Effects of Surface Material and Surface Roughness on the Nucleate Boiling Heat Transfer Enhancement

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Abstract

In this research, an experimental study was performed on the effect of surface materials and surface roughness on the heat transfer performance for the horizontal circular plate heating surface with distilled water used as the working fluid. The experimental apparatus consists of three main sections, i.e. test section, heating device for the test section, and pressure control in the pressure vessel. The test sections used in this experiment were made from two materials, copper and aluminum, having average surface roughness values of 0.2, 2.5 and 4 µm. The roughness can be measured by a MahrMarsurf PS1 model roughness meter. The results show that the measured heat transfer coefficient, based on the aluminum surface, is larger than that for the copper surface. At the roughness of 0.2, 2.5 and 4 µm, the heat transfer coefficient increases up to 23%, 21% and 22%, respectively. Furthermore, the boiling heat transfer coefficient of the distilled water increases with an increase in the roughness value. The high roughness value especially gave better heat transfer than the lower one because of more nucleation sites and cavities in highly rough surface.

Keywords*:* Pool boiling, Heat transfer, Roughness surface.

1. Introduction.

Pool boiling is one kind of heat transfer with phase change process. Normally, pool boiling heat transfer can be developed in two aspects as follows: the first improvement in the working fluids and the second improvement in the heating surface. At the current time focusing on improving the pool boiling heat transfer characteristic by heating surface roughness and material.

The examples of recent publications involving pool boiling heat transfer enhancement are summarized as follows.

McHale and Garimella [1] studied the nucleate pool boiling heat transfer characteristics of perfluorinated hydrocarbon (FC-77) using horizontal flat surfaces which are fabricated from aluminum with different surface roughness values as heating surfaces. The roughness values are 0.03 and 5.89 µm for the polished and roughened surfaces, respectively. The results indicated that the boiling heat transfer coefficient increased with increasing roughness values.

Lee et al. [2] investigated the pool boiling heat transfer coefficient of nano-porous surface make by the cost-effective and simple anodizing techniques were studied with water. The experimental results showed that the heat transfer coefficient of nano-porous coating surface was higher than that for the non-coating surface.

Yao et al. [3] experimentally studied the pool boiling heat transfer performance of water on heating surface with installed Cu nanowire (CuNW) and Si nanowires (SiNW). The results showed that the heat transfer coefficient of Cu nanowire is higher than that of the Si nanowires. Moreover, the heat transfer coefficient increased with an increase in the nanowire height.

Pranoto et al. [4] conducted an experiment to study the boiling heat transfer performance of FC-72 and HFE-7000. The heating surface made from porous graphite foam evaporators. The experimental results showed that the working fluid, HFE-7000, increased the heat transfer coefficient compared with FC-72. Moreover, the heat transfer coefficients of heating surface of fin evaporator were higher than that for block evaporator.

The purpose of this research is to study the effect of heating surface roughness and material on the nucleate pool boiling heat transfer characteristics. The boiling curves of distilled water for copper and aluminium heating surface are presented in this paper.

2. Experimental apparatus and procedure.

This research is an experimental study on nucleate pool boiling heat transfer with a horizontal plate heating surface. Fig.1 shows the experimental device which consists of three main sections: pressure control in the pressure vessel, test section and heating device for the test section.

The test section was placed inside the pressure vessel which was made by cylindrical glass which is covered with insulator of 10 mm thick to prevent lateral heat loss. The pressure vessel contained the distilled water used in the experiment. The temperature of the distilled water was measured by a T-type sheath thermocouple with a diameter of 1 mm, length of 28 cm, and deviation of ±0.1 K. During operation, the pressure inside of the tank is kept at atmospheric condition.

The boiling test section which consists of a heater (1.2 kW) placed inside a copper bar which will transfer heat from the heater to the test section installed at the upper end of the copper bar. Heat from the heater will be transferred only to the upper test section. The copper bar and the test section are covered with calcium silicate insulator which is 50 mm thick to prevent lateral heat loss. The test section used in this experiment was made from two materials: copper and aluminum. The heating surfaces have average roughnesses of 0.2, 2.5 and 4 μm. The roughness can be measured by a MahrMarsurf PS1 model roughness meter. Average roughness (Ra) and mean peak-to-valley height roughness (Rz) are shown in Table 1. The test section area contains four holes for installing sheath thermocouples with average diameter of 1mm and length of 100 mm. Thermocouples are placed at intervals of 10 mm. The distance between the uppermost sheath thermo couple and the heating surface is 20 mm. Temperatures at various locations in the test section would be used to calculate the temperature of the heating surface.

Pressure inside the tank was controlled by adjusting the water flow in the cooling coil to control the condensation rate of vapour at the outer surface of the cooling coil. Pressure inside the tank was controlled at atmospheric condition throughout the experiment.

In the experiment with high heat flux, there was film boiling which created film at the heating surface. When this happened, temperatures at various points of the test section increased rapidly. This condition can cause harm to the apparatus. Therefore, a wind blower was installed to eradicate film boiling on the heating surface; hence, the surface temperature decreased.

Table 1. Roughness of copper and aluminium heating surface.

No.	Copper Heating Surface					
	Ra = 0.2 μm		Ra = 2.5 μm		Ra = 4 μm	
	Ra	Rz	Ra	Rz	Ra	Rz
1	0.237	1.104	2.745	16.100	4.088	23.000
2	0.191	1.078	2.787	17.300	3.224	22.300
3	0.194	1.061	2.638	18.600	3.710	20.100
4	0.200	1.067	2.453	14.400	3.892	24.500
5	0.201	1.068	2.253	14.300	4.231	24.100
6	0.191	1.078	2.396	16.300	4.325	26.100
7	0.171	1.094	2.287	14.900	4.409	25.500
8	0.196	1.063	2.188	13.400	4.328	25.000
No.	Aluminium Heating Surface					
	Ra = 0.2 μm		Ra = 2.5 μm		Ra = 4 μm	
	Ra	Rz	Ra	Rz	Ra	Rz
1	0.192	0.192	2.368	14.500	4.219	22.200
2	0.213	0.213	2.419	15.500	5.343	30.500
3	0.227	0.227	2.584	16.300	4.227	25.000
4	0.220	0.220	2.378	14.600	3.538	25.300
5	0.211	0.211	2.862	18.100	3.984	24.300
6	0.202	0.202	2.847	17.600	3.978	23.300
7	0.172	0.172	2.645	17.400	3.891	22.200
8	0.194	0.194	2.227	14.200	3.499	21.000

After experimenting under each condition, the experimental apparatus was dissected and cleaned. The apparatus can be cleaned by using a high-pressure water injector to inject water on the heating surface. After that, the apparatus was dried with a blower before being assembled for use in experiments under other conditions. All tested conditions of the heat transfer equipment are shown in Table 2.

Table 2. Experimental conditions.

Classification of boiling	Saturated pool boiling
Material of heating surface	Copper and Aluminium
Heating surface roughness	0.2, 2.5 and 4.0 μm
Heat flux	40 – 800 kW/m^2

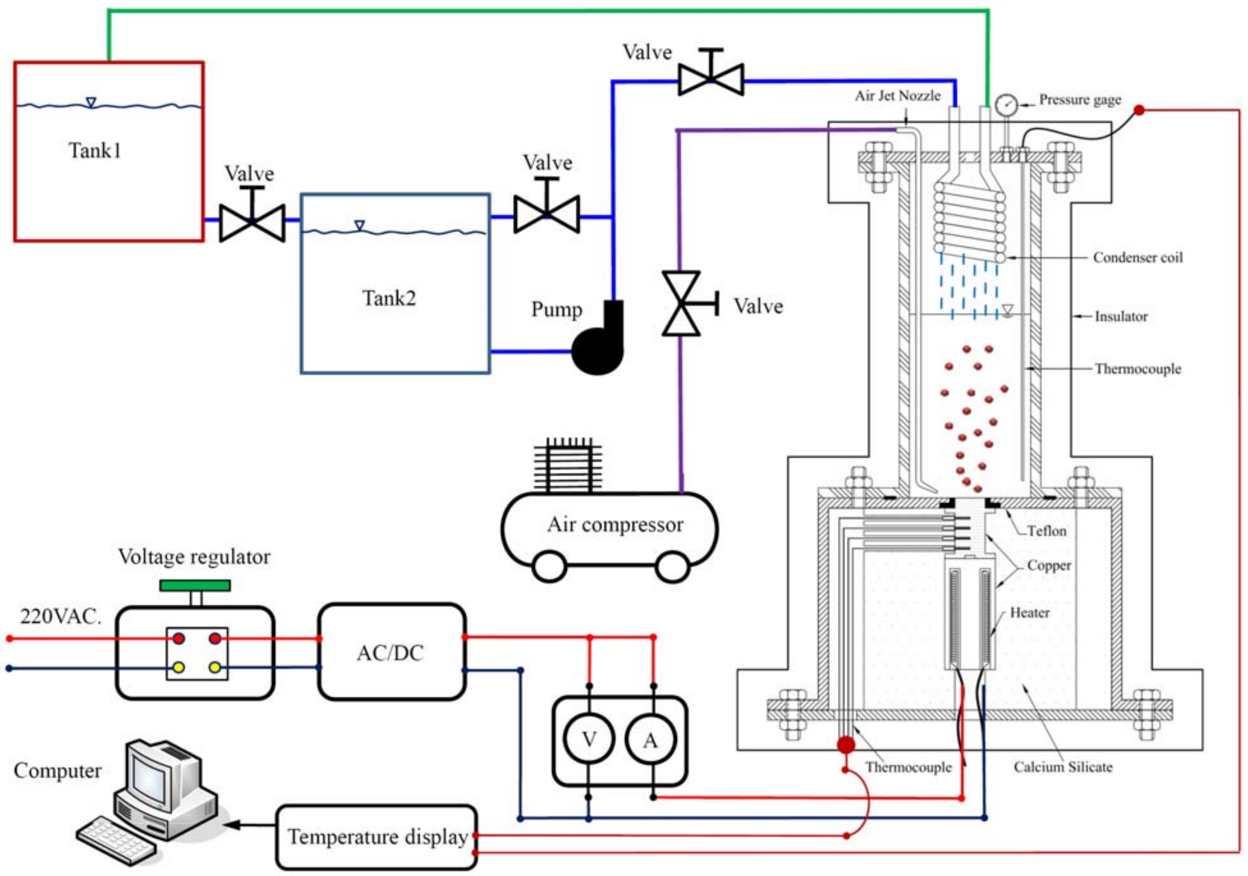

Fig. 1. Schematic diagram of experimental apparatus.

3. Data reduction

Experimental studies were carried out to observe the boiling characteristics using the flat plate heating surface. The heat fluxes, q (W/m^2), were calculated from the following equation:

$$q = \frac{IV}{A} \quad (1)$$

where I is the current (amps), V is the voltage (volts), and A is the heating surface area (m^2).

The average pool boiling heat transfer coefficient, h_b (W/m^2.K), is defined as:

$$h_b = \frac{q}{T_s - T_{sat}} \quad (2)$$

where T_s is the average heating surface temperature (K) calculated from Eq. (3), and T_{sat} is the liquid saturation temperature (K):

$$T_s = \frac{\sum_{i=1}^{4} T_i \sum_{i=1}^{4} x_i^2 - \sum_{i=1}^{4} x_i \sum_{i=1}^{4} x_i T_i}{4\sum_{i=1}^{4} x_i^2 - \left(\sum_{i=1}^{4} x_i\right)^2} \quad (3)$$

where T_i is the local temperature (K) and x is the position of the temperature measurement (m) on the test section.

The uncertainties of the heat flux and heating surface temperature are ±2.2% and ±3.7%, respectively.

4. Results and discussion.

This research studied the nucleate pool boiling heat transfer characteristics at atmospheric pressure using distilled water as working fluids. The heating surfaces were made from copper and aluminium with surface roughness of 0.2, 2.5 and 4 µm. Fig.2a shows the pool boiling curve in the form of relationships between heat flux and T_s-T_{sat} (which is the heating surface temperature minus the liquid saturation temperature). Fig.2b shows relationship between heat flux and heat transfer coefficient. The details of the experimental results are as follows.

The effect of heating surface roughness on the pool boiling heat transfer coefficient of the distilled water increases with an increase in the roughness value. The high roughness value especially gave better heat transfer than the lower one because of more nucleation sites and cavities in highly rough surface.

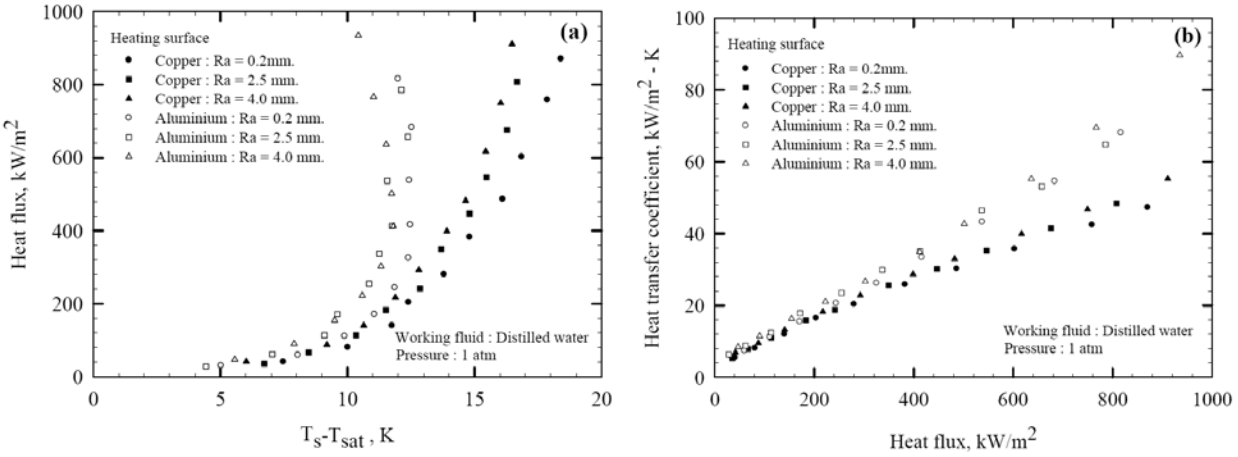

Fig. 2. Nucleate pool boiling heat transfer of distill water at 1 atm.

The effect of heating surface material on the heat transfer coefficient, based on the aluminium surface, is higher than that for the copper surface. At the roughness of 0.2, 2.5 and 4 µm, the heat transfer coefficient was increased up to 23%, 21% and 22%, respectively.

5. Conclusion.

The experimental study was performed on the effect of surface materials and surface roughness on the heat transfer performance for the horizontal circular plate heating surface with distilled water used as the working fluid.

The results show that the heat transfer coefficient, based on the aluminium surface, is higher than that for the copper surface. At the roughness of 0.2, 2.5 and 4 µm, the heat transfer coefficient was increased up to 23%, 21% and 22%, respectively. Furthermore, the boiling heat transfer coefficient of the distilled water increases with an increase in the roughness value. The high roughness value especially gave better heat transfer than the lower one because of more nucleation sites and cavities in highly rough surface.

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7. References.

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