

Roughness Effects on Nucleate Pool Boiling of R-113 on Horizontal Circular Copper Surfaces

R. Hosseini¹, A. Gholaminejad², and H. Jahandar³

Abstract—The present paper is an experimental investigation of roughness effects on nucleate pool boiling of refrigerant R113 on horizontal circular copper surfaces. The copper samples were treated by different sand paper grit sizes to achieve different surface roughness. The average surface roughness of the four samples was 0.901, 0.735, 0.65, and 0.09, respectively. The experiments were performed in the heat flux range of 8 to 200 kW/m². The heat transfer coefficient was calculated by measuring wall superheat of the samples and the input heat flux. The results show significant improvement of heat transfer coefficient as the surface roughness is increased. It is found that the heat transfer coefficient of the sample with Ra=0.901 is 3.4, 10.5, and 38.5% higher in comparison with surfaces with Ra of 0.735, 0.65, and 0.09 at heat flux of 170 kW/m². Moreover, the results are compared with literature data and the well known Cooper correlation.

Keywords—Nucleate Boiling, Pool Boiling, R113, Surface Roughness

Nomenclature

h Heat transfer coefficient (W/m²K)
 M Molecular mass (kg/mol)
 n Exponent of p_r, Cooper correlation, (1)
 P Pressure (kPa)
 P_c Critical pressure (kPa)
 P_r Reduced pressure (P_r=P/P_c)
 q Heat flux (W/m²)
 Ra Arithmetical mean deviation of the profile (μm)
 R_p Maximum peak height of the profile (μm)
 T_s Liquid Temperature (K)
 T_w Wall Surface Temperature (K)

1. INTRODUCTION

NUCLEATE pool boiling has become the subject of a considerable amount of research in these years. An important reason for such attraction is the rapid development of microelectronic devices with high heat flux dissipation, and the need for cooling them. It is this challenge that has made pool boiling popular for thermal control of high heat flux devices, because of its unique characteristics. Pool boiling

allows very large amount of heat to be removed at moderately low wall superheats.

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The optimum design of a pool boiling cooling system depends on the correct prediction of nucleate boiling characteristics. However, nucleate boiling heat transfer mechanism is a very complex one, which makes it extremely hard to predict its behavior under different circumstances. After more than 80 years of research, there is still no generalized theory or model that can adequately represent the phenomenon of nucleate boiling heat transfer [1, 2]. Because of this complexity, only separate effects are usually considered [3].

The performance of a pool boiling cooling device is inversely related to the amount of wall superheat that is required to initiate nucleate boiling. Therefore, the goal of researchers has been to find mechanisms that can reduce wall superheat. Coating the heating surface with a porous material, which increases the available nucleation sites on the heating surface, is one way to achieve low wall superheats [4]. Increasing nucleation sites would cause higher rates of vaporization, such that the required wall superheat, needed for nucleate boiling would be lowered [5]. Another way to enhance the performance is to use artificial cavities on the surface [6, 7]. For instance, Das et al. studied nucleate boiling of water on copper surfaces with micro-drilled cavities [8]. They reported up to 100% improvement in heat transfer coefficient for site spacing of 10mm in comparison to a plain polished surface.

One of the methods of improving nucleate boiling heat transfer coefficient is to roughen the heating sample. This method is much cheaper and easier to implement. In an study on nucleate boiling of n-pentane, Berenson found that maximum nucleate-boiling heat flux is independent of surface roughness [9]. However, he found a 600% increase in heat transfer coefficient by roughening the heated sample. Such significant improvement in heat transfer coefficient has also been reported in other papers [10, 11]. Berenson concluded that enhancement in heat transfer coefficient is a result of higher active cavity density [9].

Benjamin and Balakrishnan studied nucleate boiling of different fluids at moderate heat fluxes to study variation of nucleation site density with surface roughness [12]. Stainless steel and aluminum with different surface finish was used in their study. They concluded that nucleation site density depends on surface microroughness, the surface tension of the

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liquid, the thermophysical properties of the heating surface and the liquid, and the wall superheat.

In another research by Kang on pool boiling of water, he found that the effect of surface roughness is to increase the heat transfer coefficient [13]. His results showed magnified effect of surface roughness as the orientation of the tube changed from horizontal to vertical. Moreover, he found that higher ratio of a tube length to its diameter increases the effect of surface roughness on pool boiling heat transfer coefficient. Pioro et al. [3] explained that increase in heat transfer coefficient by roughness, only occurs when coincidence with the appearance of new vapor generation centers is changed, that is when the range of active sites is widened.

Roy Chowdhury and Winterton [10] studied roughness effect on pool boiling of aluminum and copper surfaces with boiling liquid of water and methanol. They found that surface roughness improvement on the heat transfer coefficient diminishes in transition boiling regime.

Recently, Jabardo et al. [14] studied surface roughness effect on pool boiling of cylindrical surfaces immersed in R134a and R123 at different pressures. They observed significant dependency on the effect of surface roughness with pressure. 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.

It is highly valuable to study the effect of surface roughness, since it is significant in designing of heat exchangers. There is still lack of experimental data in this regards. No experimental work was found concerning surface roughness effect with working fluid of R113, which is desirable for cooling applications for its low boiling point, to the best of authors' knowledge. Therefore, to get more insight an experimental study has been carried out on copper surfaces with different surface roughness. The goal of this paper is to find the extent to which the heat transfer coefficient can be increased by roughening the heated sample.

II. EXPERIMENTAL SETUP AND PROCEDURES

In order to study the effect surface roughness on nucleate boiling of R113 the setup shown in Fig. 1 was constructed. This setup consists of a transparent Pyrex cylinder with an inside diameter of 55mm and a thickness of 2.5 mm. The ends of this cylinder were flanged by heat treatment process to allow careful sealing of the working fluid. The heated surface was placed at the bottom of this cylinder. The outside diameter of the sample was 54.5mm. The gap between the sample and the glass was thermally isolated with a flexible material to avoid boiling from the circumference of the sample. The Pyrex cylinder may break without this flexible material, in case of sample overheating.

The heating surface was made of copper. To achieve different surface roughness, sand paper was applied to the sample while it was rotating at 1400 rpm as suggested in [14].

A profilometer was used to measure average roughness (R_a) of the samples, as suggested by [12, 14-17]. With this method R_a of 0.901, 0.735, 0.65, and 0.09 was achieved. Fig. 2 shows surface profile of the samples.

The sample was heated by two cartridge heaters grooved in an aluminum plate. The two parallel heaters were connected to a variable A.C transformer. A wattmeter with an accuracy of 1 Watt was used to measure the input power to the heaters. Moreover, to minimize input power oscillations, an A.C voltage regulator was used. With this method, the sample could be heated in the heat flux range of 8 to 200kW/m². To reduce thermal contact resistance between the sample and the aluminum plate, a high conductivity silicon paste was applied between them.

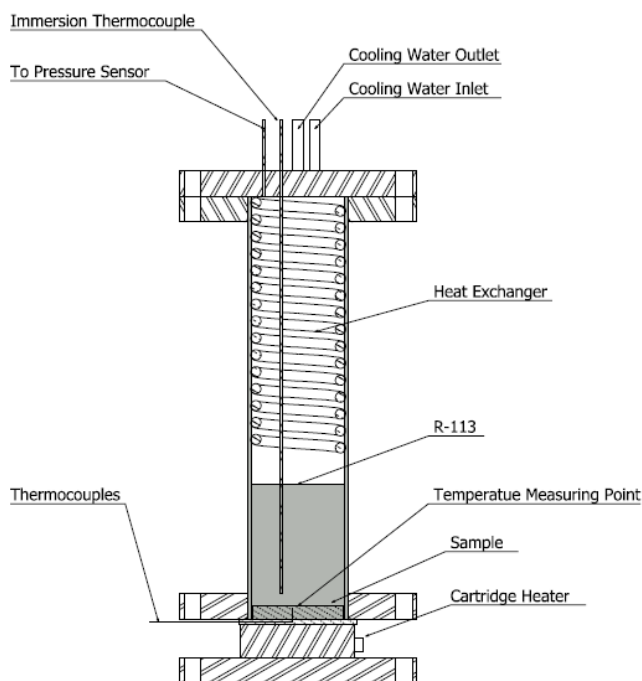


Fig. 1 A Cut View of the Experimental Setup

To measure surface temperature of the heated sample an Omega 5SRTC K type thermocouple was used. This thermocouple was installed in a groove carved by a CNC machine 0.5mm below the boiling surface. A tool was used to guarantee thermal contact between the thermocouple and the sample. Thermal resistance between thermocouple location and the boiling surface has taken into account in calculation of wall superheat.

The refrigerant R113 was used as the boiling fluid. It was filled in the cylinder from a valve suited at the top (not shown in the figure). This refrigerant has a low boiling point of 47°C at atmospheric pressure, which is very suitable for cooling applications. The temperature of this fluid was measured by

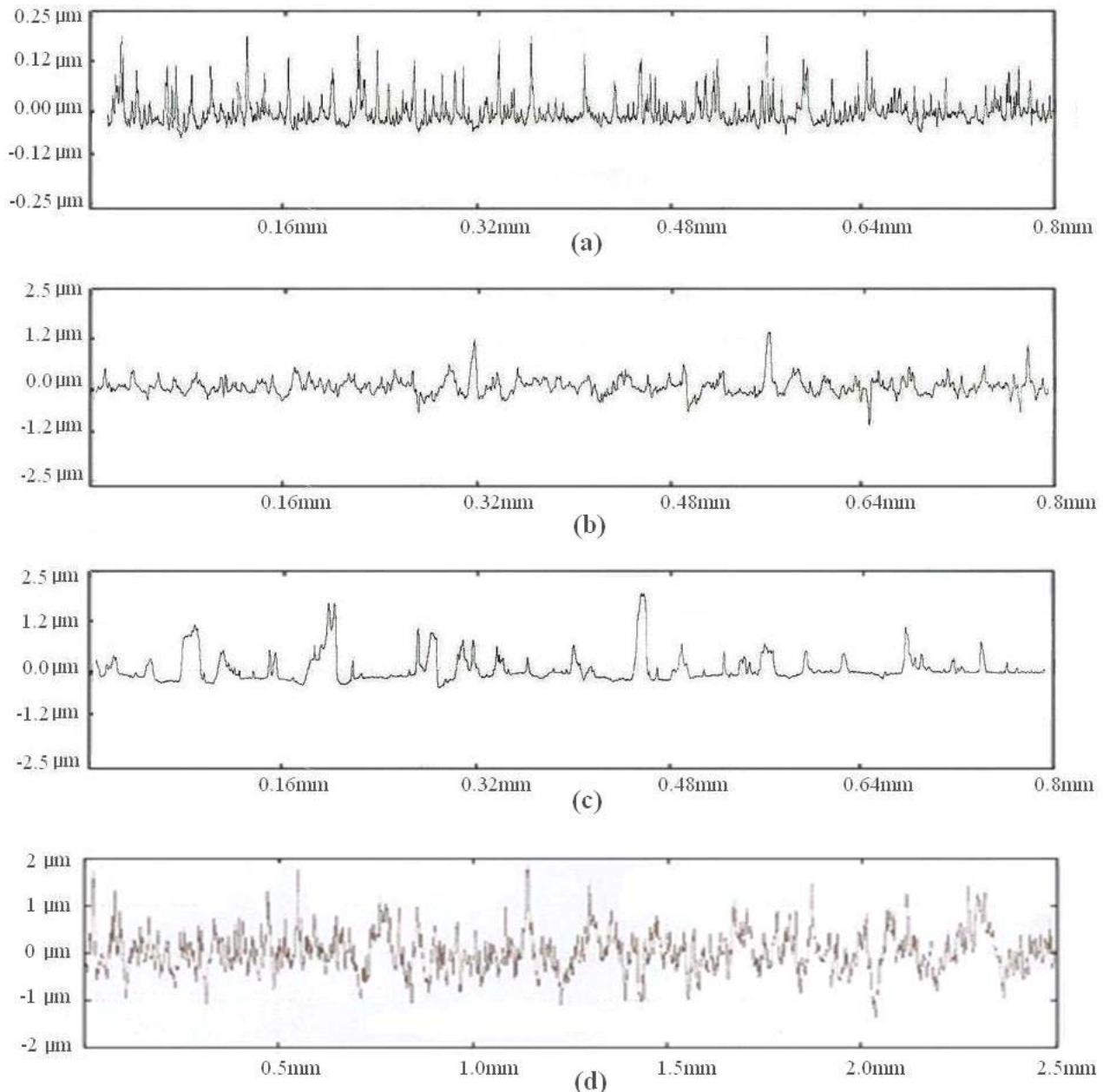


Fig. 2 Profile of the Copper Samples; (a) $Ra=0.09$, (b) $Ra=0.65$, (c) $Ra=0.735$, (d) $Ra=0.901$

Testo 0602 5792 K type immersion probe. To make sure that the readings are correct, another probe was used to measure vapor temperature in equilibrium with the liquid. Moreover, the pressure inside the cylinder was measured by a sensor suited at the top of the cylinder, which allowed further checking of the saturation temperature read by the thermocouples.

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. Water inlet and outlet temperature 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 the wattmeter reading, which measured the amount of power input to the heaters. The difference gives the heat loss from the heaters and the setup assembly to the surroundings. The difference was found to be in the range of 1% of the wattmeter reading.

Warm water from the outlet of the condenser was cooled to a specified temperature with 50% solution of ethylene glycol/water in another heat exchanger, and was then pumped again to the condenser inlet. With this mechanism we were able to maintain a constant temperature at the inlet of the condenser for different heat fluxes.

Experiments were performed at ambient pressure of 660 mmHg. Uncertainties in parameters were estimated using the root-sum-square of Kline and McClintock [18], Tab. I. The reader is referred to [19, 20] for more details of the experimental setup.

TABLE I
ESTIMATED TOTAL UNCERTAINTIES

Parameter	Uncertainty
Input Power	$\pm 1\text{W}$
Heating surface temperature	$\pm 0.7\text{K}$
Temperature of the boiling liquid	$\pm 0.7\text{K}$
Heat transfer coefficient	11%

III. REPRODUCIBILITY OF THE RESULTS

To verify repeatability of the experiments, several tests were performed. Fig. 3 shows heat flux versus wall superheat (difference between heated surface temperature and liquid) for three runs performed on the copper sample with $Ra=0.09$ under the same conditions. As one can see, the results show good reproducibility with less than 4% deviation in wall superheat for a given heat flux.

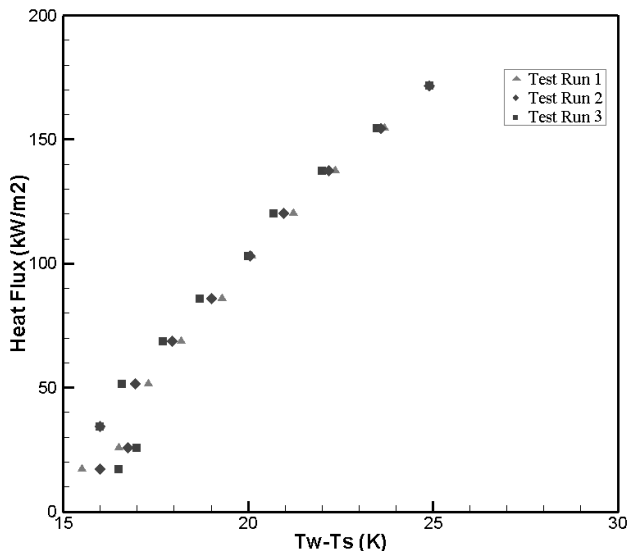


Fig. 3 Heat Flux Versus Wall Superheat for Three Tests Carried Out on Copper Sample with $Ra=0.09$ to Verify Repeatability of Results.

IV. RESULTS AND ANALYSIS

Four samples of copper with different surface roughness were tested in the heat flux range of 8 to 200 kW/m². Fig. 4 shows the corresponding heat flux versus wall superheat. It is found that as surface roughness increases, wall superheat at a given heat flux decreases. Fig. 5 shows heat transfer coefficient versus surface heat flux. Heat transfer coefficient is higher for rough surfaces at a given heat flux, which indicates better heat removal. For instance at heat flux of 170 kW/m², heat transfer coefficient of the sample with $Ra=0.901$ is found to be 3.4, 10.5, and 38.5% higher in comparison with samples with average roughness of 0.735, 0.65, and 0.09, respectively. Moreover, it is found that the enhancement increases at higher

heat fluxes in the range of 8 to 200 kW/m². Furthermore, it is found that for rough surfaces, an increment increase in Ra does not enhance the heat transfer coefficient as much as it does for polished surfaces.

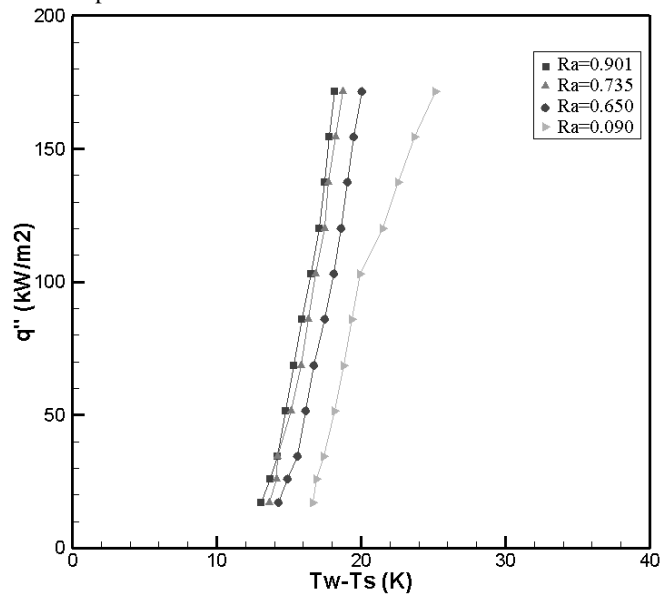


Fig. 4 Heat Flux Versus Wall Superheat for Copper Samples with Different Surface Roughness.

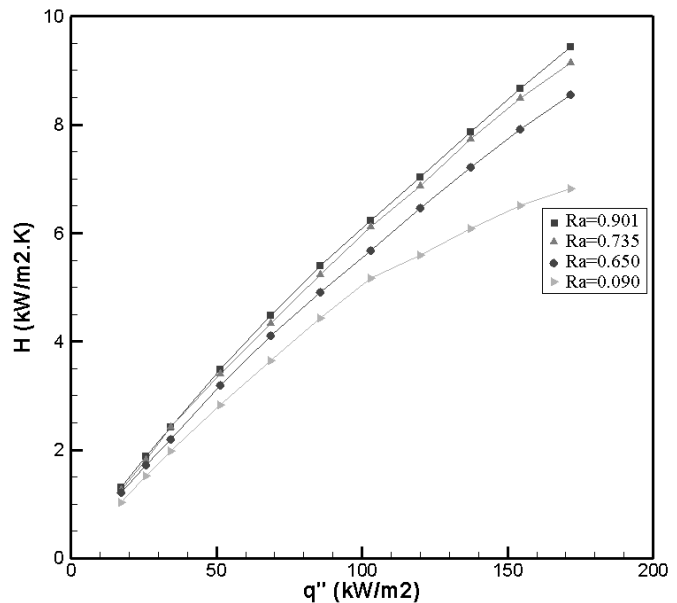


Fig. 5 Heat Transfer Coefficient Versus Heat Flux for Copper Samples with Different Surface Roughness.

Cooper has given a well known correlation for predicting heat transfer coefficient [21], (1). In his extensive study, he has related different parameters such as surface roughness to the heat transfer coefficient.

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

Where the exponent n is calculated as:

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

The parameter R_p is the maximum peak height of the surface profile in μm . However, researchers suggest using average surface roughness, R_a , instead of R_p [11, 14]. Gorenflo et al. [11] suggests using (3) which relates R_p and R_a .

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

Cooper correlation predicts an increase in heat transfer coefficient for rough surfaces. Fig. 6 shows variation of heat transfer coefficient with surface roughness, calculated from his correlation. A comparison of the current results with Cooper correlation has been carried out in Fig. 7. This figure shows the heat transfer coefficient calculated from Cooper correlation and that found from the present experiments. Each point in this figure is the result calculated at a given heat flux. As one can see, the difference between the results for rough surfaces is negligible. However, the Cooper correlation underestimates the heat transfer coefficient for polished surface with $R_a=0.09$.

V.CONCLUSION

Effects of surface roughness on nucleate pool boiling of copper surfaces immersed in R113 were experimentally studied in this report. By measuring wall superheat and surface heat flux, the heat transfer coefficient was calculated. It is found that roughening a surface improves the heat transfer coefficient of boiling. It is found that the heat transfer coefficient of the sample can be improved up to 38.5%. Furthermore, it is found that for rough surfaces, an increment increase in R_a does not enhance the heat transfer coefficient as much as it does for polished surfaces. The results have been compared with literature data and the well known Cooper correlation

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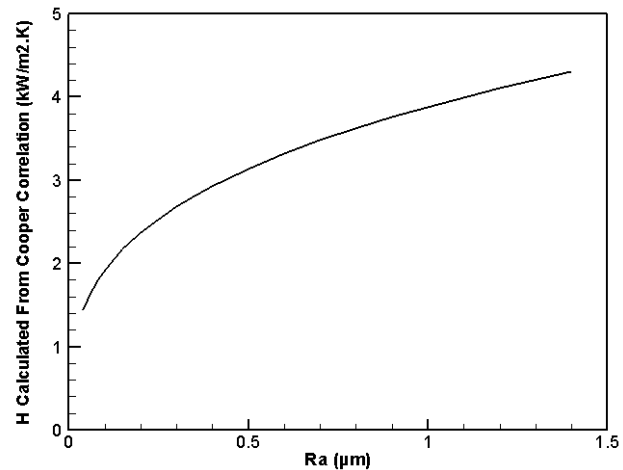


Fig. 6 Variation of Heat Transfer Coefficient vs. R_a Calculated with Cooper Correlation.

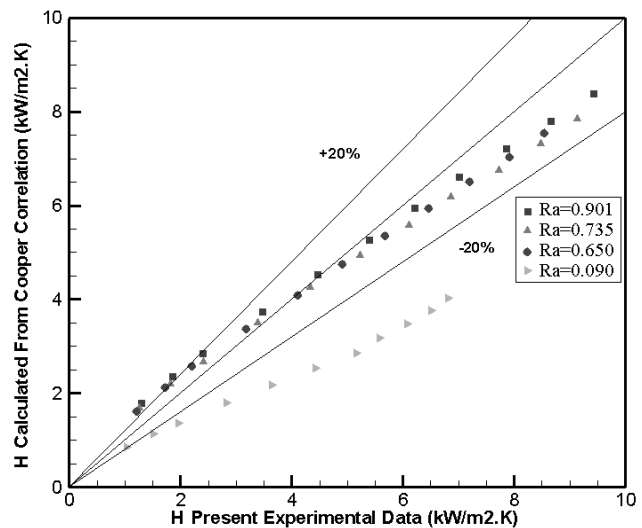


Fig. 7 Comparison of Present Results with Cooper Correlation.

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