A Technique for Enhancing Boiling Heat Transfer with Application to Cooling of Electronic Equipment

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Abstract—Particle layering is introduced as an effective and convenient technique for enhancing boiling nucleation on a surface. Because it can be applied without stress or damage to a surface, it may be implemented in immersion cooling, with boiling, of electronic equipment components. Such an enhanced surface, which has an increased number of nucleation sites, shows a decreased level of wall superheat under boiling and an increased critical heat flux (CHF) relative to superheat and CHF values for an untreated surface. Application of this technique results in a decrease of heated surface temperature and a more uniform temperature of the heated surface; both effects are important in immersion cooling of electronic equipment.

I. INTRODUCTION

The ever-increasing heat flux from electronic devices, expected to increase more rapidly in the near future, has driven the electronic cooling community toward efficient cooling technologies. A prominent cooling scheme for accommodating high power dissipation is immersion cooling with dielectric fluids such as Fluorinert (FC series by 3M) and chloro-fluorocarbons (e.g., R-113). Boiling, rather than single-phase heat transfer, may become necessary because of the high heat fluxes expected in future electronic devices. Boiling is attractive for this application also, because it yields a far more uniform temperature distribution across an array of chips on the surface.

Realizing the importance of surface microgeometry in boiling heat transfer, many have investigated special surfaces for boiling enhancement, such as sintered or flame-sprayed porous coatings [1], [2]. Others have tested mechanically grooved/finned surfaces, such as the spiral grooves, as in the original Gewa surface, and re-entrant, large diameter cavities, as in the High Flux, Thermoeorex-E and Gewa-T surfaces — Marto and Lepere [3]. Others have used dendritic surfaces [4], [5], surfaces with laser drilled holes [6] and sandblasted and KOH (potassium hydroxide) etched surfaces [7]. While these techniques, when applied in more conventional applications, have demonstrated the ability to reduce wall superheat values and to increase the critical heat flux under certain conditions, none of the above techniques, nor any others available today, have proven acceptable for use on bare semiconductor chips which are to be immersed in dielectric liquids. Tests by You [8] have shown that the embryonic bubbles required to initiate boiling when using highly wetting dielectric fluids are very small (~0.05-0.1 μm). The feature sizes of most of the schemes listed above are apparently too large to effectively trap vapor for a larger incipient bubble. Surface treatments that could be effective for initiation of boiling with highly wetting liquids, cannot be easily applied to the computer chip because they may alter or destroy the chip surface.

Many of the previous experimental reports, published prior to 1986, on the boiling incipience of dielectric fluids, were reviewed by Bar-Cohen and Simon [9]. Significant variations were noted in the reported incipience superheat values. The authors discussed possible mechanisms for delayed nucleation and presented approximate methods for calculating superheat excursions at incipience. More recently, the highly nonrepeatable and unsteady behavior of boiling incipience of a highly wetting dielectric liquid (R-113) was documented by You et al. [10]. Initiation of boiling with R-113 occurred when the heater surface was significantly above the saturation temperature (superhets of as much as 73°C in an extreme case) and a wide distribution of wall superheat (more than 20°C) was observed for repeated runs, with, ostensibly, identical boundary conditions. In You et al. [11], [12], the boiling incipience and nucleate boiling mechanisms were experimentally tested for various cases of different thermodynamic bulk-fluid conditions using FC-72 and a silicon surface. An incipience prediction method was expanded to include subcooled and gas saturated conditions.

In the present paper, a particle layered, enhanced surface is tested for saturated and gas saturated FC-72. This surface has increased nucleation sites of the correct size range. With this technique, nucleate boiling heat transfer augmentation is demonstrated. The fabrication process for this enhanced surface is not likely to harm the silicon chip since the process can be carried out at room temperature without mechanical stress or corrosive chemical treatment.

II. EXPERIMENTAL APPARATUS

A. Test Facility and Instrumentation

The present investigation was conducted using electrically heated, 10 mm² by 10 mm², square heaters in both saturated and gas saturated pools of FC-72 at atmospheric pressure. The thin film heaters were fabricated by sputtering a 0.1-μm film of platinum on a 0.15-mm thick glass substrate.
The test heater with a 0.8-µm thick film of aluminum oxide (alumina) sputtered over the platinum, served as the base boiling surfaces. The nominal measured resistance was ~1.7 Ω and dR/dT was 0.0029 Ω/K, within 3%. The thin platinum film displayed a linear relationship between temperature and resistance, allowing it to be used as both a heater and wall temperature sensor. The platinum layer thickness was uniform within an estimated 5% [13]. The heated surface faced upward for all cases. FC-72 is a dielectric fluid with high wettability, low surface tension, and low viscosity. Measurements indicated that a relatively large quantity of air (or other noncondensable gases) can be dissolved within FC-72 (48% air by volume at 1 atm and 25°C) [8].

The test facility is composed of the test section and the gas control system, gas content, and pressure control subsystems shown in Fig. 1. The gas control section contains a degassing system (boiler and condenser), an air supply system and a dissolved gas measurement device (Seaton-Wilson Aire-Ometer). A 1-kW immersion circulator/heater and a 300-W cooling unit provide uniform and constant temperature for the 32-L glass container, in which the test vessel is immersed. The test vessel was a 2-L glass container in which the test fluid and heating element reside. The test fluid temperature, measured by a platinum RTD sensor, remains constant and uniform to within 0.05°C.

The facility is monitored and controlled by a small laboratory computer that interfaces with a 30-channel data acquisition/control unit and a dc power supply programmer via IEEE-488 interface cables. DC is supplied at specified voltages by a power supply to the heating element. A series precision resistor is used to determine current. Separate voltage taps across the heating element and across the precision resistor are used to compute heater resistance and heating element power. The heating element temperature is computed from its resistance via a calibration curve obtained prior to the experiment. The pressure of the test section is measured with a Vsglyne DP-15 variable reluctance type pressure transducer and a CD-15 sine wave carrier demodulator.

**B. Test Procedure and Uncertainties**

The test liquid is first degassed using the temperature control subsystem and the boiler/condenser in the gas content control subsystem until the measured dissolved gas content is nominally less than 0.2 × 10⁻³ moles/mole (2% air by volume). It usually takes about 5 ~10 h. The degassing process is accelerated significantly (~2 h) when the test fluid is stirred by a magnetic bar. When required, gas saturated bulk fluid conditions are generated prior to the measurements. The saturation temperature of the gassy cases is assured by measuring the total pressure and the dissolved gas content.

After thermally stable bulk fluid conditions (within 0.05°C variation) are achieved, and boiling is initiated on the surface, the following three measurements are made:

1. critical heat flux (CHF) measurement;
2. nucleate boiling curve with decreasing heat flux;
3. 10 runs of boiling incipience and nucleate boiling curve with increasing heat flux.

For the CHF tests, two Fluke multimeters are used to measure the voltage drops across the heater and the precision resistor. After an initial power value is provided (~80% CHF value), the test is computer controlled to increment in power until CHF is reached and an immediate shut-off is initiated to avoid burn-out. The computer steps the heat flux by 0.5 W/cm², then collects 1000 data points in about 2 min. For each data point, the heater resistance is computed to search for a resistance jump associated with exceeding CHF. When the computer finds a wall temperature increase of more than 10°C, the power is turned off to protect the heater. If a temperature jump is not found at the particular heat flux, the average resistance is calculated using the last 500 data points and stored. Then the heat flux is increased by 0.5 W/cm² to the next value. This is repeated until the temperature jump (CHF) is observed, indicating CHF. The CHF is recorded to be the last heat flux before reaching the temperature jump, plus 0.5 W/cm².

After the CHF measurement, a decreasing heat flux curve is measured followed by 10 runs in which the increasing heat flux boiling curve is taken. Each increasing heat flux run proceeds in increments from zero heat flux to the maximum value of the test (typically ~80% of the CHF value), then power to the heater is turned off. Following a 5-min waiting period at zero heat flux, a new run is initiated. Throughout the consecutive runs of each case, the test was completely computer controlled to be identical from run to run, stepping through precisely the same supply voltage conditions. After each power setting change, a sufficient waiting time is allowed for steady state to be reached, and the temperature and heat flux are then computed as averages of 20 readings taken over a 50-s period. A deviation of less than 1°C in averaged wall temperature (averaged over 5 readings) is taken to indicate steady-state behavior before taking the final 20 readings at each heat flux. Throughout the 10 runs, transition from single-phase natural convection to nucleate boiling (DNC), as indicated by a departure from the single-phase line and a merging with the nucleate boiling line (usually showing a drop in measured wall superheat with an incremental increase in heat flux), was always accompanied by the initial appearance of columns of bubbles.
Fig. 2. Particle layering method.

Analyses were performed to evaluate the uncertainties in the measured values of heat flux and wall superheat (difference between the heating element temperature and the saturated pool temperature) for the various regimes of boiling. The techniques of Kline and McClintock [14] were used to compute the propagation of uncertainties. The computed uncertainty of heat flux is 2% and that of the wall superheat was nominally 0.7°C. The steady-state temperature and heat flux measurements of the 10 runs were within the estimated uncertainty ranges.

C. Fabrication Process of the Particle Layered Surface

A schematic of the apparatus used to produce the enhanced surface is shown in Fig. 2. Compressed air (after filtering) is passed through a “nebulizer” (manufactured by Hudson Oxygen Therapy Sales Co.) in which a solution of particles and water is contained. The mixture of particles and water vapor downstream of the nebulizer is then dried by mixing with clean air. The particles, carried by dry air, are forced to impinge upon the heating element. The nominal velocity of the impinging jet is \(~1\) m/s. The impinging time and the distance between the impinging jet exit point and the surface determine the attachment area and the thickness of the enhancement layer. Presently, alumina (\(\text{Al}_2\text{O}_3\)) particles are deposited upon the alumina surface of the heating element, located 1 cm from the jet exit over a period of about 30 min. The particles are attached via “attraction” forces, believed to be van der Waals forces, which are sufficiently strong so that the particles adhere well.

III. RESULTS AND DISCUSSION

A. Probabilistic Representation of Incipience Data

Under most conditions, initiation of boiling with dielectric fluids is retarded until the heater surface is significantly above the saturation temperature. When boiling is finally initiated, bubbling becomes visible and the wall superheat level reduces significantly. In a previous paper, You et al. [10], a means of presenting data which displays this behavior was proposed. In this method, a series of runs is made under ostensibly identical conditions. Each run begins with zero heating and passes through a series of increasing heat flux values continuing up the single-phase natural convection line until boiling is initiated. The incipience superheat (the highest wall superheat value achieved under single-phase operation) is recorded for each run. A table is then constructed which gives various superheat values and, for each value, the corresponding number of runs which passed into boiling before reaching this value. A ratio is then computed by dividing this number of runs by the total number of runs. This fraction, labeled the “probability of boiling incipience” is then plotted versus the wall superheat. This probabilistic representation is used herein to discuss the incipience data. It is expected that the present particle layering enhancement technique would create a surface for which this distribution would be altered from that of a smooth surface.

B. Base Cases

Two square heaters (heater #1 and heater #2), each with 10 mm by 10 mm heated area, are used to show the variations of the pool boiling curve (heat flux versus wall-to-saturation temperature difference) including single-phase natural convection, boiling incipience, nucleate boiling, and CHF. The pool boiling curves with the two heaters immersed in saturated FC-72, are compared in Fig. 3 and the probability of boiling incipience curves, computed from each 10 consecutive runs, are shown in Fig. 4. As one can observe from Figs. 3 and 4, one case agrees well with the other for all regimes of boiling including single-phase natural convection. Incipience wall superheat values for these untreated heaters were measured as 31.4 ± 1.3 and 33.1 ± 1.0 °C, respectively. The measured CHF values for the two heaters were 9.0 and 9.8 W/cm²; heater #1 showing a lower CHF value than heater #2.

C. Enhanced Boiling Heat Transfer with Particle Layering

By using the previously described coating procedure, alumina (\(\text{Al}_2\text{O}_3\)) particles are attached to approximately 70% of the heated area of a 10 mm by 10 mm platinum heater upon which a thin film of \(\text{Al}_2\text{O}_3\) had first been sputtered. Heater #1 was coated with nominally 0.3-μm size alumina particles and 0.3-3-μm size alumina particles were used for heater #2. Figs. 5 and 6 show scanning electron microscope (SEM) pictures of the particle layered region of 0.3-3 μm size, before the experiments, with 1000 and 2500 magnification levels, respectively.

Pool boiling curves, taken under increasing heat flux conditions, for the untreated surface and the two different particle
layered surfaces are compared in Fig. 7. The particle layering increased CHF values by ~39% and ~36%; from 9.0 to 12.5 W/cm² for heater #1, and from 9.8 to 13.3 W/cm² for heater #2. Also, the wall superheat values at a given heat flux in nucleate boiling decreased by approximately 37 and 46% for the 0.3 and 0.3~3 μm particle layered surfaces, respectively. These augmentations correspond to 11 and 14°C decreases in superheat from the nominal 30°C wall superheat of the untreated surfaces. It is surmised that the enhanced surfaces have an increased number of nucleation sites of the correct size for nucleate boiling bubble formation (~1 μm). Furthermore, one can observe in Fig. 7 that the enhanced surface boiling curve is steeper than the untreated surface boiling curve over the range of the test. This indicates that the particle layering scheme has a more uniform distribution of larger size nucleation sites than does the untreated surface. Observations during boiling revealed that the nucleation site density of the enhanced surfaces is much larger in the area where particles were applied and that, over the particle layered region, boiling persisted to significantly lower heat fluxes (as low as 0.05 W/cm²) than on the untreated surface. Natural convection heat transfer from the surface was unaltered however by the presence of the enhancement region with the two different sizes of alumina particles. This may suggest a negligible heat transfer improvement via fin effect.

With this particle layering technique, wall superheat values at boiling incipience were also decreased for both enhanced surfaces — see Fig. 8. The 0.3 μm and 0.3~3 μm particle layered surfaces showed 27.0 ± 0.1°C and 18.4 ± 0.2°C wall superheat values, respectively, whereas 33.1 ± 1.0°C was measured for the untreated heater #2 alumina surface. Thus the enhanced surfaces apparently include an increased number of nucleation sites of the correct size (~0.1 μm) and shape (re-entrant) for embryonic bubble retention. The particle layering scheme, in which there are smaller sizes and shallower depths of cavities, may generate re-entrant type cavities.

It appears that particle attachment is an effective and easy-to-implement technique for enhancing nucleation in the application of immersion cooling, with boiling, of electronic modules. Though the present enhancement technique was tested with FC-72, the same technique can be extended to other highly-wetting liquids such as other Fluorinerts (FC series by 3M), chlorofluorocarbons (e.g., R-113) and other refrigerants, as well as to water. For water, a larger particle size may be needed to provide the correct size for the nucleation sites, since embryonic bubbles of water vapor are known to be larger.
Fig. 8. Probability of boiling incipience versus single-phase natural convection wall superheat; effects of particle layering.

Fig. 9. Pool boiling curves; effects of dissolved gas content with the particle layered surface.

than those of highly wetting dielectric fluids. A test whereby particles were allowed to collect on the wall of a heater showed that the surface attachment forces were too weak to retain the particles when washed with water (with FC, vigorous washing could not remove the particles). Thus to apply with water, another method of particle attachment must be developed. In the present application of FC-72 immersion cooling with boiling, the 0.3–3 μm size particles were found to be better than 0.3-μm size particles.

D. Dissolved Gas Effects with the 0.3–3-μm Particle Layered Surface

The effects of dissolved gas (air) on the boiling behavior of the 0.3–3 μm alumina particle layered surface (heater #2) are discussed next. Typical increasing heat flux boiling curves and probability curves for displaying boiling incipience are plotted for a saturated base case and for two gas saturated comparison cases, in Figs. 9 and 10, respectively. All three cases were tested at 1-atm total pressure. The dissolved air content values of the two gassy cases were 0.0026 and 0.0043 moles/mole; corresponding bulk fluid temperatures were 35 and 15°C, respectively. Thus the “gassy subcooling” values, defined as $T_{\text{sat}}(P_t) - T_{\text{sat}}(P_v)$, were 21 and 41°C, based on the FC-72 saturation temperature of 56°C at 1 atm.

The nucleate boiling curves taken under increasing heat flux conditions, Fig. 9, obviously show enhancement for the gassy cases over the saturated case. Nucleation sites were more dense within the particle layered area for the three cases, indicating enhanced nucleation regardless of bulk fluid conditions. The gas saturated case at 35°C showed only a few degrees of decrease in superheat from that of the saturated case and the gas saturated case at 15°C showed only 8°C decrease from the saturated case at a heat flux of ~10 W/cm². This indicates that the gas partial pressure values within the bubbles at the wall are relatively low despite high values in the bulk fluid, perhaps as a result of the poor penetration of dissolved gas to the near-wall fluid. It is presumed that the gas component has been depleted from the near-wall fluid by bubbles departing the surface during previous boiling periods (You et al., [15]). In contrast, under single-phase and very low heat flux boiling, wall superheat values of the gassy cases were shifted by essentially the amount of gassy subcooling, $T_{\text{sat}}(P_t) - T_{\text{sat}}(P_v)$. The effect of dissolved gas on the higher heat flux portion of the nucleate boiling curve appears to become significant for the gassy case only at higher levels of dissolved gas content (0.0043 moles/mole — gas saturation at 15°C). The above observations on the dissolved gas effect are consistent with those of You et al. [12], [15], where a detailed description of the gas effect and a discussion of the possible physics, respectively, can be found.

In a study of boiling incipience on a sputtered cylindrical heater by You et al. [11], dissolved gas content exceeding 0.005 moles/mole affected boiling incipience superheat but no discernible effect of dissolved gas was observed at values lower than 0.005 moles/mole. However, the present boiling incipience data show, in Fig. 10, that increasing dissolved gas content reduces wall superheat values dramatically when boiling FC-72 off the particle layered surface. When the bulk fluid was gas saturated at 15°C ($C_g = 0.0043$ moles/mole), 4 out of the 10 runs showed negative wall superheat values at boiling incipience (recall that the saturation temperature is that of the degassed fluid). This indicates a strong effect of dissolved gas within the embryonic bubbles for the gassy cases. Clearly, the present enhancement scheme is very desirable for improving boiling incipience behavior of highly wetting dielectric fluids.
In addition to the above beneficial effect of the particles on incipience, the measured CHF values were increased by 68 and 111% for the gas saturated cases at 35°C and at 15°C, respectively, from the CHF value of the saturated case (13.5 W/cm²). For the higher gas content case, 0.0043 moles/mole (gas saturated at 15°C), the CHF was 28.5 W/cm². This value is approximately 3 times that of the untreated (no particle layering) surface in saturated FC-72 at the same total pressure. Note that, since these data were taken with a thin film heater, some of this augmentation in CHF may have been due to an increase in the heater effective thickness; thicker heated walls are known to display higher CHF values than those taken on thin walls (Taylor et al., [16]).

E. Durability Test: 25 h of Operation with the 0.3–3 μm Particle Layered Surface

Heater #2, with 0.3–3 μm particles, was powered at ~6.1 W/cm² and allowed to boil at that heat flux in saturated FC-72 for 25 h. This test was conducted to investigate the durability of the present enhancement technique under fully developed nucleate boiling of FC-72, where many bubbles are rapidly departing and strong fluid motion is generated by the wakes of departing bubbles. During this durability test, wall superheat readings were taken every 30 min. These data are plotted in Fig. 11. Boiling curves and probability curves for displaying boiling incipience are compared for the cases taken before and after the durability test in Fig. 12. The characteristics of boiling incipience, nucleate boiling, and single-phase natural convection were almost identical and no significant wall superheat differences due to prolonged boiling were detected. The measurement of CHF values before and after the durability test showed 13.3 and 13.5 W/cm², respectively. This consistency in boiling behavior lent confidence that the adhesion of the particles to the surface is fairly strong.

F. Durability Test: 6 d of Operation with the 0.3 μm Particle Layered Surface

A similar durability test, including 10 runs of saturated case before and after the durability test, was performed at identical conditions to those of the durability test for the 0.3–3 μm particle layered surface except that 0.3-μm size particle layered heater (#1) was used for longer time (6 d). The change in wall superheat at 6.1 W/cm² and a comparison of the before and after cases are shown in Figs. 13 and 14. Although the fully developed nucleate boiling regime appeared almost unaltered (within 1–2°C), the incipient wall superheat decreased from 27.0 ± 0.1°C (before the durability test) to 12.7 ± 0.1°C (after the durability test) and the CHF increased from 12.5 to 15.1 W/cm² (see Fig. 14). The increasing heat flux curve produced after the durability test, the left curve in Fig. 14, shows that the superheat excursion has disappeared, resulting in a smooth transition from single phase convection to nucleate boiling. The change in the nucleate boiling curve was larger at lower heat fluxes (~5 W/cm²) than at higher heat fluxes. That there have been such changes may indicate that the particle layered structure has been changed during the durability test. It should be noted that the changes in incipience superheat and CHF were in the favorable direction (decreasing wall superheat at incipience and increasing CHF).

G. Microgeometry of the particle Layered Surfaces

Surface microgeometry was viewed with SEM after completing the experiments described previously. Figs. 15 and 16 show the microgeometries of 0.3–3 μm (heater #2) and 0.3 μm (heater #1), alumina particle layering. The larger
scale structures for the 0.3–3 μm size surface than for the 0.3-μm size surface, Figs. 15 and 16, apparently resulted in the better boiling heat transfer, for the 0.3–3 μm size case, Figs. 7 and 8. A comparison of particle distribution between Fig. 5 (before experiment) and Fig. 15 (after experiment) indicates that the particles have been displaced during the 25-h nucleate boiling period. The particles were more uniform before the experiment than after. However, it appears that particles did not detach during the durability test, in spite of this displacement. The particle displacement is shown more clearly in Fig. 16, a photo of the surface with the smaller size particle (0.3 μm), after 6 d of boiling. In this figure, one can see two different areas: a smooth base surface and a particle coated area. An accumulation of 0.3-μm particles produced larger scale structures (Fig. 16), thus resulting in the lower boiling incipience superheat at low heat fluxes.

H. Particle Layering with Ultra-Violet (UV) Light Cure Glue

Although pool boiling heat transfer was considerably improved by the particle layering, stronger attachment may be required in some environments. One notes that although fluid washing does not remove the particles, it is easy to mechanically scrub them off (as with a swipe of the finger). Therefore, the present particle layering technique was modified to include the application of a thin glue layer (ultra-violet light cure glue, UV glue) to the base alumina surface prior to particle attachment. Without exposing the glued surface to the UV light, the alumina particles (0.3–3 μm) are deposited.

The glue is then hardened by UV light. The resulting surface is permanent. With this surface, one cannot scrub the particles off with a swipe of the finger. SEM pictures of this surface are shown in Fig. 17. Upon viewing the microstructures and those in Fig. 5 (particle layered without using glue), one may notice that smaller particles are surrounded by the glue. Thus many small-scale structures have been eliminated in the UV glued particle layered surface.

The increasing heat flux boiling curves of two 0.3–3 μm particle layered cases, one with and the other without UV glue, are compared with the base case (untreated alumina thin film surface) curve in Fig. 18. Although the enhancement of nucleate boiling heat transfer was inferior with the glued surface to that of the particle layered surface without glue, the particle layering with glue was still an effective technique for enhancing nucleation over the bare surface value. A ~10°C wall superheat decrease was achieved by the glued particle surface over the untreated case. The difference in incipience performance between glued and unglued particle surfaces may be caused by the loss of boiling sites of smaller scales due to glue layer, as discussed previously. Almost identical CHF values were measured (13.5 W/cm²) for the two particle layered cases (with and without the glue layer) and no difference in the single-phase natural convection regime was recognized. Also, boiling incipience probability curves in Fig. 19 show no discernible change on wall superheat when gluing was used.

Therefore, the use of a glue layer in the present particle enhancement technique did not make a severe difference; it results in about 4 ~9°C higher wall superheat values at the same heat flux within the nucleate boiling regime, which is a
minor penalty. The combination of increased wall superheat in the nucleate boiling regime and no change in incipient wall superheat actually resulted in a decrease of incipient superheat excursion.

**IV. SUMMARY AND CONCLUSIONS**

The proposed enhancement with particle layering appears to create numerous nucleation sites of submicrometer size. With this technique, boiling heat transfer augmentation is demonstrated when using a highly wetting dielectric liquid (FC-72); boiling incipience is achieved at a lower superheat, nucleate boiling continues with smaller superheat, and CHF values are increased. The same technique can, most likely, be extended to other highly wetting liquids. With this technique, the alumina particles are attached to the boiling surface by either intermolecular attraction forces or with glue. During the present experiments with FC-72, use of 0.3–3 μm size particles indicated better boiling performance than use of 0.3-μm size particles.

**Fig. 16.** Surface microgeometry taken by SEM; 0.3-μm alumina particle layered surface, after experiment. (a) 1000 magnification. (b) 2500 magnification.

**Fig. 17.** Surface microgeometry taken by SEM; 0.3–3 μm alumina particle layered surface with UV glue, after experiment. (a) 1000 magnification. (b) 2500 magnification.

**Fig. 18.** Pool boiling curves, particle layering with UV glue; 0.3–3 μm alumina particles.

When boiling with gassy fluid, negative boiling incipience superheats are found with the particle layered surface whereas with the untreated surface incipience superheat values were
positive. A gas saturated case at 15°C and 1 atm showed the highest critical heat flux among the cases tested (28.5 W/cm²). Therefore, particle layering is an appropriate enhancement technique for the highly wetting dielectric liquids, in which a relatively large amount of gas is dissolved.

For instances where strong attachment of the particles is necessary, a glued layer is proposed. When glue is employed, there is a 4–9°C increase in wall superheat over the unglued particle layered surface superheats within the nucleate boiling regime. The glued surface did not display superheat excursion at boiling incipience, however, and the CHF values remain unaltered when the glue is used to attach the particles.

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