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Roughness effects on nucleate pool boiling of water on horizontal stainless steel cylinder

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Abstract

Nucleate boiling heat transfer (NBHT) has been considered an effective way to remove the higher heat flux at a given temperature difference compared with a single phase heat transfer. The present study is an experimental investigation of roughness effects on nucleate pool boiling of water on horizontal stainless steel cylinder. The cylinders were treated by different sand paper grit sizes to achieve different surface roughness. The average surface roughness of the sex samples was 0.98, 0.81, 0.65, 0.48, 0.24 and 0.08 µm, respectively. The experiments were performed in the heat flux range of 5 to 110 kWm^{-2}. 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. The experimental data show that bubble departure frequency and nucleation site density increase and bubble departure diameter decreases with increasing the surface roughness. A new model for the prediction of heat transfer coefficient is proposed, which predicts the experimental data with a satisfactory accuracy.

Keywords: Nucleate Pool Boiling, Horizontal Cylinder, Water, Surface Roughness

1. Introduction

Nucleate Boiling Heat Transfer (NBHT) has been considered an effective way to remove the higher heat flux at a given temperature difference compared with a single phase heat transfer. Conventional and enhanced boiling of liquids have a wide range of industrial applications that include power generation, chemical and petrochemical industries, refrigeration and cryogenics, electronics cooling, desalination of seawater and in nuclear power plants, either for heating or electricity generation. Over the past years there has been extensive research to address issues such as bubble growth, bubble dynamics, effects of heater surface characteristics, fluid-surface interaction, and fluid properties, among others. Surface roughness has long been known to have a significant impact on the boiling process. Berenson found that maximum nucleate-boiling heat flux is independent of surface roughness. 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 (Gorenflo et al., 2004). Berenson concluded that enhancement in heat transfer coefficient is a result of higher active cavity density (Berenson, 1962). Benjamin and Balakrishnan studied nucleate boiling of different fluids at moderate heat fluxes to study variation of nucleation site density with surface roughness (Benjamin and Balakrishnan 1996). They used stainless steel and aluminum with different surface finish in their study. Their results have shown that nucleation site density depends on surface microroughness, the surface tension of the 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 (Kang, 2000). His results have shown that 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. (2004) 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 (1985) investigated 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. Jabardo et al. (2009) 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. The goal of this research is to study the effect of surface roughness on bubble dynamic and heat transfer coefficient in water nucleate pool boiling at atmospheric pressure.

2. Experiments

Fig. 1 schematically demonstrates the experimental equipment used in the present investigation. The cubic shaped boiling vessel is made of stainless steel containing approximately 20 L of test liquid and is connected to a vertical condenser to recycle the evaporated fluid. The assumptions related to saturation pool boiling condition hold true for this investigation due to the fact that the used boiling vessel has high volume relative to the boiling area and it is thermally insulated to minimize heat loss. System is continuously monitored and regulated to preserve predetermined operating condition. The saturation pressure (P = 1atm) is controlled by adjusting the mass flow rate of the cool water in the condensation loop. The water temperature and mass flow rate passing through the cooling coil are adjustable. Also, for safety reasons, a pressure relief valve is mounted on the top of the tank. The vessel is equipped with two heaters: 1) auxiliary heater, which is a simple element to rise the bulk temperature to saturation temperature (P = 1atm), and 2) rod heater, which consists of an internally heated stainless steel rod equipped with four thermocouples stainless steel shielded and embedded along the circumference of the rod, close to the heating surface (0.75 mm). To minimize thermal contact resistance between each thermocouple and sheath, silicon paste is injected into the location of placing each thermocouple.

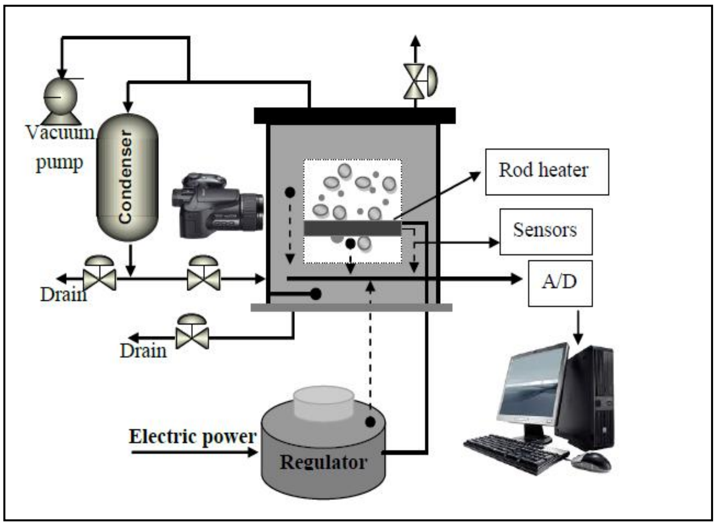

Fig. 1: Scheme of experimental apparatus used in this investigation.

A total of six test pieces of varying surface roughness were fabricated. The average roughness (Ra) of the test surface is measured by a portable surface roughness tester (TR200). The rod heater operates with variable A/C electrical power input providing variable heat fluxes. Details of the rod heater are given in Fig. 2. A PC-based data acquisition system was used to record some of the measuring parameters. By means of two observation glasses positioned at both sides of the tank, the test section was easily observable, allowing ease of photography during the experiments (Hamzekhani et al., 2014). The electrical input power of the rod heater was calculated by the product of electrical voltage, current and cosine of the difference between input electrical voltage and current. The temperature drop due to the existence of small distance between surface and thermocouple location was calculated by applying heat conduction equation for cylinders:

$$\frac{1}{r}\frac{d}{dr}\left(kr\frac{dT}{dr}\right) = 0 \quad (1)$$

In Eq. (1), k is the temperature dependent thermal conductivity of the heater, which was approximated to a linear function of temperature.

The axial heat loss from the heated length to the unheated length of this rod was calculated to be less than 0.1 % of the total heat transfer (Hamzekhani et al., 2014). The boiling heat transfer coefficient was calculated simply by Newton's cooling law and known value of wall temperature. Visual information related to bubbles was recorded by Casio EX-FH100 digital camera. This camera can record high-speed movies at 1,200 fps which is sufficient for the analysis of bubble motion. The typical photo specification was: shutter speed: 1:1000 s, ISO: 800, F: 5.5 and focal length: 100 mm (Approx)

The experiments have been entirely performed at saturation temperature at atmospheric condition. Initially, the entire system, including the rod heater and the inside of the tank were cleaned and the test solution was introduced. Following this, the tank band heater was switched on and the temperature of the system was allowed rising to the saturation temperature. In the next step, the rod was heated with maximum power. After the system reached the steady state, significant data including surface temperature and visual information were recorded. The information was gathered by decreasing the power in various intervals and recording the measurements upon reaching the steady state. Some runs were repeated two or even three times to ensure the reproducibility of the experiments. The measured data was including: A) Wall temperature: this parameter was calculated based on the recorded temperatures of the thermocouples inside the rod heater and by application of Eq. (1).

The arithmetic averages of four thermocouples were assigned to the actual wall temperature, B) Bubble diameter: this parameter was derived by analysis of the captured photos of the heating surface. Notably that formation of very large bubbles is due to the bubbles coalescence and development of very small bubbles is because of bubbles breakage phenomenon. Both of these phenomena are the results of shearing of vapor through liquid phase. Locations of development for both of these bubble types are relatively far away from the heating surface and are not directly induced by the boiling phenomenon. Therefore the extreme over-sized and under-sized bubbles were ignored and the averages of the remaining bubbles were assigned to the actual bubble diameter. The diameters of the non-spherical bubbles were calculated by projected area of the bubbles using SigmaScan, the image analysis software, C) Bubble departing frequency: the individual bubble nucleation sites were monitored in the slow-replay of the visual information and the arithmetic average frequencies of various nucleation sites were assigned to the bubble departing frequency, D) Nucleation site density: This parameter was measured by analysis of the high speed recorded films of the heating surface. The bubble nucleation sites have been counted by slow-replay of the visual information of the boiling phenomenon. Nucleation site density was calculated by division of the counted nucleation sites to the total heating area.

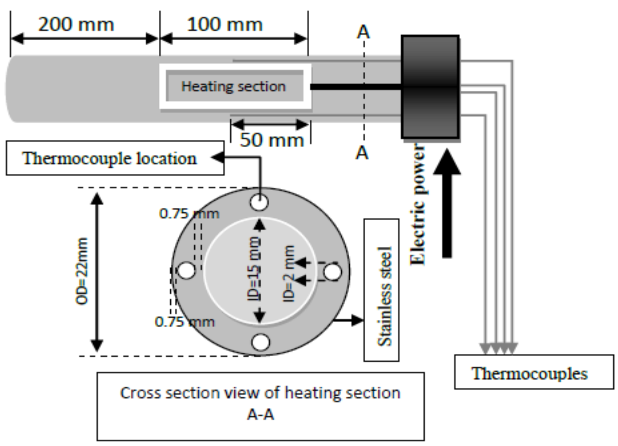

Fig. 2: Details of the rod heater.

Fig. 1: Scheme of experimental apparatus used in this investigation.

3. Uncertainly

The heat transfer coefficient is calculated from the following formula:

$$h = \frac{q}{\Delta T_w} = \frac{I.V}{A.\Delta T_w}\left(\frac{W}{m^2 K}\right) \quad (2)$$

Based on the theory of errors, the maximum relative error in calculating the heat transfer coefficient can be obtained from the Eq.3:

| (3)

The electric current flowing through the heating wire and the voltage taken from the power supply to the heater element are measured by a digital multimeter (SA 8515). The minimum accurate readable value is 0.08 A and 1 volt, hence

$$|\delta I|_m = \frac{0.08 * 100}{3.12} = 2.5641\% \quad (4)$$

$$|\delta V|_m = \frac{1 * 100}{220} = 0.45455\% \quad (5)$$

A micrometer measures the heating surface diameter and its value to be 22 mm. The minimum accurate readable value of the micrometer is 0.02 mm. The vernier measures the heating surface length and its value to be 100 mm and the minimum accurate readable value of the vernier is 0.2 mm, hence

$$|\delta A|_m = \frac{0.1 * 100}{22} + \frac{0.2 * 100}{100} = 0.290909\% \quad (6)$$

The temperature difference is measured by K-type thermocouples. The minimum accurate readable value is 0.2 ℃, hence

$$|\delta \Delta T_w|_m = \frac{0.2 * 100}{10.5} = 1.9048\% \quad (7)$$

Substitute Eq.4-7 in Eq.3, then

$$|\delta h|_m = 2.5641 + 0.45455 + 0.290909 + 1.9048 = 5.214359\% \quad (8)$$

4. Result and discussion

Fig. 3 presents the boiling heat transfer coefficient of water at different roughness as a function of heat flux. The results suggest that the boiling heat transfer coefficient, an increase with either increasing heat flux or increasing surface roughness. This is attributed to the agitation effect resulted from the mobility of the vapor bubbles emitted from the tube wall nucleation sites, and then travel through the liquid pool. The increase in heat flux activates greater number of nucleation sites. Also, an explanation for observed enhancement in heat transfer coefficient could be given by considering the role of surface roughness, and subsequent modification of bubble dynamics which helps promote large number of active nucleation sites. In addition, the experimental results have shown that the heat transfer coefficient increases by about 60% for water.

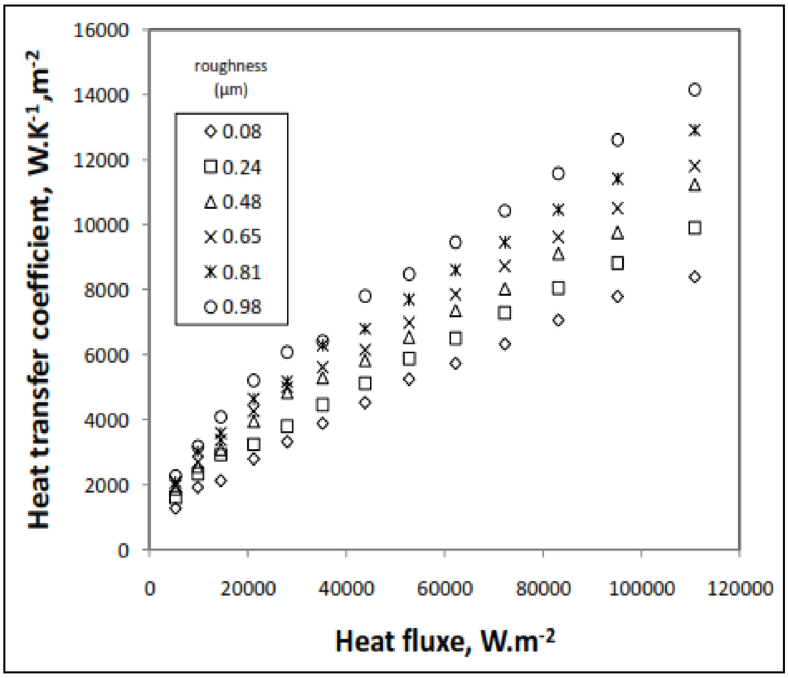

Figure 3. Variation of heat transfer coefficient with heat flux for different roughness

Fig. 4 shows that the measured bubble departing diameter as function of heat flux at various surface roughness. Bubble diameter increases with increasing of heat flux. Also, the data show that bubble diameters decrease with increasing surface roughness.

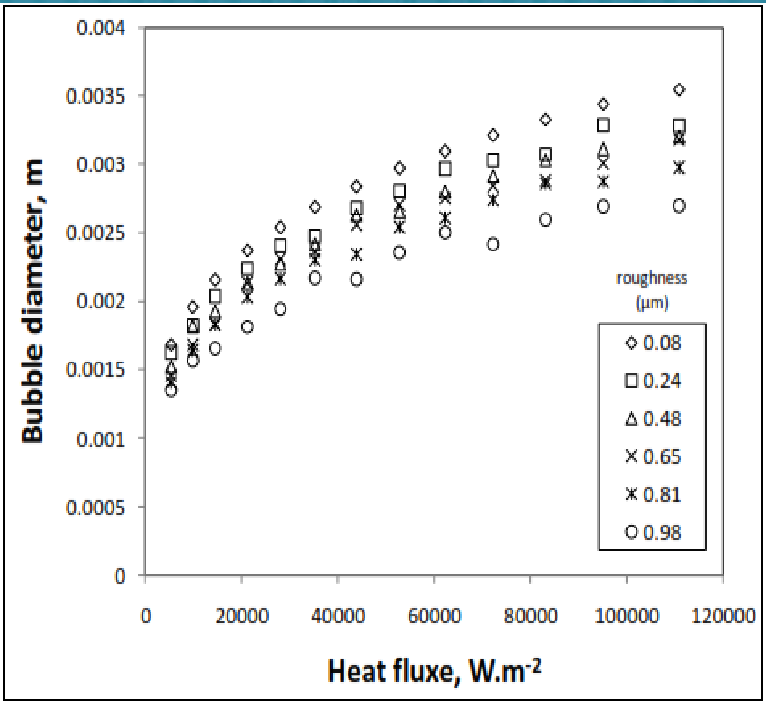

Figure 4. Variation of bubble diameter with heat flux for different roughness

Fig. 5 presents the bubble departing frequency as a function of heat flux at various surface roughnesses. The data indicate that bubble departure frequency increases with increasing of either heat flux or increasing the surface roughness at same condition. It is due to the reducing bubble diameter with increasing surface roughness.

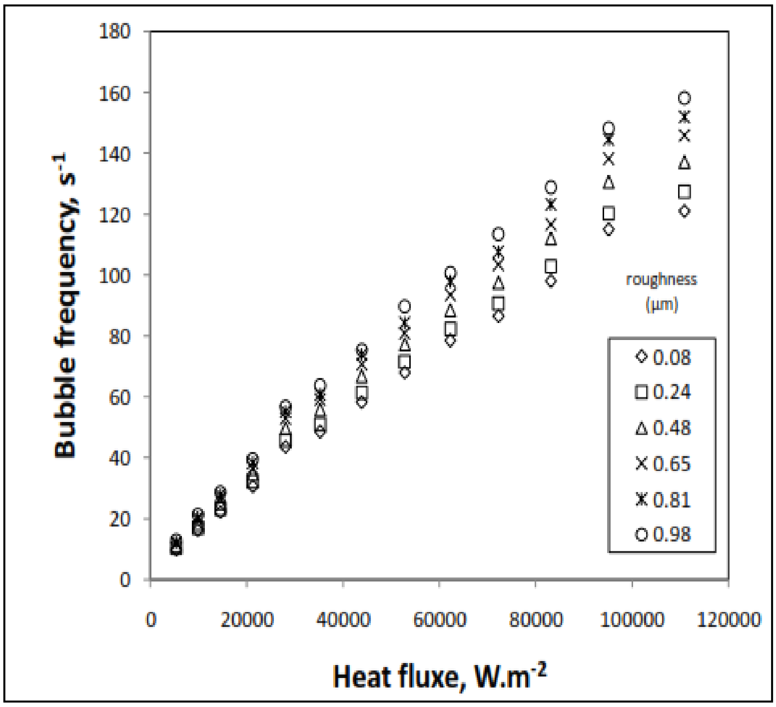

Figure 5. Variation of bubble frequency with heat flux for different roughness

Fig. 6 presents the nucleation site density as a function of heat flux at various surface roughnesses. The represented data suggest that nucleation site density increases with either increasing heat flux or increasing the surface roughness.

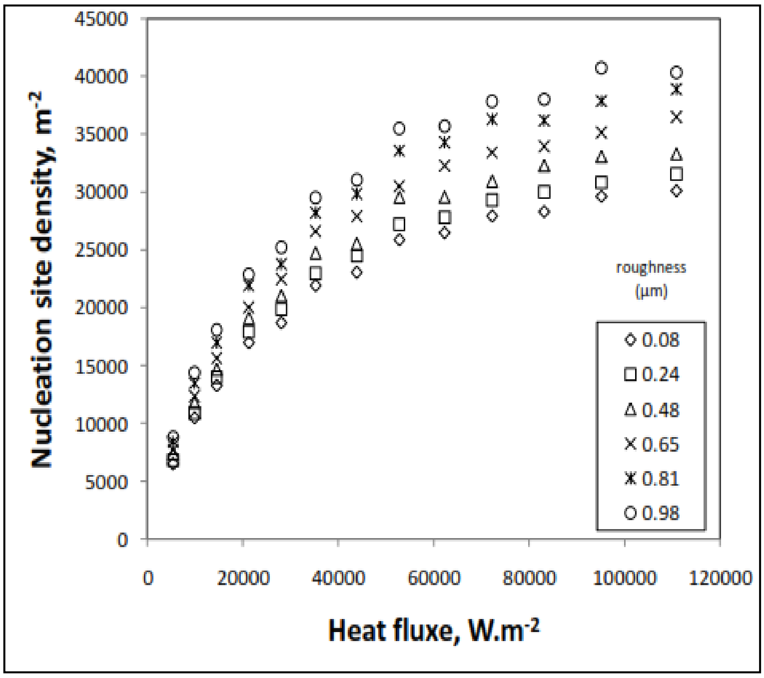

Figure 6. Variation of nucleation site densities with heat flux for different roughness

5. New model

In this study, by considering the effect of surface roughness on bubble dynamic, a new experimental model based on surface roughness has been proposed as:

$$\frac{hd_b}{k_l} = A_1\left(\frac{\rho_v f d_b^2}{\mu_v}\right)^{A_2}\left(\frac{\frac{N}{A}\alpha}{f}\right)^{A_3}\left(\frac{Ra}{Ra_0}\right)^{A_4} (A_1= (22.314),\ A_2= (70.55),\ A_3= (2.5),\ A_4= (0.028),\ Ra_0 = 0.08) \quad (9)$$

$$f = c_1\left(\left(\frac{Ra}{Ra_0}\right)^{c_2}\right)q^{c_3} \qquad (c_1= (.0007),\ c_2= (1.105),\ c_3= (0.08433)) \quad (10)$$

$$\frac{N}{A} = b_1\left(\left(\frac{Ra}{Ra_0}\right)^{b_2}\right)q^{b_3} \qquad (\mathbf{b_1} = (\mathbf{11.294}),\ \mathbf{b_2} = (\mathbf{.0095}),\ \mathbf{b_3} = (\mathbf{0.4928})) \quad (11)$$

$$d_b = e_1\left(\left(\frac{Ra}{Ra_0}\right)^{e_2}\right)q^{e_3} \qquad (e_1 = (.002),\ e_2 = (-0.0156)\ and\ e_3 = (0.0249)) \quad (12)$$

$\alpha, f, \frac{N}{A}, d_b, Ra, c_{pl}, k_l$ *and* ρ_l are heat transfer coefficient, bubble frequency, nucleation site density, bubble diameter, roughness, liquid heat capacity, thermal liquid conductivity and liquid density respectively.

Fig. 7 presents the experimental versus predicted values of heat transfer coefficients. The results show significant improvement on predictive capability of the model and experimental data.

6. Conclusion

An experimental investigation on the effect of surface roughness on heat transfer coefficient for water under nucleate saturated pool boiling conditions has been performed and the following results have been obtained:

- The results show significant improvement of heat transfer coefficient as the surface roughness is increased.

- The experimental data show that bubble departure frequency and nucleation site density increase and bubble departure diameter decreases with increasing the surface roughness.
- A new model for the prediction of heat transfer coefficient is proposed, which predicts the experimental data with a satisfactory accuracy.

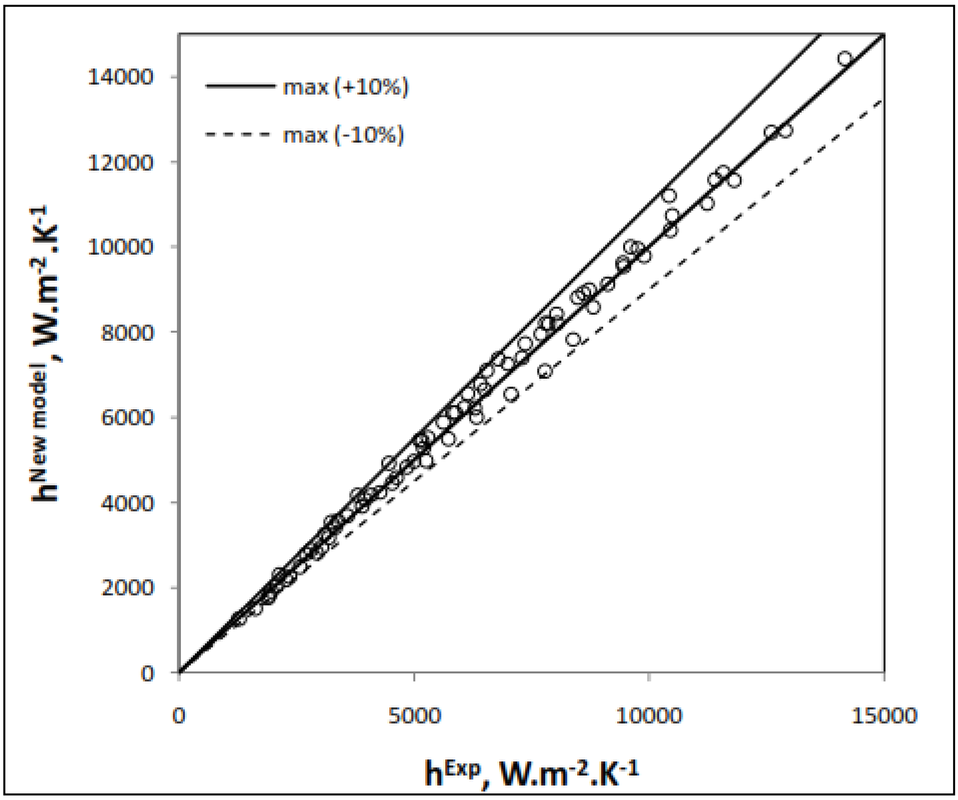

Figure. 7 Experimental data versus predicted values of heat transfer coefficients by the new model

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