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# Concerning The Effect of Surface Material on Nucleate Boiling Heat Transfer of R-113*

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## Abstract

This paper presents results of an experimental investigation carried out to determine the effects of surface material on nucleate pool boiling heat transfer of refrigerant R113. Experiments were performed on horizontal circular plates of brass, copper and aluminum. The heat transfer coefficient was evaluated by measuring wall superheat and effective heat flux removed by boiling. The experiments were carried out in the heat flux range of 8 to 200 kW/m$^2$. The obtained results have shown significant effect of surface material, with copper providing the highest heat transfer coefficient among the samples, and aluminum the least. There was negligible difference at low heat fluxes, but copper showed 23% better performance at high heat fluxes than aluminum and 18% better than brass.

**Keywords:** Boiling Heat Transfer, R-113, Nucleate Boiling, Surface Material

## 1. Introduction

With the continuing increase in power dissipation density from electronic components such as CPU chips and micro-processors, high heat flux compact cooling mechanisms needs to be developed. Boiling heat transfer has received considerable attention in the past decades due to its high capacity of heat removal. Among the many methods of two phase flow heat transfer, pool boiling is a very attractive technique due to its low cost and simplicity, as it is considered here.

After the first pioneering study of Nukiyama [1] on pool boiling regimes, much research have been carried out. Despite more than half a century, prediction of boiling heat transfer coefficient is still a challenge [2]. In general, the effect of surface characteristics on the boiling process depends on thermophysical properties of the sur- face, interactions between the solid surface, liquid and vapor, and surface microgeometry. Because of the com- plexity of the problem, only separate effects are usually considered [3].

Some researchers claimed significant enhancement in the coefficient of heat transfer for rough surfaces [4-6]. Roy Chowdhury and Winterton [5] studied roughness and contact angle effect on pool boiling of aluminum and copper surfaces immersed in saturated water and methanol. They observed that rough surfaces present better heat transfer coefficient at low heat fluxes, while in transition boiling the enhancement was not considerable. Moreover, they observed that heat transfer coefficient is strongly affected by the extent to which a liquid wets the surface. They found that good wetting (low contact angle) increases CHF (critical heat flux) and heat transfer coefficient at a given heat flux. The same result was obtained by Kang [7] when he studied the effect of roughness on pool boiling of a cylinder at different orienttations. He found that increase in surface roughness gives no plausible change in heat transfer coefficient at high heat fluxes for horizontal tubes. This was related to poor liquid agitation and bubble slug formation on the tube surface at high heat fluxes. However, he observed that the effect of roughness is magnified as the orientation of a tube changes from the horizontal to vertical because the change in tube orientation gives much stronger liquid agitation and smaller bubble coalescence. Pioro *et al*. [3] came to a similar result. They proposed that surface roughness may affect heat transfer coefficient only when surface changes coincide with the appearance of new vapor generation centers, which would increase active cavities.

The effect of pressure and surface roughness was investigated by Jabardo *et al*. [8]. They experimentally studied roughness and surface material effects on nuc-

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leate boiling heat transfer of cylindrical surfaces, boiling in R-134a and R-123 at different reduced pressures. They observed that very rough surfaces present better boiling thermal performance than smoother ones only at low heat fluxes, while the trend shifts in the high heat flux range. They also found that the slope of the (h vs. q) is strongly dependant to surface material. The slope was co-nsiderably lower for stainless steel sample than for copper or brass. In another study, Ribatski and Jabardo [9] carried out experiments on different surface materials boiling in different halocarbon refrigerants. They found that the effect of surface material depends on the boiling fluid. They observed better performance of brass surface than copper and stainless steel for boiling fluid of R-11, while the copper and brass performance was close for boiling fluid of R-12.

Despite many experimental and numerical studies, there is still lack of experimental data concerning the influence of surface material on nucleate pool boiling heat transfer. The objective of the present study is to investigate surface material effects on nucleate pool boiling of R-113. No experimental work was found in the literature concerning this matter to the best of authors' knowledge.

## 2. Experimental Setup and Procedures

A cut view of the experimental setup is shown in **Figure 1**. The setup consists of a pyrex cylinder with an inner diameter of 55 mm and a thickness of 2.5 mm. The refrigerant R113 was filled in this cylinder from a valve suited at the top (not shown in the figure). The test liquid boiled from a heated horizontal circular plate made of three different materials of brass, copper and aluminum. The diameter of this sample was 54.5 mm. The gap between the sample and the glass was thermally isolated to avoid boiling from the circumference of the sample.

Wall surface temperature was measured by an Omega 5SRTC K type thermocouple installed in a groove carved by CNC machine. A tool was used to guarantee thermal contact between the thermocouple and the sample. A K type thermocouple was immersed in a hole drilled 0.5 mm below the boiling surface. In calculation of wall superheat thermal resistance of the heated sample wall between thermocouple location and the boiling surface is taken into account.

Two parallel connected cartridge heaters were used to provide heat flux to the circular plate in the range of 8 to 200 kW/m$^2$. The heaters were inserted in two grooves carved by CNC machine on an aluminum plate. The sample was placed on this plate. To reduce thermal contact resistance silicon heat sink paste was applied between the plate and the sample. The power to the heaters was maintained by a variable A.C transformer and was measured by a wattmeter with an accuracy of ± 1 watt. Moreover, to minimize input power oscillations, an A.C voltage regulator was used.

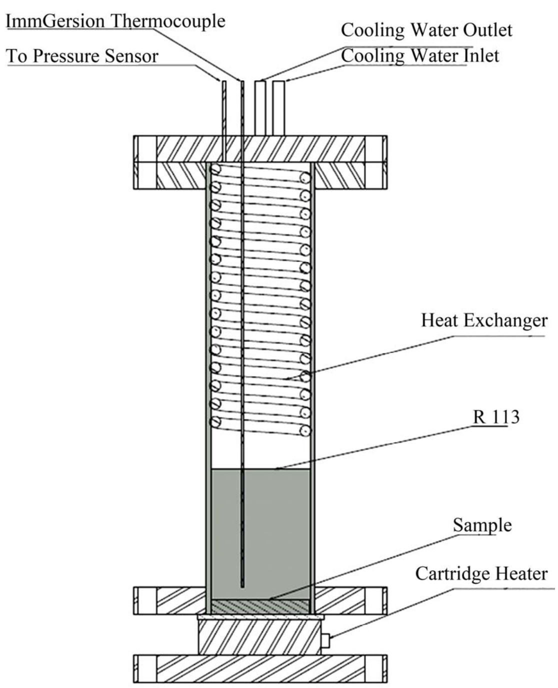


**Figure 1. A cut view of the experimental setup.**

A copper coil heat exchanger was used to condense R-113 vapor. The cooling water was pumped through this heat exchanger in a closed loop system. The warm outlet water was cooled with 50% solution of ethylene glycol/water in another heat exchanger.

The temperature of the inlet and outlet water was measured by immersion thermocouples connected to Omega Daq 5500 datalogger. Moreover, the water flow rate was measured by a rotameter which permitted calculation of the heat absorbed by the condenser. This was compared with wattmeter reading. The difference was the heat loss from the heaters to the surrounding and was in the range of 2% of the wattmeter reading.

To measure R-113 saturation temperature, Testo 0602 5792 K type immersion probe was used. To assure that the reading of this temperature is correct, another immersion probe was used to measure the vapor temperature in equilibrium with the liquid. Moreover, the pressure of the system was measured by a sensor suited at the top. The experiments were performed at atmospheric pressure. A safety valve was also used to prevent overpressure in the case of cooling water failure.

Uncertainties in parameters were estimated using the root-sum-square of Kline and McClintock [10], **Table 1**.

## 3. Characteristics of The Heating Surface

The heating surface was made of copper, brass and aluminum. All of the samples were treated by sand paper of 100 grit size. The sand paper was applied with the sample rotating at 1400rpm by a regular lathe machine as suggested by [8]. Average surface roughness of the three samples would be different, although the surface finishing process was the same. Therefore, a profilometer should be used to measure Ra of the surfaces as suggested by [8,11-14]. **Figure 2** shows the results of the profilometer. Ra of copper, brass and aluminum was 0.901, 1.404 and 1.285µm, respectively. In addition to measuring surface roughness, the microstructure was visually determined by SEM as shown in **Figure 3**.

**Table 1. Estimated total uncertainties.**

| Parameter | Uncertainty |
|---|---|
| Heat transfer area | ± 0.2% |
| Heating surface temperature | ± 0.7K |
| Temperature of the boiling liquid | ± 0.7K |
| Heat transfer coefficient | ± 19.3% |

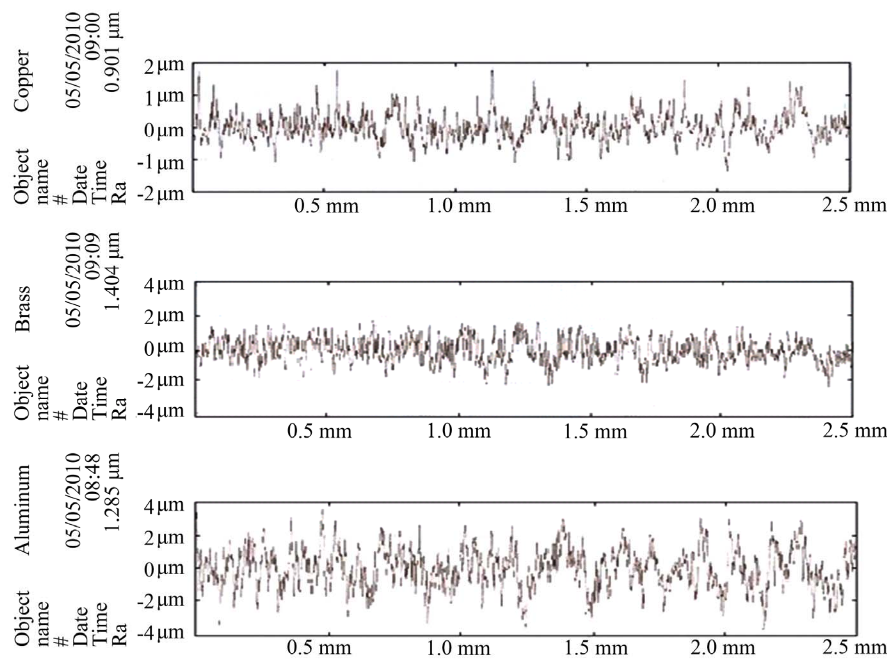


**Figure 2. Profile of the three heating samples used.**

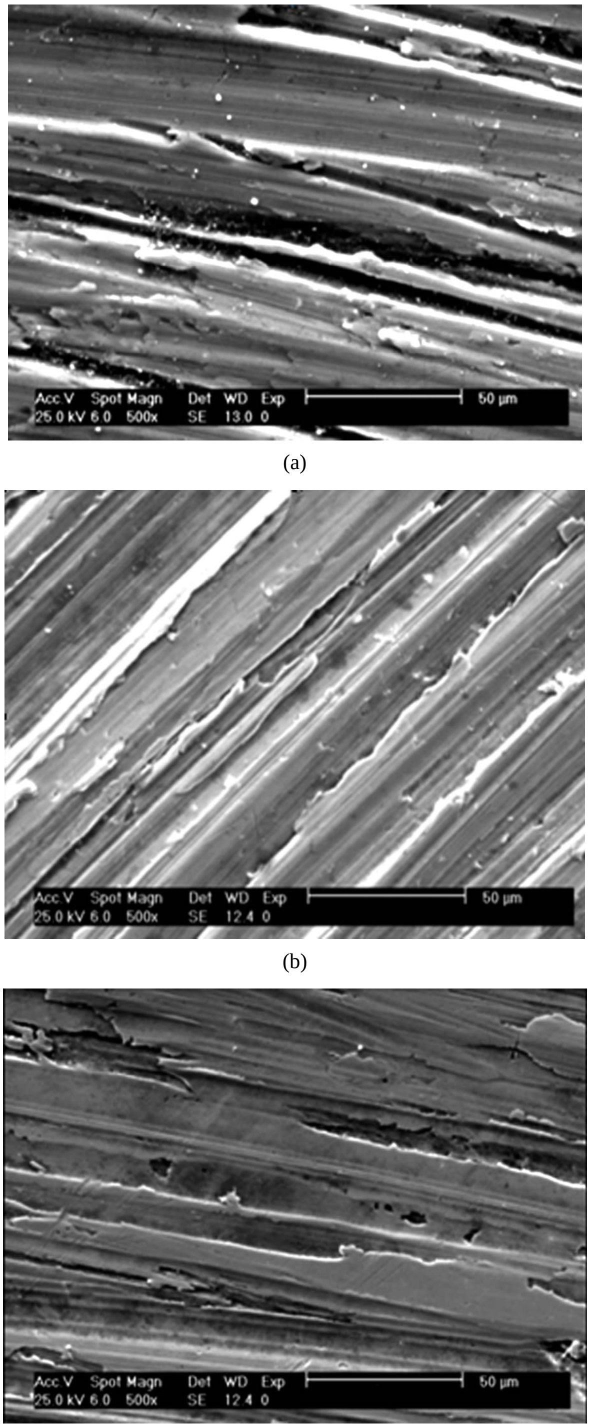


**Figure 3. Micro-photographs of the three samples (500× and 25.0 kv) (a) aluminum sample; (b) brass sample; (c) copper sample.**

## 4. Reproducibility of The Experimental Data

To verify repeatability of the experimental data, several tests were performed on copper sample for different heat fluxes. The results are shown in **Figure 4**. **Figure 4(a)** shows the results when the heat flux increases and **Figure 4(b)** shows the results when the heat flux decreases. It is observed that surface temperature of increasing power input was 0.2˚C to 0.3˚C slightly higher than those for decreasing power input for the same heat flux. This was observed in all of the experiments.

## 5. Results

The effect of heating surface material over the boiling curve is shown in **Figure 5** for decreasing heat flux data. It should be noted that first the sample was heated up to heat flux of 200 $kW/m^2$, and then the heat flux was decreased slowly and the corresponding data was recorded. It is observed that thermal performance of copper is slightly better than the other samples, despite having the least surface roughness. The enhancement is more considerable in high heat fluxes. At heat flux of 168 $W/m^2$ copper sample has 23% higher heat transfer coefficient than aluminum sample and 18% than brass sample.

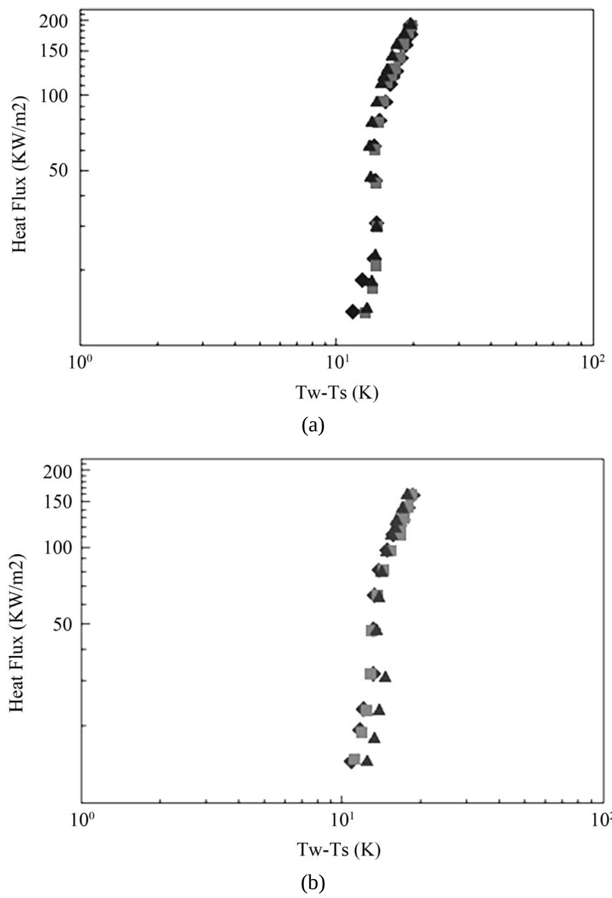


**Figure 4. Heat flux versus wall superheat for copper sample to verify repeatability of results. (a). heat flux increasing direction; (b). heat flux decreasing direction.**

Moreover, the results of You *et al*. [15] and Cornwell and Einarsson [16] have been plotted in **Figure 5** for comparison with current data. You *et al*. [15] data are obtained from pool boiling of a 0.13 mm chromel wire with highly wetting fluid of R-113. Cornwell and Einarsson's data [16] are also obtained from nucleate boiling on the outside of a horizontal 27 mm stainless steel tube with working fluid of R-113. Furthermore, the data calculated from the Cooper correlation [17], equation 1, (calculated with copper sample properties) have been plotted in **Figure 5**. The experimental results of copper sample deviate from cooper in the range of -15 to 27%.

The Cooper correlation relates different parameters to the heat transfer coefficient as:

$$h = 55q^{0.67} p_r^n \left(-\log_{10} P_r\right)^{-0.55} M^{-0.5} \quad (1)$$

where the exponent $n$ is calculated as:

$$n = 0.12 - 0.2\left(\log_{10} Rp\right) \quad (2)$$

There is a parameter in cooper relation, *Rp*, which depends on surface roughness. However, roughness of the present samples was measured in terms of average surface roughness, *Ra*. There is still some debate regarding the relation between these roughness parameters [8]. Gorenflo *et al*. [6] suggests using equation 3 which relates *Rp* and *Ra*.

$$Rp = \frac{Ra}{0.4} \quad (3)$$

Change in the heat transfer coefficient is plotted for different surface roughness in **Figure 6**. As one can see, the heat transfer coefficient clearly increases with increase in Ra. However, some thermophysical properties such ther- mal conductivity and wettability of the boiling surface influence the heat transfer coefficient that are absent in the Cooper correlation, equation 1.

The difference in performance can be attributed to better wettability of copper than aluminum (no data was found for wettability of brass in the literature) [18]. As the contact angle between the boiling fluid and the surface decreases, that is the liquid better wets the surface, heat transfer coefficient would increase [3]. Moreover, growth rates of vapor bubbles, and hence heat transfer coefficient depends on thermal conductivity of the boiling surface [19]. Mann *et al*. [19] showed that with increase in wall thermal conductivity, the heat transfer coefficient would increase. According to their modeling, with simplifying assumption of constant wettability and nucleation site density, copper surface would result in 13% higher heat transfer coefficient in comparison with steel surface. However, bubble site densities are very sensitive to changes in the wall thermal conductivity. For instance, bubble site densities on steel walls are about 30% smaller than those on copper walls [20], which would cause further increase in the heat transfer coefficient of the copper surface.

## 6. Conclusions

An experimental study of nucleate pool boiling of R-113 on three different heated surfaces of brass, copper and aluminum were carried out. All of the samples were treated with the same method and the average surface roughness, Ra, was measured, respectively. The samples were heated in the range of heat flux of 8 to 200 kW/m$^2$

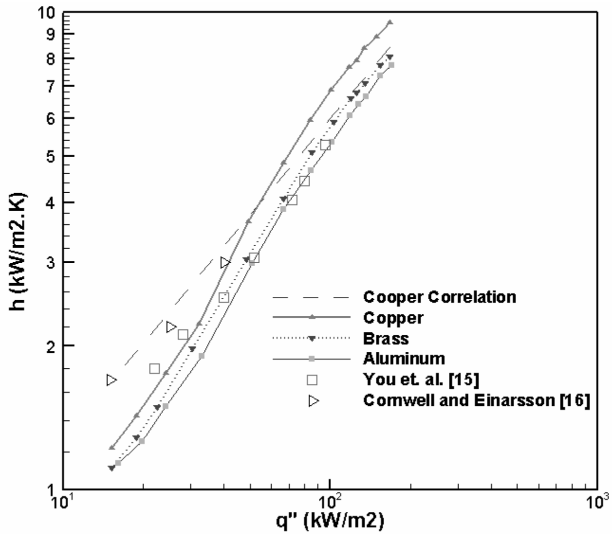


**Figure 5. Boiling curve of refrigerant R-113 for different surface materials and comparison with cooper correlation and data from literature.**

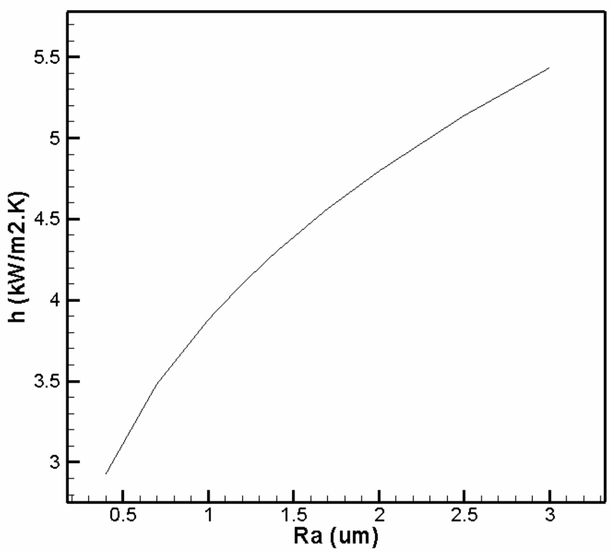


**Figure 6. Variation of heat transfer coefficient vs Ra according to cooper correlation.**

and the corresponding coefficient of heat transfer was calculated. It was found that copper has the best thermal performance among the samples, although it had the least *Ra*. After copper, brass has better performance than aluminum. The enhancement is found to be more considerable at high heat fluxes.

## 7. Acknowledgements

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