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Nucleate pool boiling heat transfer in a highly wetting liquid on micro-graphite-fiber composite surfaces

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Abstract—This paper presents results of an experimental study on heat transfer enhancement in nucleate pool boiling of a highly wetting liquid, pentane, on graphite fiber composite surfaces. Two kinds of composites are investigated: graphite–copper (Gr–Cu) consisting of graphite fibers in a copper matrix and graphite–aluminum (Gr–Al) consisting of graphite fibers in an aluminum matrix. Micro-graphite fibers of 8–10 μm in diameter are embedded in the matrices with fibers being arranged perpendicular to the boiling surface. The highly wetting liquid has a nominal contact angle of between 2 and 4° of most known surfaces. Pool boiling heat transfer performances of the graphite composites are compared with those of pure metal surfaces in the hysteresis region, which is commonly encountered within boiling startup periods, and the developed boiling region in which the overall performance is determined. It is revealed that the presence of graphite fibers reduces hysteresis effects in the startup region and also enhances overall performance in the developed region. In the hysteresis region, hysteresis temperatures are reduced more on the Gr–Al surface than on the Gr–Cu surface. In the developed boiling region, however, the heat transfer performance is enhanced more on the Gr–Cu surface than on the Gr–Al surface.

INTRODUCTION

In recent years, considerable effort has been directed toward the investigation of immersion boiling heat transfer associated with highly wetting liquids. These studies were motivated mainly by two factors: one is that highly wetting liquids, such as the 3M's FC family and Dupont's Freons, are considered suitable for immersion cooling as a means of thermal control of microelectronic components because of their high dielectric strength, and because they are chemically inert, environmentally safe, and nontoxic. The other factor is that the loss of heat transfer performance due to thermal hysteresis phenomenon during boiling startup impedes the practical application of immersion cooling in the electronic industry [1]. This is mainly because of low surface tension and near-zero static contact angles of these liquids interfering with the trapping and preservation of vapor in the surface. As a result, a superheat of 20–30°C is commonly encountered. The stringent operating temperature limits on microelectronic devices show a reduction by half in reliability for every 10°C increase in junction temperatures. Composite surfaces for immersion boiling were proposed to cope with this shortcoming, and were first investigated by Blagojevic *et al.* [2]. It was discovered that heat flux on a non-isothermal surface was less sensitive to surface temperature variations in the critical heat flux region. Recently, the use of high thermal conductivity (1200 W m^{-2} °C) micro graphite-fibers as energy extractors has attracted considerable interest [3]. Since 1992, research has been focused on improving nucleate pool boiling heat transfer performance on graphite–copper (Gr–Cu) composite surfaces with highly wetting liquids. It was disclosed that the use of micro-composites has practical advantages that include: less fouling, reduced sensitivity of the critical heat flux to excess temperature variations [4], augmented boiling heat transfer performance of up to six times [5], and suppression of undesired thermal hysteresis during the startups [6]. Figure 1 depicts a micro-configuration of a composite surface with micro graphite-fibers of 8–10 μm diameter imbedded in a copper matrix magnified 3000 times. It shows that on the composite each fiber tip appears as a plateau with a rugged surface, while the valleys (matrix material surface) between the plateaus are filled with a large number of microsized low-lying trenches and intermingled narrow grooves. This micro-configuration acts as nucleation sites among which the fibers role like fins promoting efficient heat dissipation through the entire composite structure. The process required for the bubble growth-departure cycle was found to be substantially reduced [7].

In the present study, an experiment is carried out on nucleate pool boiling in a highly wetting liquid, pentane, on both graphite–aluminum (Gr–Al) and graphite–copper (Gr–Cu) composites with a fiber

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NOMENCLATURE

A_{hys}	hysteresis area [W °C cm^{-2}]	q/A	heat flux, W m^{-2} in equation (1) [W cm^{-2} elsewhere].
c	thermal capacity [J kg^{-1}]		
C	coefficient in equation (1)		
f_h	hysteresis boiling curve	Greek symbols	
f_n	normal boiling curve	ΔT	wall superheat [°C]
Gr–Al	graphite–aluminum composite	ΔT_{max}	maximum wall superheat of hysteresis curve [°C]
Gr–Cu	graphite–copper composite		
k	thermal conductivity [W (m °C)$^{-1}$]	ΔT_{min}	minimum wall superheat of a hysteresis curve [°C]
MRHF	minimum restart heat flux		
n	exponent in equation (1)	ρ	density [kg m^{-3}].

volume concentration of 50%. A pure aluminum and a pure copper surface are also tested for comparison. The liquid, pentane, has a nominal contact angle of between 2 and 4° on most known surfaces. Emphasis is placed on two items: (a) overall boiling heat transfer performance, pertaining to the fully developed boiling region at heat fluxes of up to 35 W cm^{-2}, and (b) boiling hysteresis, which is important during the onset of boiling. The research demonstrates that the presence of graphite fibers in the boiling surfaces results in a substantial enhancement in nucleate pool boiling heat transfer performance.

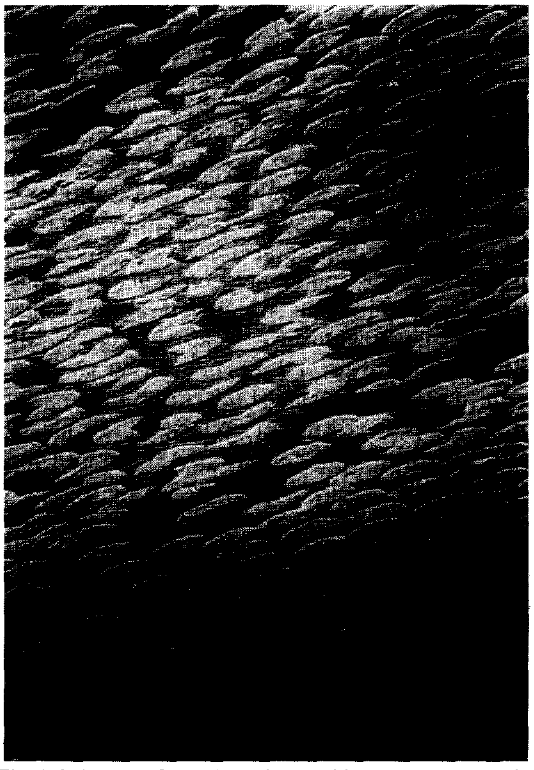

Fig. 1. Micro-configuration of a graphite–copper composite surface.

EXPERIMENTAL SYSTEM

Experimental facility

The pool boiling test facility is illustrated in Figs. 2 and 3. Its major components included a heat source assembly, test boiling surface, boiling vessel, condenser assembly, and data acquisition system. An aluminum rod was used to conduct heat from the cartridge heater (heat source) to the Gr–Al or pure aluminum specimen, while a copper rod was used for testing the Gr–Cu or pure copper specimen. The boiling surface, which was 2.54 cm in diameter and 1.0 cm in thickness was placed on top of the heat source assembly. K-type thermocouples were employed to measure the temperatures along the heat transfer path. Heat loss was monitored by placing thermocouples on the conducting rod. Heat fluxes and boiling surface temperatures were determined from these thermocouple measurements using the Fourier conduction law through linear extrapolation taking into account heat loss. The boiling vessel assembly, shown in Fig. 2, consisted of a glass boiling vessel, auxiliary heater, inner glass sleeve, and two optical windows for visualization. The auxiliary heater, in close contact with the outer surface of the glass vessel, was used to maintain the test liquid at saturated conditions. The inner glass sleeve isolated convective waves produced by the auxiliary heater. The test liquid level was maintained at 8 cm above the boiling surface. Thermocouples were placed at 1 cm and 4 cm from the boiling surface to measure the bulk temperature of the test liquid. The vapor generated during the boiling process was recovered in the condensers by cooling water. The condensate was collected in the condensate collector and returned by gravity through the condensation line to the boiling vessel, thus forming a close loop. In order to maintain the pressure inside the experimental apparatus at atmospheric pressure, the top of the Liebig condenser was open to the atmosphere.

A precision digital multimeter (Keithley Instruments, model 196) was used to read voltage outputs from the thermocouples. It has an accuracy of 0.005%

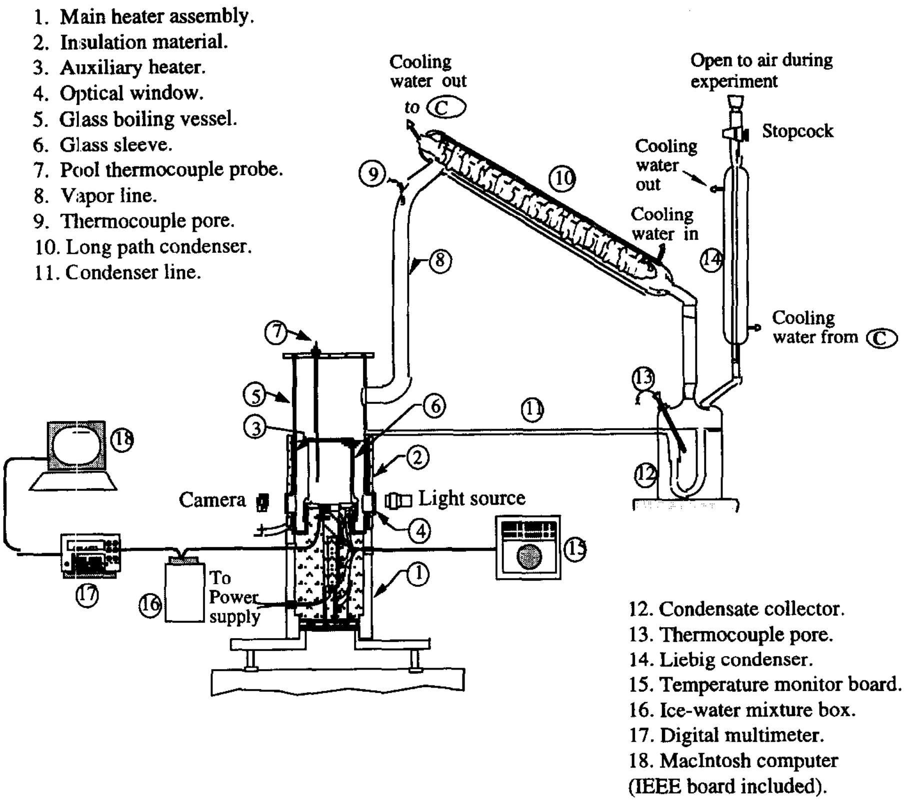

Fig. 2. Nucleate boiling apparatus.

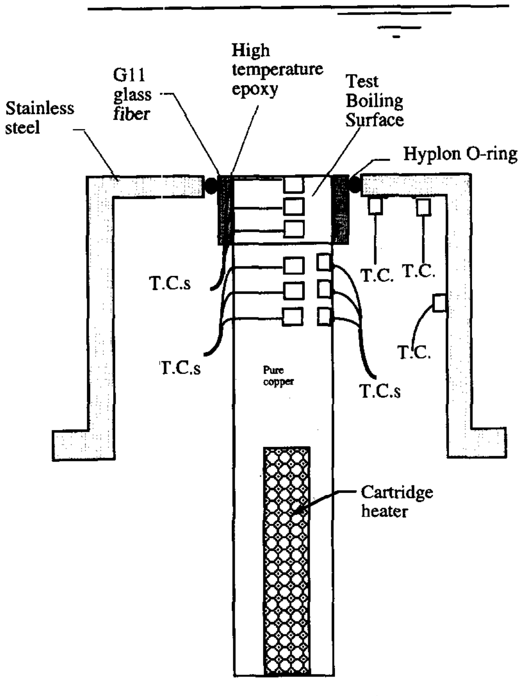

Fig. 3. Detailed drawing of boiling surface assembly.

in this pool boiling experiment. All thermocouples were calibrated using a platinum resistance thermometer. The uncertainty of temperature difference measurements along the conducting rod, including calibration and instrumentation errors, was estimated to be within 0.05°C. The impact of temperature difference measurement error on heat flux measurement ranges from 37% at low heat flux level (natural convection) to 2.1% at high heat flux (fully developed nucleate boiling) by means of the Kline and McClintock's method [8]. The reason for such a large variation in heat flux measurement uncertainty is mainly due to the relatively large conduction heat loss from the rod in the natural convection region compared to that at nucleate boiling. More details of the uncertainty analysis can be found in Liang [9].

Test procedure

The tested boiling surfaces included two micrographite composites, Gr–Al and Gr–Cu, a pure aluminum and a copper reference surface. Two kinds of experiments were conducted : overall boiling performance and boiling hysteresis during startup/restart.

Overall boiling performance. After boiling vigorously for 20 min for degassing, the heater was turned off and the system was sealed by turning off the stopcock of the Liebig, allowing the test liquid to cool down to the room temperature. Subsequently, the auxiliary heater was used to heat the test liquid to the saturated temperature followed by gradually turning up the cartridge heater to a preset voltage level. Temperature measurements started after both the test piece and the conducting rod reached steady state, which was confirmed by time invariance of the thermocouple readings. The waiting period for steady state in each test varied from 15–30 min. The power supply to the cartridge heater was gradually raised for a subsequent test with a higher heat flux. The process was repeated to cover the entire vapor mushroom region to complete an overall boiling curve.

Boiling hysteresis during startup/restart. Simulation of the effect of different restart conditions was first proposed by You *et al.* [10]. Here, the procedure used in hysteresis tests was similar to that for overall performance tests but with a slight difference. After degassing, the start-up/restart hysteresis simulation experiment began with a stepwise heat-up process from zero heat flux to a fully established nucleate pool boiling state. This was followed by a stepwise cool-down process to a desired minimum preset power output, and then a restart to begin an increasing heat flux cycle. The minimum power output, called minimum restart heat flux (MRHF), was maintained for about one hour in order to stabilize the nucleation sites.

In order to ascertain repeatable surface conditions, the heating surface was polished using an identical procedure. The test element was first polished on a polishing wheel using 320, 400, 600, and 1500 grades of silicon carbide sand paper (Mager Sci.). Then a 6 μm diamond abrasive compound (Mager Sci.) was employed to polish the element on a grinder polisher with Mager's Nylon polishing cloths, followed polishing with a 1 μm diamond abrasive compound to obtain the final desired mirror-like surface finish. Prior to each test, the element was polished by the 1 μm diamond abrasive compound to remove any oxidation, deposition, or contamination.

RESULTS AND DISCUSSIONS

The overall boiling performance curves, illustrated in Fig. 4, begin with a heating process from zero heat flux, then enter the single-phase natural convection region, and complete with a fully established nucleation boiling state. The entire vapor mushroom region is covered. The maximum heat flux reached here is about 35 W cm^{-2}.

The normal nucleate boiling curves, represented by dash–dot lines in Figs. 5a–d, were derived from two hours of fully established nucleate boiling at approximately 15 W cm^{-2}, followed by a stepwise reduction in power output to zero heat flux. The startup/restart hysteresis at various values of the MRHF is defined as a deviation between a normal boiling curve and its corresponding heat-up cycle. A series of consecutive cool-down/heat-up cycles constituted a test which took about 72 h without fouling or deposits formed. Experiments were conducted three to six times on each specimen with random cool-down/heat-up cycles. Figures 5a–d illustrate averaged results calculated from these replicate runs.

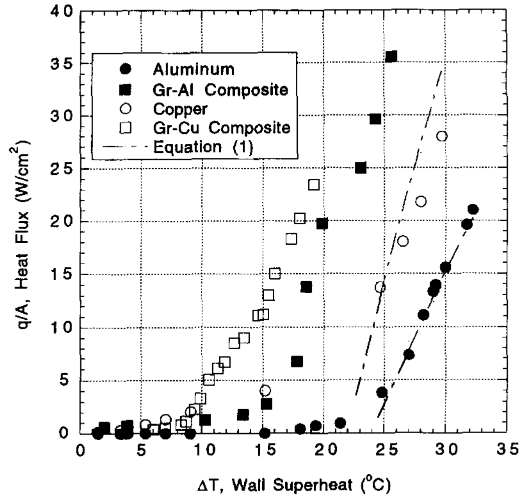

Fig. 4. Comparison of overall boiling performance among aluminum, copper, graphite–aluminum, and graphite–copper.

Comparison of overall performance

Figure 4 correlates heat flux vs. wall superheat data for both the graphite–aluminum (Gr–Al) and graphite–copper (Gr–Cu) composites as well as the pure aluminum and copper reference surfaces. It is seen that the Gr–Cu composite gives the highest boiling heat transfer coefficient, while the lowest one is found on the aluminum surface with the Gr–Al and the pure copper surfaces lying in between. This enhancement in boiling heat transfer performance on the composites is attributed to the micro-graphite fibers embedded in the matrix. Indeed, the presence of micro-graphite fibers results in an increase in heat dissipation and a reduction in surface superheat values of about 10°C on both copper-base and aluminum-base surfaces. The enhancement is due to higher thermal conductivity of graphite fibers and the higher temperature at the fiber tips (fin effects) than the surrounding base matrix. The spots on the fiber tip with higher temperature can serve as 'potential' nucleation sites which can be activated at a lower excess surface-averaged temperature, expediting the commencement of nucleation.

The difference in the boiling curves between the pure aluminum and pure copper surface reflects a variation in the thermophysical properties of the boiling surface materials. However, thermal properties alone cannot explain the mechanism. It is known that

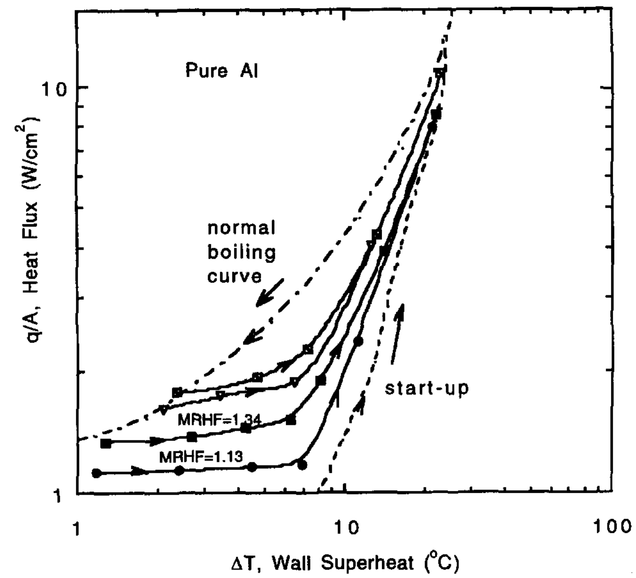

Fig. 5a. Start-up/restart hysteresis on pure aluminum surface.

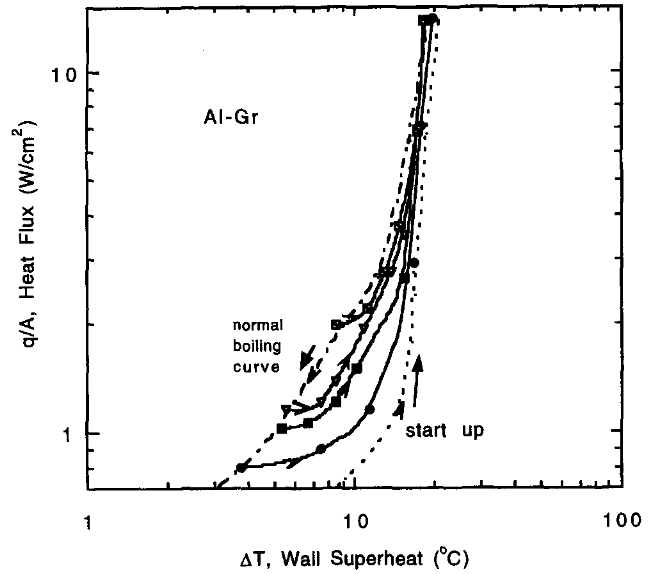

Fig. 5b. Start-up/restart hysteresis on 50% Gr–Al composite surface.

boiling heat transfer performance is, to a great extent, determined by surface micro-texture and wetting conditions. In the present study, the former factor can be eliminated through polishing the test surface with an identical procedure prior to each run, while the latter can be neglected with the use of pentane which is a highly wetting liquid. In turn, this implies that heat transfer dissipation depends substantially on the thermal properties of the heating surface, in agreement with the observations of Magrini and Nannel [9] under different experimental conditions. Taking into consideration the factors affecting nucleate pool boiling, an empirical correlation modified from Magrini and Nannel [9] is proposed:

$$\Delta T = C\left(\frac{q}{A}\right)^{n}\left\{1+\frac{4\times 10^{4}}{\sqrt{(k\rho c)_{s}}}\right\}^{0.75}. \qquad (1)$$

Here, ΔT is the wall superheat in °C; q/A, heat flux in W m^{-2} °C; and $(k\rho c)_s$, heating surface effusivity. The magnitudes of the coefficient C and the exponent are changed from the original values to account for the present experimental conditions as 0.75 and 0.2, respectively, for the pure metal surfaces. Figure 4 plots

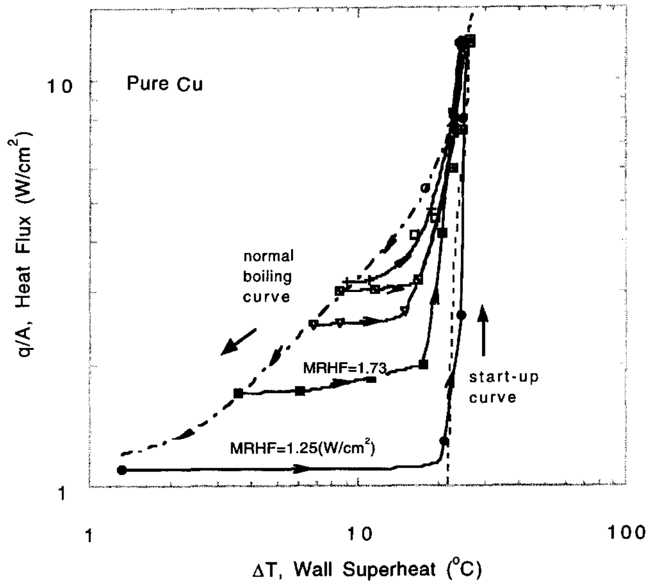

Fig. 5c. Start-up/restart hysteresis on pure copper surface.

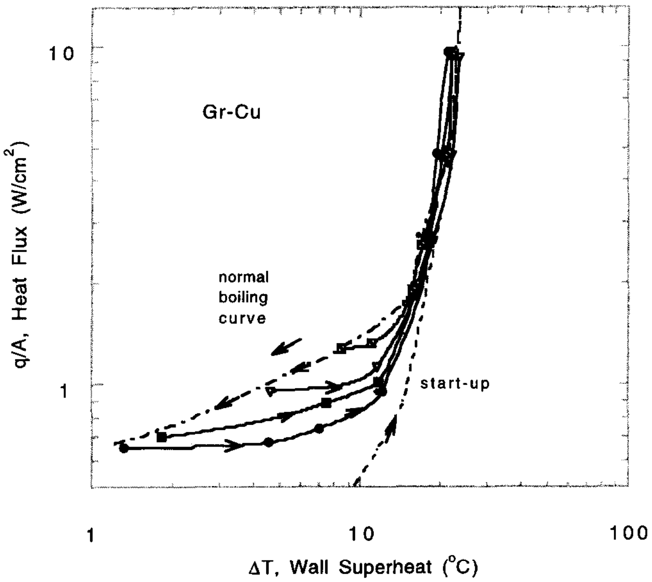

Fig. 5d. Start-up/restart hysteresis on 50 percent Gr–Cu composite surface.

heat flux q/A against the wall superheat ΔT with equation (1) being superimposed for comparison. The test data agree satisfactorily with equation (1).

Boiling hysteresis during startup/restart

A reduction in hysteresis for nucleate pool boiling on the copper matrices with micro-graphite fibers was first investigated in 1996 [6] for copper matrices with various graphite fiber contents. The mechanisms for the hysteresis reduction can be summarized as follows: (1) according to embryo theory, more micro-cavities of correct size, about 0.05–0.1 μm, are formed for nucleation on graphite fiber tips than on pure material surfaces. They can be easily activated to form nuclei. (2) With a higher temperature on the fiber tips than on the base material, and with an easier activation, nucleation during the start-ups tends to be activated on the fiber tips at a relatively lower surface-averaged temperature. Similarly, during cool-down processes most cavities on the pure material surfaces are drowned and thus lose the nucleation sites, while locally higher temperature graphite fiber tips will retain enough effective nuclei to act as nucleation seeds for the next process. (3) The poorly-wetted fiber tips prevent the vapor in the cavity from being flooded by the intruding liquid when immersed.

Two additional materials, Al–Gr composite and pure aluminum, were tested for comparison with the copper-base materials. Figures 5a–d illustrate hysteresis curves of pure aluminum, Gr–Al composite, pure copper, and Gr–Cu composite, respectively. It is revealed that the extent and characteristics of hysteresis are quite different among the four surfaces, pure materials as well as composites. Generally speaking, the boiling curves of the pure specimens change abruptly at a certain wall superheat, as evidenced by an abrupt change in the q/A–ΔT gradient. In contrast, the micro-graphite composites demonstrate a moderate transition, as evidenced by a gradual change in the slope from single-phase natural convection to nucleate boiling process. In order to provide a quantitative description of boiling hysteresis, those curves in Figs. 5a–d were replotted to determine the maximum temperature overshoot and the hysteresis area. The maximum temperature overshoot is defined as the temperature at an intersection of the tangent to the single phase convection curve with nucleate boiling curves, while the hysteresis area is defined as

$$A_{\mathrm{hys}} = \int_{\Delta T_{\mathrm{min}}}^{\Delta T_{\mathrm{max}}} [f_{\mathrm{normal}}(T) - f_{\mathrm{hysteresis}}(T)]\,\mathrm{d}T.$$

Here, ΔT_{min} is the minimum wall superheat of a minimum restart heat flux (MRHF) and ΔT_{max} denotes the intersection between the restart hysteresis and the normal boiling curve, as schematically illustrated in Fig. 6. Figures 7 and 8 show the minimum restart heat flux plotted against the maximum temperature overshoot and hysteresis area (A_{hys}), respectively.

It is seen in Figs. 7 and 8 that in the case of the pure copper surfaces, both the maximum temperature overshoot and hysteresis curves experience an abrupt fall at the MRHF of approximately 3.0 W cm^{-2}, signaling a near termination of hysteresis phenomena. This implies that both A_{hys} and $T_{\mathrm{TOS,MAX}}$ diminish with an increase in MRHF and that beyond the MRHF of 3.0 W cm^{-2} all nucleation sites become activated. Compared to the MRHF of 3.0 W cm^{-2} for pure copper, a lower value of 2.2 W cm^{-2} is found for pure aluminum. On the other hand, boiling hysteresis terminates at an MRHF of 1.2 W cm^{-2} on the Gr–Cu composite, while it terminates at a higher MRHF of 2.0 W cm^{-2} on the Gr–Al composite.

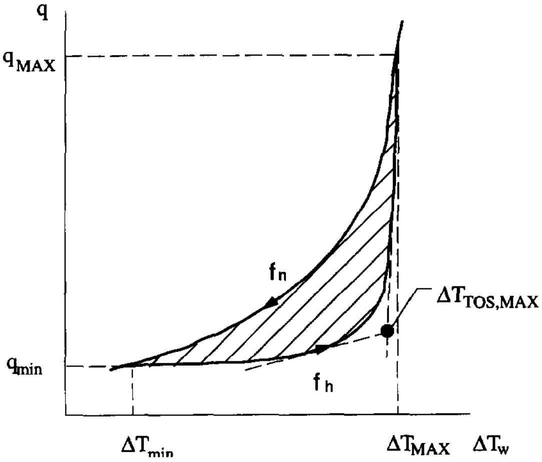

Fig. 6. Definition of hysteresis area.

One cannot draw a conclusion from an examination of hysteresis curves which composite surface is superior in reducing undesirable hysteresis phenom-

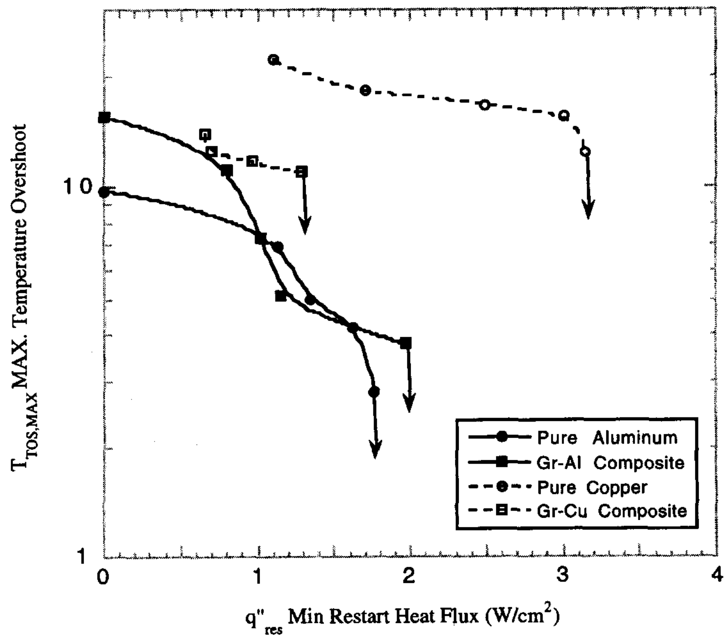

Fig. 7. Hysteresis temperature (maximum temperature overshoot) vs. minimum restart heat flux.

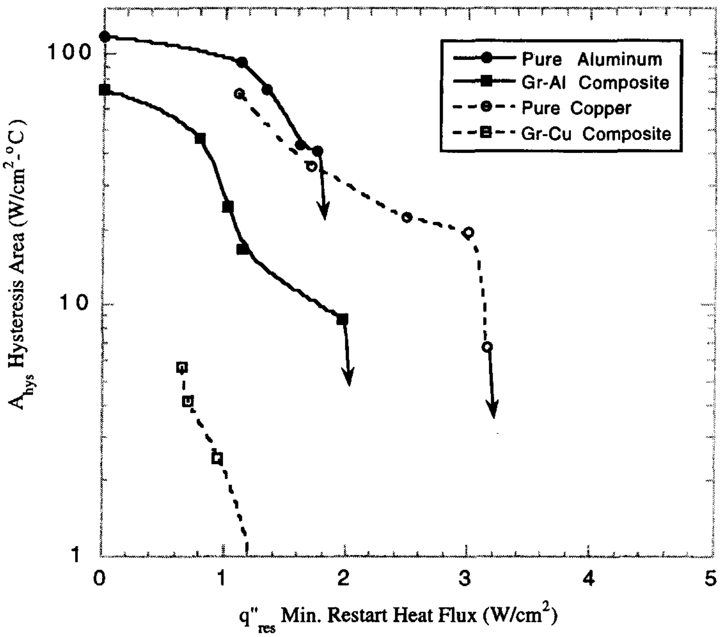

Fig. 8. Hysteresis areas vs. minimum restart heat flux.

ena. For example, Fig. 7 suggests the Gr–Al composite to be better than the Gr–Cu composite because of a lower maximum hysteresis temperature overshoot at a desired minimum restart heat flux. On the other hand, Fig. 8 indicates that Gr–Cu composite to be superior to its counterpart based on a lower value of the hysteresis area at the same minimum restart heat flux.

CONCLUDING REMARKS

An experimental study has been performed to study nucleate boiling in pentane, a highly wetting liquid, on two micro-graphite composite surfaces and pure metal surfaces to determine fully developed pool boiling performance and hysteresis phenomena at boiling startups. It was found that the heat transfer coefficient is enhanced in the presence of micro-graphite fibers: highest on the Gr–Cu composite and lowest on the aluminum surface with the Gr–Al composite and the pure copper in between. The presence of micro-graphite fibers results in an enhancement in heat dissipation and lower surface superheats compared to the pure metal surfaces. The mechanisms of such an enhancement have been found to be: (1) a relatively higher temperature forms on the fiber tips due to the higher thermal conductivity of micro-graphite fibers resulting in the shortening of the bubble nucleation period, (2) a large number of embryo cavities of correct size are formed on the graphite fiber tips thus activating nucleation at a lower surface superheat, and (3) the poorly-wetted property of graphite fibers prevents the vapor in the cavity from being flooded by an intruding liquid once immersed.

A modified empirical correlation of Magrini and Nannel [9]

$$\Delta T = C\left(\frac{q}{A}\right)^n \left\{1+\frac{4\times 10^4}{\sqrt{(k\rho c)_s}}\right\}^{0.75}$$

is proposed to correlate the ΔT–q/A relation of both pure metal surfaces.

The boiling startup/restart hysteresis at various maximum-restart-heat-fluxes (MRHFs) is defined as a deviation between the normal boiling curve and the corresponding heat-up cycle. This hysteresis is diminished at the MRHF of 3.0 W cm^{-2} on the pure copper, 2.2 W cm^{-2} on the pure aluminum, 2.0 W cm^{-2} on the Gr–Al composite, and 1.2 W cm^{-2} on the Gr–Al, respectively. The parameters, maximum temperature overshoot and hysteresis area, have been employed to quantify the extent in the reduction of hysteresis. Based on the maximum hysteresis temperature, the Gr–Al composite is found to be superior in the reduction of hysteresis, while the Gr–Cu composite is better based on the hysteresis area.

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