Influence of surface roughness on pool boiling heat transfer

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Abstract. Experimental study of pool boiling heat transfer from the rough surface at pressure 1 bar, 5 bar and 10 bar is presented. Experiments are carried on 20 mm diameter copper sample at saturated condition of distilled water. Unidirectional scratches are made by different grit sandpaper. The surface roughness value R_a is varied from 0.106 µm to 4.03 µm. The effect of R_a on heat transfer at different pressure is reported. The variation in heat transfer coefficient with the heat flux for samples of different R_a is also examined. The predicted critical heat flux (CHF) by Kim's model is found to in good agreement with present experimental values with mean absolute error of 12.06%.

Keywords. Surface roughness, pool boiling, critical heat flux, and heat transfer coefficient .

1. Introduction

The surface characteristics is a vital parameter in the pool boiling heat transfer (PBHT). Many investigators have reported CHF enhancement due to pin-fin structure, rough surface, porous surface, microchannel structure, surface coating etc. The preparation of rough surface is easy and cheap. It can be obtained by surface machining, polishing by sandpaper, sintering, chemical treatment like dry or wet etching etc. Few outcomes reported in the literature claim the adverse effect of roughness on heat transfer. However many investigators have reported the CHF enhancement due to surface roughness. Few literature is also available which describes the effect of surface roughness on surface wettability and nucleation site density. Summary of the experimental conditions used in the literature is presented in Table 1. Anderson and Mudwar [1] carried pool boiling experiment in FC-72 to examine the effect of rough surface on heat transfer. Rough surface of R_a = 0.6-1.0 µm was prepared by 600 grit SiC sandpaper. The CHF for the rough sample was found to be 20.5 W/cm^2. They reported the insignificant role of surface roughness in CHF enhancement. Benjamin and Balakrishnan [2] conducted pool boiling experiments using rough surface in water, CCl_4, acetone, and n-hexane. They concluded that increased nucleation sites due to surface roughness resulted in the enhanced heat transfer. Remarkable heat transfer enhancement was reported by Kang [3] for vertically oriented rough surface. McHale et al. [4] conducted experiments on the sample of R_a=0.038 µm–10.0 µm. Rough samples were prepared by polishing and EDM. Bubble nucleation characteristics were also studied by visualisation technique. Enhancement in HTC of water was found to be 100% for the roughest surface. They commented that surface area enhancement due to increase in roughness does not signify the HTC enhancement. In another study, Jones et al. [5], found that contact angle does not change apparently for different surfaces and heat flux conditions. Ahn et al. [6] performed anodization to modify the surface wettability of the Zircaloy-4. Contact angle of the bare surface reduced from 49.3° to 0° for the treated surface whereas R_a increased from 0.15 µm to 0.32 µm. CHF of the superhydrophilic surface was found to be 1924 kW/m^2. Liquid spreadability was significantly improved due to surface roughness. The effect of surface roughness on CHF remained unclear in their study.

Table 1. Details of the experimental studies available in the literature

Author	Base Material	Boiling Fluid	Characteristics	Fabrication Technique	Size/Shape /Type of the structure	CHF	HTC
Anderson and Mudwar [1]	Cu	FC-72	Rough surface [R_a=0.6-1.0 µm]	SiC polishing	12.7x12.7 mm^2	205 kW/m^2	-
Jones et al. [5]	Al	FC-72	Smooth [R_a=0.38 µm] Rough [R_a=1.08,2.22,5.89, 10 µm]	Smooth-Mechanical Polishing Rough-EDM	25.4x25.4 mm^2	~190 kW/m^2	14 kW/m^2 K
Ahn et al. [6]	Zr-4	DI water	ψ=0-43.3°, R_a=0.15-0.32 µm	Anodization (time-0-600 s)	20x25 mm^2; rectangular	1924 kW/m^2	-
Dong et al. [8]	Si	Ethanol	[a]Micropillar [d=5,10,20,50,100µm; h=5,50µm] [b]Nanowire [d=0.3-0.8µm; h<1.32µm]	Micropillar-Dry etching Nanowire-wet etching ($AgNO_3$+HCL)	Microstructure	[a]~620 kW/m^2 [b]~650 kW/m^2	[b]45 kW/m^2 K
Kruse et al. [9]	SS	DI water	Mound like microstructure [R_a=1.4,4.6,7.4,7.8]	Femtoscale laser process	Hybrid microtructure	1420 kW/m^2	67.4 kW/m^2 K
Saeidi et al. [10]	Cu & Al alloy	DI Water	Aluminised copper surface [R_a=41nm; h=406nm; Θ =66°]	Aluminising	Coating	1227 kW/m^2	70 kW/m^2 K
Li et al. [11]	Ni	Water	Chemically treated nano-cone array [R_a=0.027 µm -0.22 µm; Θ=90°-5°; r=1-1.45]	Electro chemical process	Foil [1x5 mm^2]	1700 kW/m^2	70 kW/m^2 K
Kim et al. [12]	Cu	DI water	Unidirectional scratches [R_a=0.041 µm -2.36 µm]	Polishing	-	1625 kW/m^2	-
Kim et al. [13]	Al	DI water	[R_a=0.11 µm -2.93 µm]	Hot water treatment	-	2150 kW/m^2	-

Hosseini et al. [7] prepared rough copper, brass, and aluminium surfaces by polishing with sandpapers and conducted pool boiling experiments in R113. HTC for copper sample was found to be higher than that for brass and aluminium, although it had least R_a. Dong et al. [8] investigated the effect of the micro/nano structures like micro-pillars (MP), micro-cavities (MC), nanowires (NW) and nano-cavities (NC) on the bubble departure characteristics and nucleation density. Microstructures were fabricated by dry and wet etching. It was found that nanostructure helps to reduce the bubble departure diameter, accelerate the bubble frequency and delays the bubble coalescence. They noticed that cavity radius and wall superheat have vital role in the bubble nucleation density. Kruse et al. [9] fabricated multiscale structure on 304 stainless steel surface by femtosecond laser surface process (FLSP). It formed a self-organised mount like structures covered by layer of nanoparticles. The surface roughness R_a was varied from 1.4 µm to 7.8 µm. The sample of R_a =1.4 µm was found to have CHF of 1420 kW/m^2 which was higher than that of R_a =7.8 µm. However the HTC for R_a =7.8 µm was 38.68% higher than that for R_a =1.4 µm. They commented that surface wettability and its wicking ability enhance the cooling effect. Additionally it was found that boiling curves moved towards left with increase in R_a. Saeidi et al. [10] reported the pool boiling characteristics of the aluminised copper sample in DI water. They found that CHF of aluminised surface is 37% higher than that of untreated copper surface. The treated surface had shown higher surface roughness and contact angle compared to the untreated surface. Despite higher contact angle, CHF for treated surface was found to be higher which suggests that CHF is not the function of contact angle only. Li et al. [11] examined the compound effect of nano-scale roughness, contact angle and wetted surface area on HTC. The samples were prepared by electrochemical deposition on the Ni foil and nano-cone array was obtained where R_a found to be unchanged. HTC decreased with decrease in the contact angle whereas HTC enhanced with increase in wetted surface area. Kim et al. [12] studied the effect of surface roughness on surface wettability for the sample of R_a varying from 0.041 µm to 2.36 µm. Wettability found to be increased due to capillary wicking through the narrow scratches. They commented that CHF enhancement due to rough surface is the consequences of capillary wicking and reduced contact angle. Kim et al. [13] studied pool boiling characteristics of rough and superhydrophilic surface aluminium sample. Hot water treatment resulted in the formation of superhydrophilic nanoscale protrusions on the aluminium surface which proved significant heat transfer.

The presented literature suggests that rough surface has influence on the surface wettability, nucleation site density and wetted surface area. Few investigators have reported that increase in nucleation site density resulted in the early bubble coalescence which deteriorates the heat transfer. The pattern of roughness like sintered surface or unidirectional scratch is also found to be important which can retard the bubble coalescence. Present study explores the possibility of heat transfer enhancement by the unidirectional scratches with wide range R_a ranging from 0.106 µm to 4.03 µm. The effect of R_a on pool boiling of water is extensively studied at pressure P=1 bar, P=5 bar and P=10 bar. The CHF is predicted by Kim's model which considers the effect of R_a on heat transfer.

2. Experimentation

2.1. Experimental Setup

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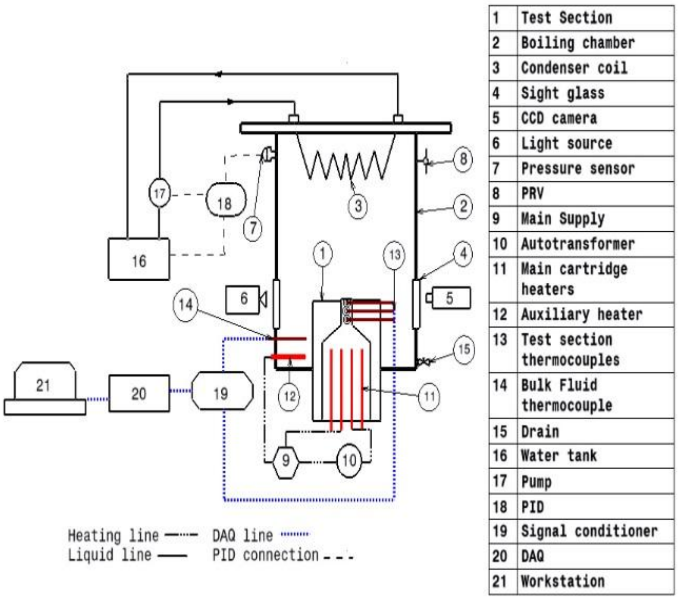


Figure 1. Experimental Setup

The experimental setup, as shown in Figure.1, mainly includes a boiling chamber, test section, condenser unit, and CCD camera. The rectangular chamber has removable top and bottom flanges. The top flange is integrated with condenser coil whereas the test section is fitted to bottom flange. K-type thermocouple and pressure transducer are inserted into the boiling chamber to measure the bulk fluid temperature (T_l) and chamber pressure, respectively. Transparent borosilicate glass is provided to the wall of boiling chamber for the visualization study. Auxiliary heaters of 2000W capacity are used to maintain the saturation condition of the distilled water. The setup is integrated with NI-9213 temperature module to acquire temperature readings.

2.2. Test Section

20 mm diameter and 20 mm length copper samples are prepared and characterized. The high density cartridge heaters are inserted in the heating block. The sample is fixed on the heating block with perfect surface contact. The assembly of sample and heating block is perfectly insulated with glass wool bed as shown in Figure. 2. An O-ring and high-temperature non-corrosive RTV silicone gasket are used between the test sample and insulation block to prevent leakage and to avoid edge effect during the boiling test. K-type sheathed thermocouples of 1 mm diameter are used to measure the temperature of the test sample at different locations. The thermocouples are implanted at 2 mm, 6 mm, and 10 mm in the test sample from the top surface and the temperatures T_{m-1}, T_m, and T_{m+1} correspond to these thermocouple readings, respectively.

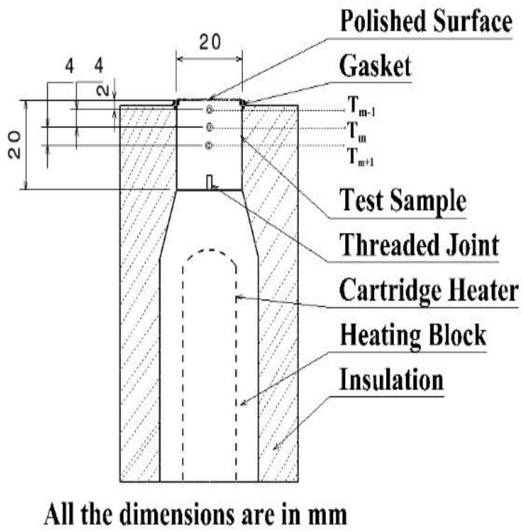


Figure 2. Test Section

2.3. Experimental Procedure

The characterized sample is sequentially cleaned by acetone, ethanol and distilled water before each trial. The known quantity of DI water is filled in the boiling chamber during each trial. DI water is rigorously boiled before each trial by the auxiliary heater to remove the dissolved gases. Thereafter test is conducted by giving incremental heat input to the test sample. The incremental heat input is measured by the wattmeter. After steady state is reached, the temperature of the sample at known location are recorded and the procedure is repeated for different heat flux values. The pressure in the chamber is maintained by a proportional integral derivative (PID) pressure controller system. The main heater and test sample are considered as the axisymmetric system. Due to uniform surface roughness, the heat flux from the surface is considered as uniform. The heat flux dissipated to the boiling fluid and the surface temperature can be estimated by the thermocouple readings.

The heat flux from the top surface of the sample is calculated by Eq. (1). where Δx is the distance between two thermocouples.

$$q'' = -k_{Cu}\frac{T_{m-1}-T_{m+1}}{2\Delta x} \tag{1}$$

The surface temperature of the sample is calculated by using Eq. (2).

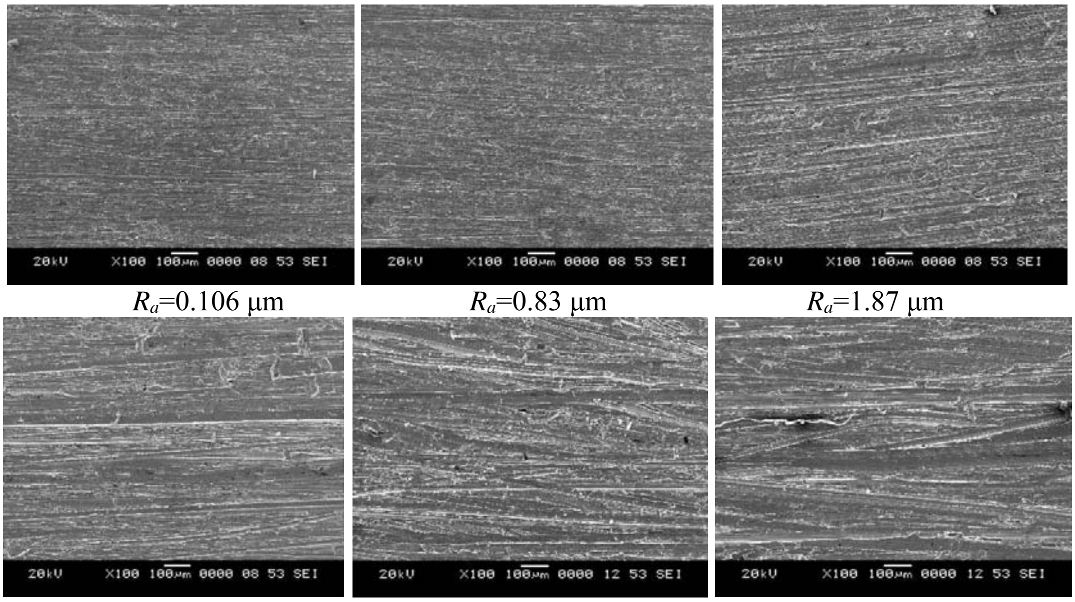
$$T_w = T_{m-1} - q''\left(\frac{x_{m-1}}{k_{Cu}}\right) \tag{2}$$

where, x_{m-1} is the distance between the surface of a sample and a top thermocouple (T_{m-1}) and is equal to 2 mm, as shown in Figure. 2. Heat transfer coefficient (HTC) between the surface and water is estimated by Eq. (3).

$$\boldsymbol{h} = \frac{\boldsymbol{q''}}{(\boldsymbol{T_w}-\boldsymbol{T_l})} \tag{3}$$

3. Result and Discussion

SEM images in Figure.3 shows the pattern of unidirectional scratches obtained after polishing by different grit sandpaper. Table 2 shows the average of roughness parameters measured at six different location of the sample. The R_a is considered as a representative roughness parameter in the present study. The roughness values viz. R_a, S_m and R_z found to be increased with increase in the grit of the sandpaper.



R_a=0.106 μm R_a=0.83 μm R_a=1.87 μm

R_a=3.17 μm R_a=3.59 μm R_a=4.03 μm

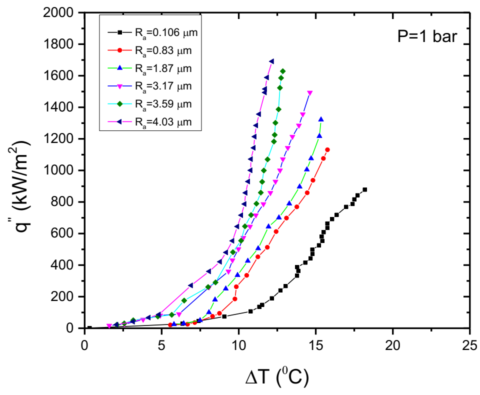
Figure 3. Unidirectional scratches on the sample

Table 2. Roughness parameters in μm

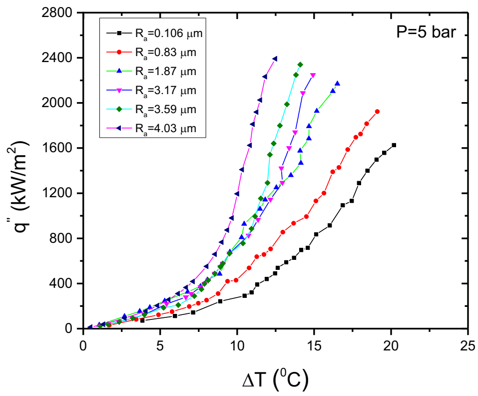
R_a	R_z	R_q	S_m
0.106	1.20	0.14	13.2
0.83	7.05	1.07	26.8
1.87	13.30	2.40	35.7
3.17	22.91	4.12	42.2
3.59	27.55	4.09	44.8
4.03	26.50	4.95	45.2

3.1. Effect of surface roughness on heat flux

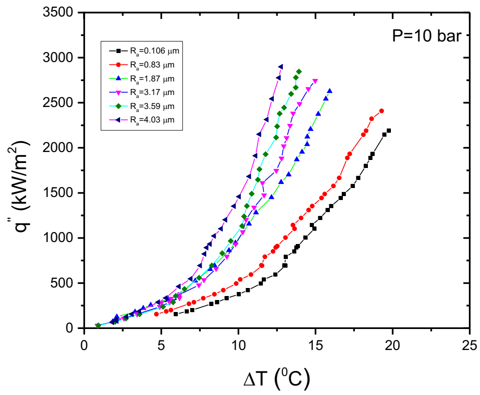
Present study is carried on wide range of R_a varying from 0.106 μm to 4.03 μm at 1 bar, 5 bar and 10 bar. Boiling curves obtained at 1 bar, 5 bar and 10 bar pressure is shown in Figure.4. It is found that boiling curves move towards left with increase in R_a, which means that at constant wall superheat, pool boiling heat transfer increases with increase in the surface roughness. The identical boiling performance is found at high pressure. The onset of boiling temperature is considerably dropped with increase in R_a as well as pressure.



(a)



(b)



(c)

Figure 4. Boiling curve of the sample having different R_a at (a) P=1 bar (b) P=5 bar (c) P=10 bar

The variation in the non-dimensional heat transfer coefficient with the non-dimensional heat flux at different pressure is shown in Figure.5. It is found that HTC increases monotonously with the heat flux at all pressure. The HTC value also increased with increase in R_a. Thus it is commented that significant surface cooling is achieved in the pool of water due to surface roughness. The upper limit of heat transfer, so called critical heat flux (CHF) from the surface is identified when the vapor blanket formed over the entire surface. This acts as a barrier for the heat transfer from the surface the bulk fluid. The HTC drops after formation of vapor blanket. The CHF is plotted in Figure.6 with R_a at different pressure. It is found that CHF increases with increase in the R_a as well as pressure. The HTC corresponding to CHF is plotted in Figure.7 with R_a at different pressure. HTC increased with increase in R_a at all pressures. Thus it is commented that CHF and HTC enhancement is achieved by making surface rough. This result can be explained by bubble dynamics and wettability study. Mean spacing between scratches increased with increase in roughness. Thus intermediate distance between two nucleated bubbles on the scratch is increased. Bubble coalescence is retarded at high heat flux (close to CHF) and thus instability in the liquid supply to the nucleation site does

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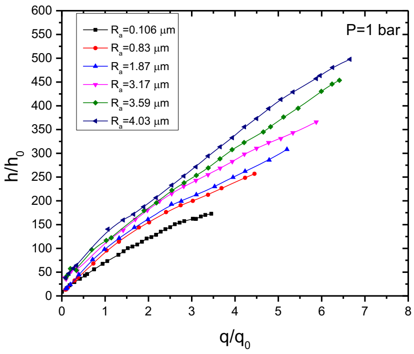
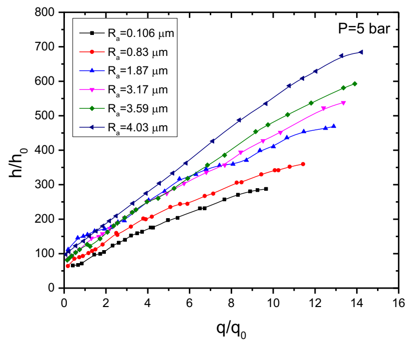
not occur. Increased wettability in the scratches helps to avoid complete dry-out of the boiling surface low heat flux.



(a)



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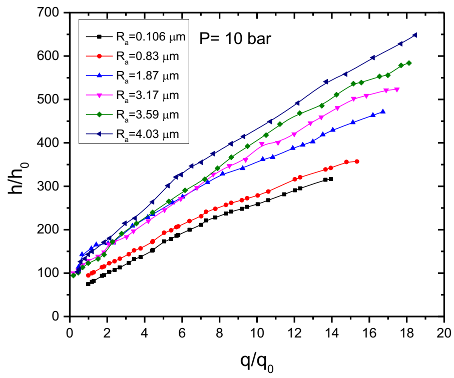

(c)

Figure 5. Variation in non-dimensional h with non-dimensional q'' for different R_a at (a) P=1 bar (b) P=5 bar (c) P=10 bar

4. CHF Model

Kim et al. [12] developed a model as given in Eq. (4) considering the forces acting on the bubble. The growth force due to evaporation, surface tension force, gravity force and capillary force due to capillarity through unidirectional scratches are considered. The force balance at the bubble departure is estimated at which bubble tends to spread horizontally over the surface. This is recognized as CHF and thus it is predicted by the Kim's Model. The value of S and C in the Kim's model is taken as 0.811 and 87.8. The CHF is predicted for the present experimental conditions and compared with the present experimental CHF values in Figure.8. The predicted CHF is found to be in good agreement with the experimental CHF with The mean absolute error (MAE), obtained by Eq. (5), between predicted and experimental CHF is 12.06 %.

$$q''_{CHF} = S \times h_{fg}\rho_v{}^{0.5} \times [\sigma g(\rho_l - \rho_v)]^{0.25} \times \left[\frac{2}{\pi} + \frac{\pi}{4}(1+\cos\theta) + \frac{4C\cos\theta}{1+\cos\theta}\left(\frac{R_a}{S_m}\right)\right]^{0.5} \quad (4)$$

$$MAE = \frac{1}{N}\sum \frac{\left|D_{b_{pred}} - D_{b_{exp}}\right|}{D_{b_{exp}}} \times 100 \tag{5}$$

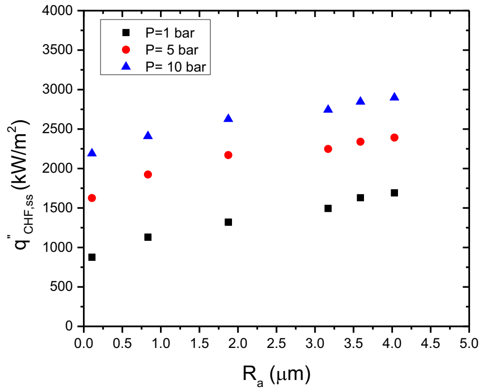

Figure 6. Variation in CHF with R_a at different pressure

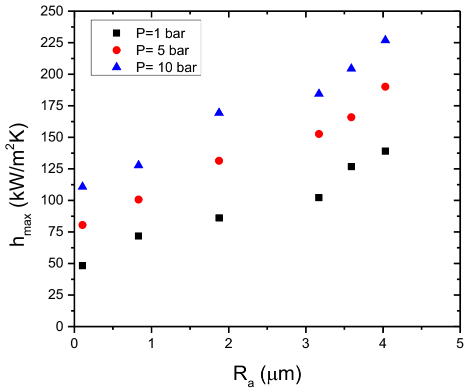

Figure 7. Variation in maximum HTC with R_a at different pressure

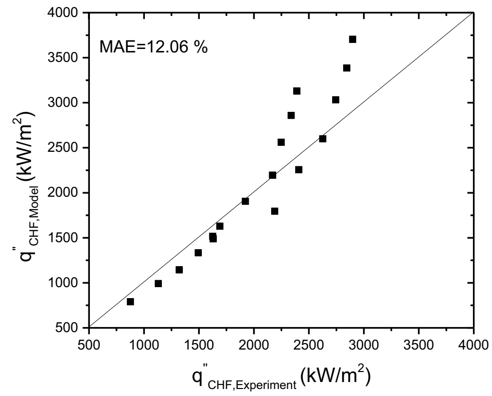

Figure 8. Comparison between predicted and experimental CHF

5. Conclusion
In the present study, influence of surface roughness on pool boiling heat transfer at high pressure was examined with wide range of R_a. It was found that the unidirectional scratches significantly improve the cooling effect in pool boiling of water. CHF and corresponding HTC were found to be enhanced due to increase in R_a. The enhanced heat flux can be justified by combined consideration of R_a and S_m. Kim's model was used to predict the CHF where MAE between predicted and experimental CHF is 12.06%.

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