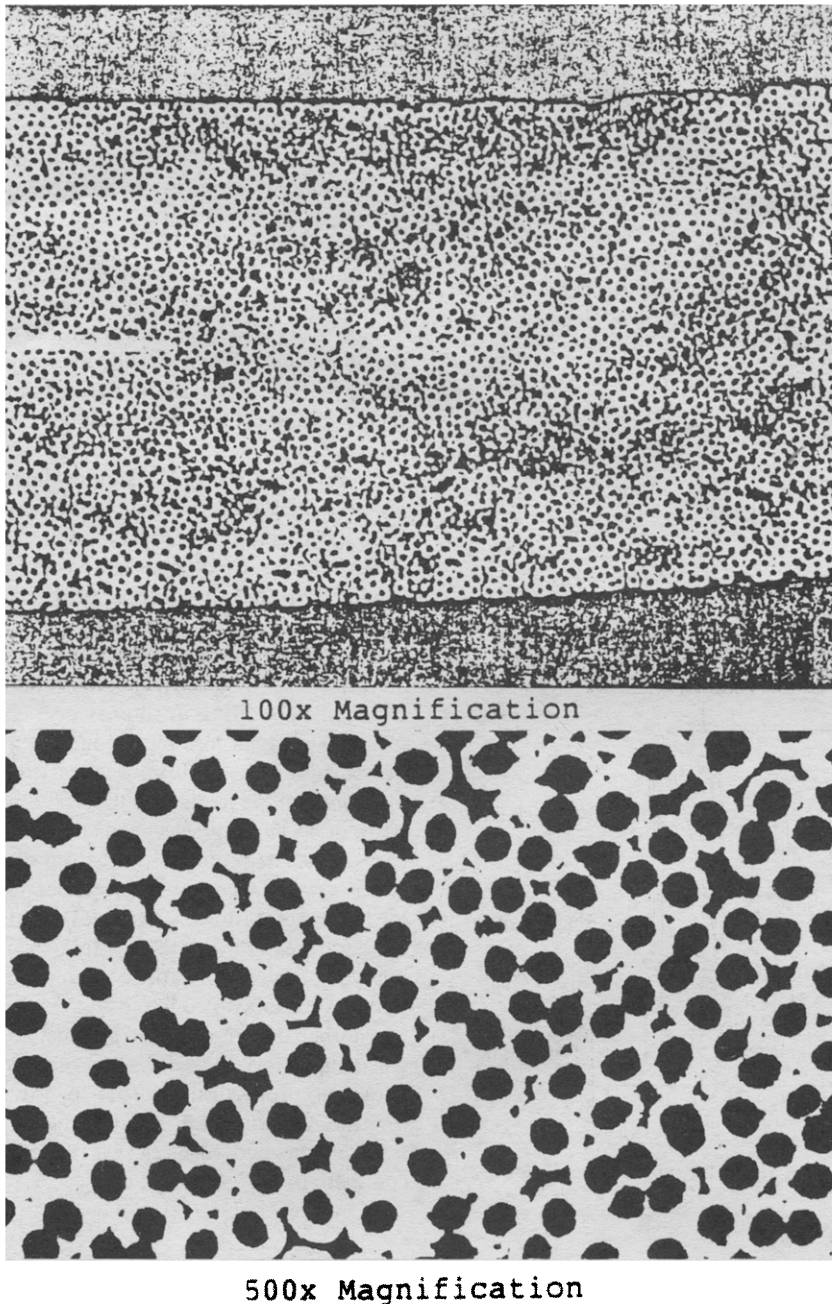


FIG. 2. Photomicrographs of the surface on a graphite fiber reinforced copper composite produced by SPARTA.

properties internal to the heat transfer surface. Key properties in the Gr-Cu composites include (i) high thermal conductivity in the fiber direction of up to $1200 \text{ W m}^{-1} \text{ K}^{-1}$ for the advanced pitch based graphite fiber, as compared with $401 \text{ W m}^{-1} \text{ K}^{-1}$ for pure copper at 300 K; (ii) low density at 6.14 g cm^{-3} , lighter than pure copper with 8.93 g cm^{-3} . Other unique aspects of this material are a modulus near 140 Msi and a negative coefficient of thermal expansion. By controlling both the directional layup and the volume fraction of the fiber, the directional conductivity, coefficient of thermal expansion, strength and stiffness

can be tailored to optimize the thermal/structural performance of the cooling concept.

The hypothesis is that the high thermal conductivity fiber (perpendicular to the boiling surface) may provide an intrinsic enhancement of heat transfer, bubble formation and departure frequency. The fiber diameter of 0.008 mm is comparable to the critical size for the bubble nucleation sites in boiling water. It is smaller than those of pores on pool boiling surfaces and re-entrant cavities on integral 'roughness' surfaces. Hence, each fiber tip on the surface may act as a site activator for bubble nucleation. The local

high thermal conductivity provides a more efficient conduction path to or from the surface nucleate site.

3. POOL BOILING APPARATUS AND TEST PROCEDURE

Figure 3 depicts a pool boiling experimental apparatus. The heating surface was constructed with a Gr-Cu composite plate 25 mm in diameter and 10 mm thick. Being polished with a 1 μm diamond abrasive, it was attached to a heating copper block of 25 mm

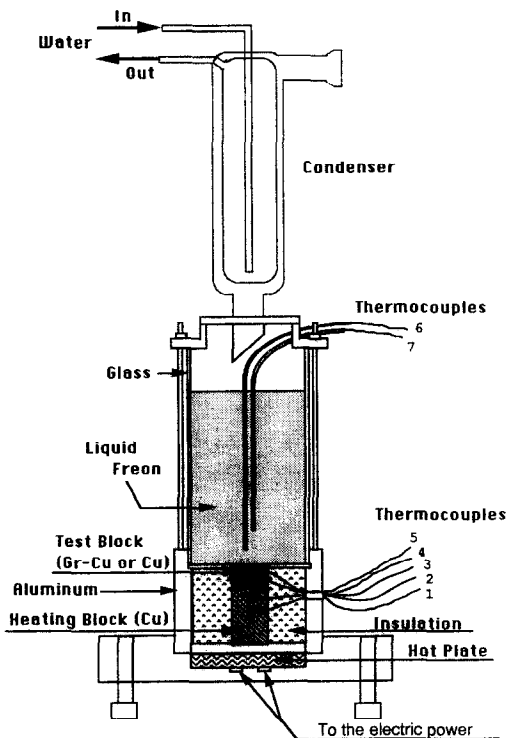


FIG. 3(a). A schematic of the pool boiling apparatus.

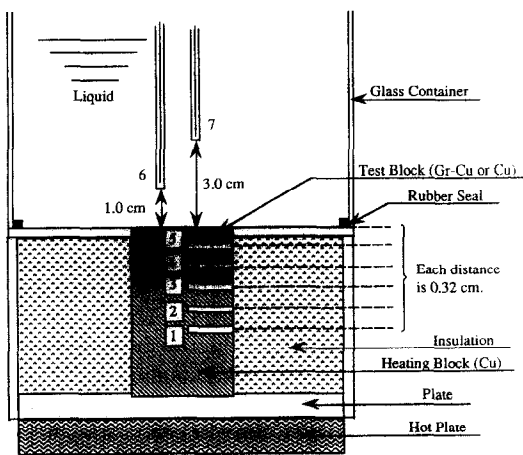


FIG. 3(b). Detailed information of thermocouple positions.

diameter and 41 mm long. The lower end of the copper block was in contact with an electrically heated hot plate. Three 30-gage copper-constantan thermocouples (Nos. 1, 2 and 3) were installed in the copper block at a 3.2 mm interval on the centerline, with one at the composite-copper interface. Two similar thermocouples (Nos. 4 and 5) were placed in the composite plate also at a 3.2 mm interval from its interface with the copper block. Their temperature measurements were used to determine the boiling surface temperature T_s through a linear extrapolation of T_4 and T_5 . The heat flux through the composite into the liquid was calculated using the temperatures from thermocouple readings and the distance between the thermocouples. Two 30-gage copper-constantan thermocouples (Nos. 6 and 7) measured saturated liquid temperatures (T_{sat}). A recorder/datalogger manufactured by Wahl Instruments, Inc., Culver City, California, was employed for temperature recordings.

Both the Gr-Cu composite and copper blocks were insulated around the surfaces in a glass container of circular cross section. The edge of the upper end of the composite block was undercut with a bevel and an undersize thin stainless-steel mating piece was attached by a shrink fit to provide a continuous surface to keep heat loss by conduction at a minimum. Power input (heat flux) was varied to cover the nucleate boiling regime. Freon 113 with a boiling point of 47.1°C was selected as the boiling liquid.

A condenser mounted on the top of the test-vessel cover served to condense the vapor formed. At the lower heat-flux rates, it was possible to control the temperature of the test refrigerant by varying the cooling-water flow rate and thus obtained limited data for boiling of a subcooled liquid.

Another experiment was conducted with the Gr-Cu composite replaced with a pure copper surface (isotropic properties) in order to provide a baseline for the experimental study. The only difference between the two surfaces was the internal thermal conductivity.

4. EXPERIMENTAL RESULTS

To the knowledge of the authors, this is the first experimental study of boiling on fiber reinforced composite surface. Two Gr-Cu surfaces and one pure copper surface were used to boil Freon 113. After filling the test vessel with Freon 113, power was turned on and the liquid was boiled rigorously for a period of time. The liquid depth at filling in all cases was 11 cm. The variation in T_{sat} resulted solely from the change in hydrostatic pressure with depth when the cooling-water rate was maintained constant. The liquid bulk temperature T_l or T_{sat} could be controlled by varying the cooling-water flow rate. The difference between T_{sat} and T_l is the degree of subcooling. In temperature recordings, which are not shown here, the temperature rise is nearly linear, begins to level off

at about 15 min and reaches a steady state at 20 min. Hence, at every change in the power input, the steady temperatures were read after a duration of 20 min.

In every test series, power input was raised from a low value to a maximum and lowered to the original value at the same power interval. Figure 4 reveals that the boiling heat transfer coefficient h_b underwent the phenomenon of hysteresis with h_b taking higher values for increasing ΔT_s than that for decreasing ΔT_s . Here, h_b is defined as

$$h_b = \frac{q}{A \Delta T_s} = \frac{k \Delta T_x}{L \Delta T_s}$$

where ΔT_s is the difference between the surface temperature T_s and the saturated liquid temperature T_{sat} , which was measured by thermocouple 7. k denotes the thermal conductivity of Gr-Cu which is $1000 \text{ W m}^{-1} \text{ K}^{-1}$ and the thermal conductivity of copper which is $401 \text{ W m}^{-1} \text{ K}^{-1}$. ΔT_x is the temperature

difference between two locations (thermocouples 4 and 5) at a distance of L (3.2 mm). Sometimes, the hysteresis loop is crossed over, as illustrated in Fig. 4(b).

Figure 5 shows the variation of ΔT_s with power input, which is a straight line for power exceeding 20 V. The variation is a concave curve at low power inputs, 0–20 V. The variation of h_b with power input is shown in Fig. 6. It is a straight line through the origin. The data scattering is approximately $\pm 100\%$ which can be partially attributed to gradual oxidation of the heater surface. Other factors which contribute to data scattering include subcooling, liquid depth and cooling-water rate.

The nucleate boiling heat transfer performance is depicted in Fig. 7, hollow squares for the Gr-Cu surface ($k = 1000 \text{ W m}^{-1} \text{ K}^{-1}$) and solid square for the pure copper surface ($k = 400 \text{ W m}^{-1} \text{ K}^{-1}$). The value of h_b for Gr-Cu is higher than that for pure copper by a factor of over 6 to 3, respectively at lower and higher values of superheating, ΔT_s .

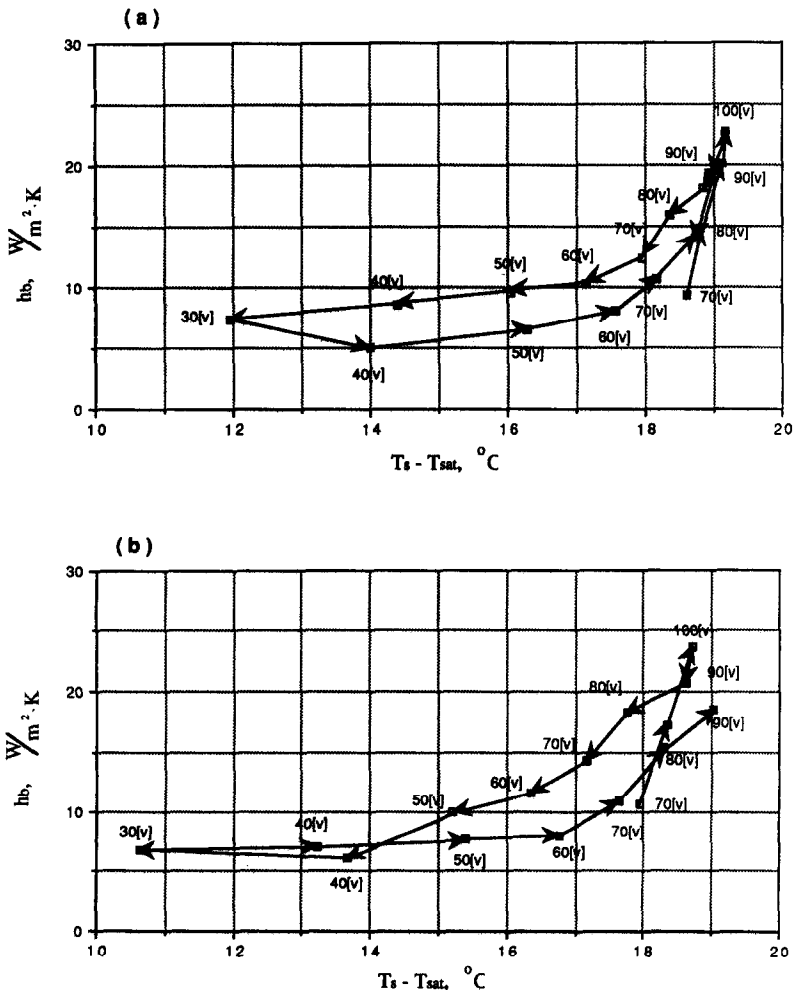


FIG. 4. Plots of h_b vs $T_s - T_{sat}$ for test cycles for a composite surface.

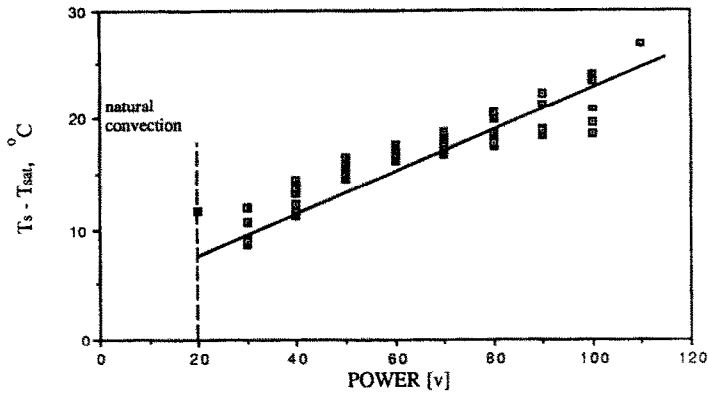


FIG. 5. Plots of $T_s - T_{sat}$ vs power for a composite surface.

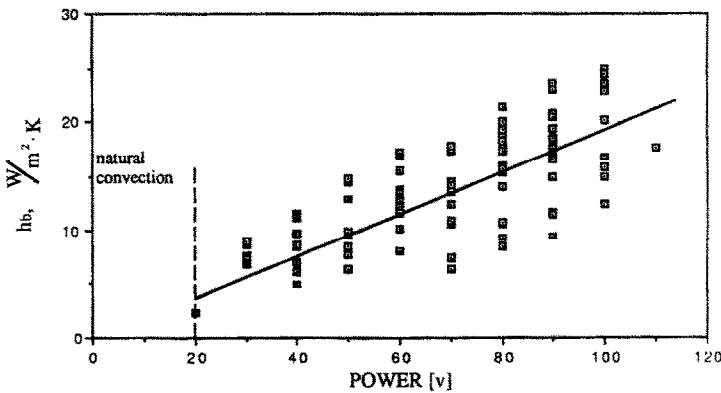


FIG. 6. Plots of h_b vs power for a composite surface.

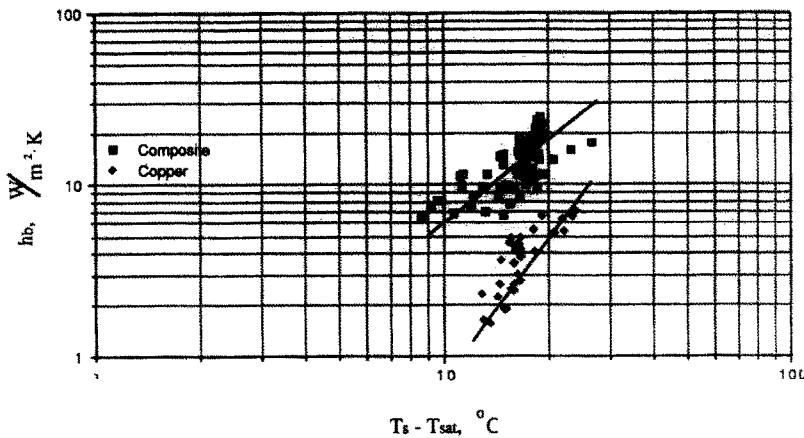


FIG. 7. Plots of h_b vs $T_s - T_{sat}$ for both composite and copper surfaces.

5. CONCLUSION AND REMARK

The reproducibility of test data for nucleate pool boiling of Freon 113 on the Cu-Gr composite surface is good, with large scattering. Like boiling of Freon 113 on a pure copper surface, oxidation occurs on the composite surface. It is revealed from this study that the nucleate boiling heat transfer coefficients on the

composite surface are higher than those on the pure copper surface by a factor of over 6 to 3, respectively at lower and higher values of superheating. The disclosure warrants more studies on the nucleate boiling heat transfer of other liquids on the composite surface.

An attempt was made during the study to investigate the hypothesis that each tip of the high thermal conductivity fiber on the surface may act as a site

activator for bubble nucleation. However, the nucleation of too many bubbles on the surface made it impossible to match nucleation sites with fiber tips. A future study is planned to prove the hypothesis using a surface with only a few fibers. Upon the validation of the hypothesis, the nucleation site cavity can be enhanced by selective tailoring of the internal characteristics of the boiling surface.

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EBULLITION ACCRUE SUR UNE SURFACE COMPOSITE CUIVRE-GRAPHITE

Résumé—Une étude expérimentale est conduite pour déterminer les performances de transfert thermique par ébullition nucléée d'une surface composite cuivre-graphite (Cu-Gr) dans du Freon 113. Le milieu composite en fibres de graphite à très haute conductivité thermique de 0,0008–0,010 mm de diamètre, dans une matrice de cuivre (50% de fraction d'aire). La conductivité thermique dans les directions des fibres est plusieurs fois celles dans les deux autres directions. La surface de chauffage est construite avec une plaque composite Cu-Gr de 25 mm de diamètre et de 10 mm d'épaisseur. Le flux thermique dans le régime nucléé est comparé au cas du chauffage en cuivre pur. Les coefficients de transfert sur la surface composite sont plus grands d'un facteur entre 6 et 3 par rapport au cuivre pur, respectivement pour la plus faible et la plus forte valeur de surchauffe. La surface composite peut servir comme surface à haut flux à l'ébullition avec les avantages d'aucune perte de pression supplémentaire, d'aucun encrassement et d'un coût faible.

INTENSIVIERTES SIEDEN AN EINER GRAPHITDOTIERTEN KUPFEROBERFLÄCHE

Zusammenfassung—Der Wärmeübergang beim Behältersieden an einer graphitdotierten Kupferoberfläche (Gr-Cu) wird mit R113 experimentell untersucht. Dieses Material besteht aus Graphitfasern von extrem hoher Wärmeleitfähigkeit und Durchmessern im Bereich 0,0008–0,010 mm, die in eine Kupfermatrix eingelagert sind (50% Flächenanteil). Die Wärmeleitfähigkeit in Längsrichtung der Faser ist mehrfach größer als in die beiden anderen Richtungen. Die Heizfläche besteht aus einer Gr-Cu Platte mit 25 mm Durchmesser und 10 mm Dicke. Die Wärmestromdichte bei den Blasensiederversuchen ist von gleicher Größenordnung wie diejenige bei einer isotropen reinen Kupferplatte. Es zeigt sich, daß die Wärmeübergangskoeffizienten an der neuen Platte um einen Faktor 3–6 größer sind als diejenigen an der Kupferoberfläche, was einer geringeren bzw. größeren Überhitzung entspricht. Die neue Oberfläche kann deshalb als Hochleistungssiedefläche dienen mit folgenden Vorteilen: kein zusätzlicher Druckverlust, keine Verschmutzung und niedrige Kosten.

ИНТЕНСИВНОЕ КИПЕНИЕ НА ПОВЕРХНОСТИ КОМПОЗИТА МЕДЬ–ГРАФИТ

Аннотация—Проводится экспериментальное исследование с целью определения характеристик теплопереноса при пузырьковом кипении в большом объеме, вызванном композитом медь–графит, помещенным в хладагент 113. Композитная среда состоит из обладающих сверхвысокой теплопроводностью графитовых волокон диаметром 0,0008–0,010 мм, отвердевающих в медной матрице (доля их площади составляет 50%). Матрица имеет высокую теплопроводность в направлении волокон, которая в несколько раз больше, чем в двух других направлениях. Поверхность нагрева представляет собой пластину из композита диаметром 25 мм и толщиной 10 мм. Тепловой поток при кипении в пузырьковом режиме сравнивается со случаем изотропной чистой меди, используемой в качестве поверхности нагрева. Показано, что коэффициенты теплопереноса при кипении на композитной поверхности превышают полученные для медной поверхности более, чем в 6 и 3 раза соответственно при низких и высоких значениях перегрева. Следовательно, композитная поверхность может служить поверхностью кипения при большом тепловом потоке благодаря таким преимуществам, как отсутствие избыточного перепада давления и погрешностей измерений приборов, а также низкие затраты.