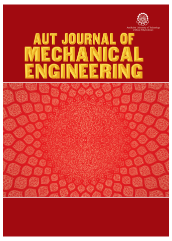

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Experimental Study of Subcooled Pool Boiling around a Circular Rough Cylinder

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ABSTRACT: Subcooling degree and surface roughness are two major parameters that have a considerable effect on boiling heat transfer. In the present study, the effects of subcooling degree on pool boiling heat transfer coefficient and surface temperature distribution are investigated experimentally. Tests are conducted for saturated and subcooled water with different subcooling degrees in the local atmospheric pressure (863 mbar) around a horizontal stainless steel cylinder with specific surface roughness. The test section is a pool with dimensions of 120×400×550 mm^3 and test case is a circular cylinder with 80 mm length, 9 mm diameter and 0.794 µm average surface roughness. In this research, experiments are performed for the degrees of subcooling between 5.5°C to 45.5°C and for the heat fluxes between 0.31 kW/m^2 to 125.62 kW/m^2. Results show that by increasing the degree of subcooling for a specific average surface roughness, average surface temperature is decreased and due to changes in the mechanism of heat transfer from nucleate boiling to natural convection, heat transfer coefficient is also decreased. In the region of natural convection, the variation of heat transfer coefficient with heat flux is low and when boiling process begins, this variation is more considerable. Furthermore, for lower heat fluxes (less than 5 kW/m^2), the temperature difference between upper and lower sides of the test case is less than 1°C which increases for higher heat fluxes so that for more than 100 kW/m^2, it reaches to 6°C.

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1- Introduction

When a solid surface is immersed in liquid and its temperature exceeds the saturation temperature of the liquid at corresponding pressure, vapor bubbles can form, grow, and detach from the solid surface. This phase change process is called boiling, and the energy transport involved is classified as convective heat transfer with phase change. Two types of boiling are commonly distinguished: pool boiling and flow or forced convective boiling. Pool boiling refers to boiling under natural convection conditions, whereas in forced flow boiling, liquid flow over a hot surface is imposed with external means [1, 2]. Fig. 1 shows saturated pool boiling curve for water at atmospheric pressure. According to the boiling curve, for excess temperature (the difference between the surface temperature and the saturation temperature) less than 5°C, the major mechanism of heat transfer is natural convection and with the increase of excess temperature, nucleate boiling begins. Nucleate boiling exists until excess temperature reaches 30°C and after that, transition boiling occurs and when the excess temperature is more than 120°C, film boiling takes place.

Natural convection from a horizontal cylinder has been studied extensively, and many correlations are presented to calculate heat transfer coefficient. Churchill and Chu [4] have recommended a single correlation for a wide range of Rayleigh number as Eq. (1):

$$Nu_D = \left\{0.60 + \frac{0.387 Ra_D^{1/6}}{\left[1+(0.559/Pr)^{9/16}\right]^{8/27}}\right\}^2 \qquad (1)$$

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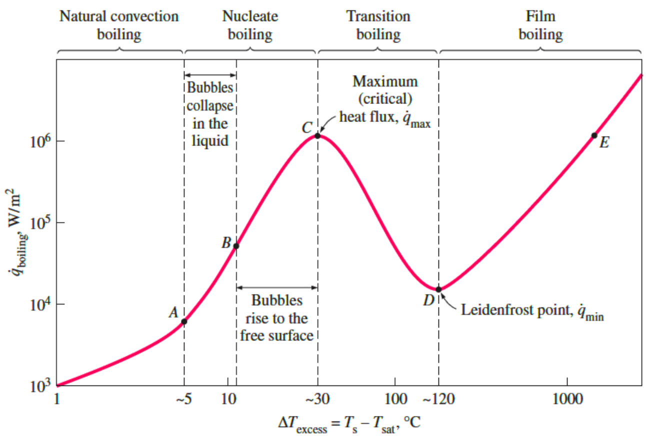


Fig. 1. Pool boiling curve for water at 1 atm [3]

where Nu_D, Ra_D, and Pr are Nusselt number, Rayleigh number and Prandtl number, respectively.

In the nucleate boiling region, heat transfer rate depends on the nature of nucleation on the surface. In addition, type and condition of the hot surface affect boiling heat transfer. Due to the complexity of nucleate boiling regime, complete and reliable analytical model to estimate heat transfer has not been presented yet and therefore, it should be convenient to rely on empirical correlations. Rohsenow [5] has proposed one of the most practical relations as follows:

$$q'' = \mu_l h_{fg}\left[\frac{g(\rho_l-\rho_v)}{\sigma}\right]^{1/2}\left[\frac{C_{pl}(T_s-T_{sat})}{C_{sf} h_{fg} Pr_l^n}\right]^3 \qquad (2)$$

where q'', μ_l, h_{fg}, g, ρ_l, ρ_v, and σ denote boiling heat flux, liquid viscosity, evaporation enthalpy, gravitational acceleration, liquid density, vapor density and surface tension, respectively.

Also, C_{pl}, T_s, T_{sat} and Pr are the specific heat of the liquid, surface temperature, liquid saturation temperature and Prandtl number of the liquid, respectively. Furthermore, the coefficient C_{sf} and the exponent n depend on the solid–fluid combination, and they are determined experimentally. Note that all of the properties are evaluated at the saturation temperature.

Boiling process takes place in various engineering systems such as heat exchangers, evaporators, and boilers. Several parameters, such as subcooling degree and surface roughness affect the boiling phenomenon. Analysis of these parameters is important due to their considerable effects on heat transfer and consequently on the efficiency of the systems and equipment. For instance, in the pressurized water reactors, 33 percent increase in critical heat flux can improve the produced power density up to 20 percent [6]. Lee and Singh [7] experimentally studied the influence of subcooling degree on pool boiling in the nucleate boiling regime. They performed tests on a hot wire with a small diameter and found out that for low and moderate superheat, when the degree of subcooling increases, nucleate pool boiling heat transfer increases whereas it is insensitive to the subcooling at high superheat. Kang [8] investigated the effect of surface roughness on subcooled pool boiling heat transfer. Test cases were smooth and rough surfaces with a surface roughness of 15.1 and 60.9 nm. The results of this study show that increasing surface roughness enhances heat transfer and this effect is magnified as the orientation of the tube changes from horizontal to vertical. Pioro et al. [9] reviewed the studies about the effects of various surface characteristics on pool boiling heat transfer in nucleate boiling regime. Based on this review, it is found that different parameters such as thermophysical properties, surface finish, dimensions and microstructure of the surface affect nucleate pool boiling heat transfer. They also surveyed the relations to calculate heat transfer during nucleate pool boiling [10]. Accuracy assessment of the presented correlations indicates that Rohsenow [5] and Pioro [11] relations are more accurate and convenient. Kang [12] experimentally studied the effect of inlet subcooling degree on pool boiling heat transfer in a smooth vertical annulus with a closed bottom. He found out that an increase in the liquid subcooling degree leads to high changes in the heat transfer coefficient so that decreasing subcooling degree from 50°C to 0°C leads to 461% increase in heat transfer coefficient. Kang [13] also studied the effects of water subcooling degree on heat transfer in smooth vertical annuli with various gap spacing. Based on the results, empirical correlations have been developed to predict heat transfer coefficient in these geometries. Su et al. [14] studied subcooled pool boiling on a downward-facing horizontal disk in a confined space. They found out that pool boiling on a downward-facing disk is far weaker than that occurring on upward-facing one. Furthermore, with an increase in the diameter of the disk, boiling heat transfer decreases. Coulibaly et al. [15] experimentally investigated the effect of coalescence of the bubbles, which are formed on the hot surface during subcooled nucleate pool boiling. Results of this study show that heat transfer is enhanced only when the coalescence occurs at least 2 ms after the bubble formation and very fast coalescence occurring after nucleation does not result in the increased heat fluxes. Rousselet et al. [16] experimentally studied the subcooled pool film boiling on small horizontal cylinders at near-critical pressures. One of their findings is that the effect of liquid subcooling on the heat transfer coefficient is dependent on the wall superheat and its effect decreases with an increase in the wall superheat. According to the experimental measurements, they also presented a new correlation to predict the subcooled pool film boiling heat transfer coefficient. In recent studies, more attention has been paid to the effect of microstructures and nanoparticles on heat transfer in nucleate boiling regime [17-20].

According to the literature survey, pool boiling takes place in several equipment, and therefore the study of the parameters that affect this phenomenon is necessary. It is also clarified that surface roughness and subcooling degree have considerable effects on pool boiling heat transfer. In previous studies, these two parameters have been examined separately for various geometries. In this study, the effect of subcooling degree on heat transfer coefficient and surface temperature for a horizontal circular cylinder with specific surface roughness during pool boiling is investigated experimentally.

2- Experimental Setup and Procedure

The experimental apparatus is shown in Figs. 2 and 3. This collection consists of a Plexiglas pool with 15 mm thickness. The base of this pool is 400×120 mm^2 and its height is equal to 550 mm where 70 mm on top of it, is always empty. To preheat pool water, which is 22 L, two heating elements with a power of 1500 W are used. Also, to make the temperature of water uniform, a pump with a flow rate of 20 L/min circulates the water in the pool. In order to measure the temperature of water and surface of the test case, six thermocouples (K-type) with an accuracy of 0.1°C are installed in the pool and on the hot surface. Six thermometers are used to display the measured temperatures with a resolution of 0.1°C.

Test case, shown in Fig. 4, is a circular stainless steel cylinder with 80 mm long and 9 mm diameter. It is located 120 mm above the bottom of the pool. The test case is heated by a 350 W heating element, which is fed with a 500 W variac. To adjust the required heat fluxes, electrical voltage and current are measured by a voltmeter with an accuracy of 0.1 V and a multimeter with an accuracy of 0.01 A, respectively. To make sure that heat flux becomes uniform, the gap between the cylinder and the heating element is filled with fireclay material. Also, ends of the test case are insulated by Teflon.

Since the temperature of the upper and lower sides of the cylinders is predicted to be different, two K-type thermocouples are installed on each side, to measure the surface temperature (Fig. 5). By measuring temperature along the test case, no major changes in the temperature of the cylinder in the axial direction are observed and consequently, the heat flux is regarded as one dimensional. To prevent the short circuit between the thermocouple wire and the test case, an electrical insulator covers the tip of the wires. Also, to minimize the thermal contact resistance, thermal paste is used at the junctions.

Since the surface roughness has a considerable effect on the boiling process and consequently on heat transfer coefficient, in this study, specific roughness is created on the heating surface by using a proper sandpaper. Roughness is measured by a surface roughness measuring device (Mahr M2 Perthometer). Average surface roughness in this research is 0.794 μm, which is different from that of Kang study [8]. The typical measured roughness of the surface is depicted in

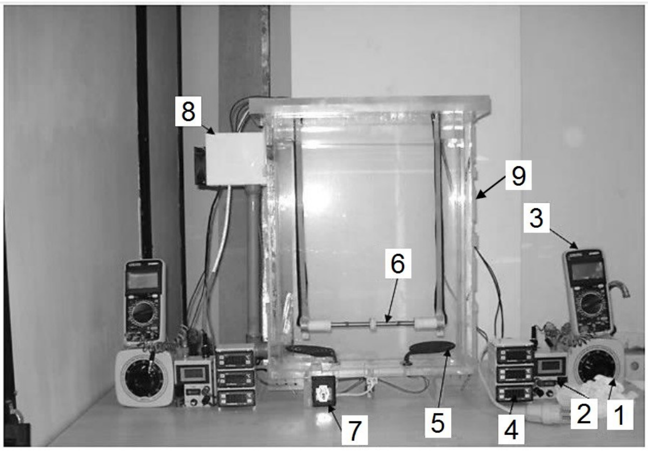


Fig. 2. Experimental setup, (1) Variac, (2) Voltmeter, (3) Multimeter, (4) Thermometer, (5) Preheater, (6) Test case, (7) Switch, (8) Pump, (9) Pool

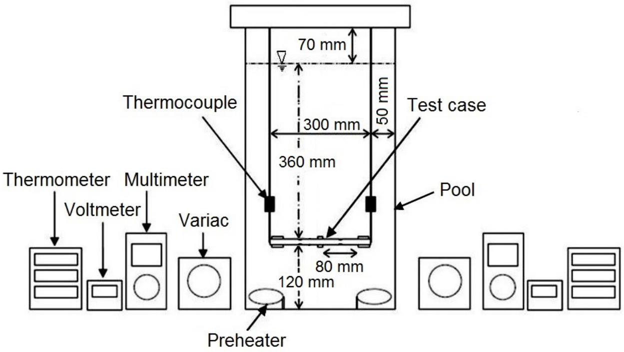


Fig. 3. Schematic of the equipment and pool dimensions

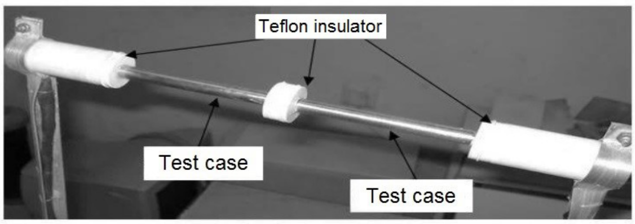


Fig. 4. Test case

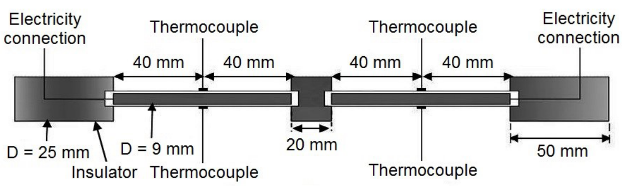


Fig. 5. Dimensions of the test case and location of the thermocouples

Fig. 6. As seen, the roughness is almost uniform.

Tests are performed according to the following steps and procedures:

- The temperature of the pool is adjusted and becomes uniform by using the heating elements and circulating pump. In this study, experiments are conducted for the water temperature of 50, 70, 80, 90 and 95.5°C. Based on the local ambient pressure, 863 mbar, boiling temperature of the water is 95.5°C. Hence, tests are performed in saturated and subcooled conditions with subcooling degree of 5.5, 15.5, 25.5 and 45.5°C.
- When the pool temperature becomes uniform and steady, the power of the heating element located in the test case is adjusted by using the variac, voltmeter, and multimeter. Note that heat fluxes between 0.31 and 125.62 kW/m^2 are investigated in this research.
- Measurement and recording the surface temperature is begun.
- In order to visualize the procedure of formation, growth, coalescence and departure of the bubbles on the hot surface, a high-speed camera, MotionBLITZ, is used.

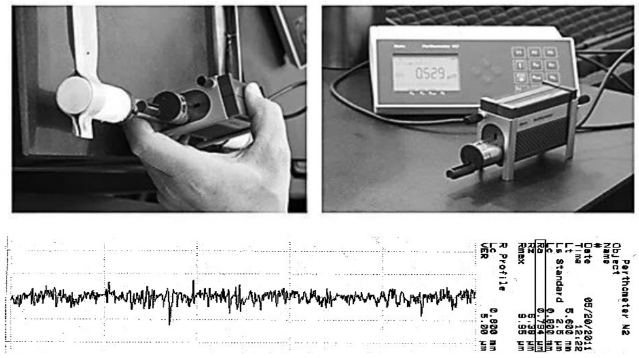


Fig. 6. Surface roughness measuring device, Mahr M2 Perthometer, and typical output

3- Methodology

Boiling heat transfer coefficient (h) is calculated by Newton's cooling law defined as Eq. (3). In this relation, q'' is the heat flux and ΔT is the temperature difference between average surface temperature and pool temperature.

$$h = \frac{q''}{\Delta T} \tag{3}$$

Heat flux over the test case at steady-state condition is determined by Eq. (4). In this equation, V, I and A are the electric potential difference, electric current and surface area, respectively. The surface area of the test case is calculated by Eq. (5) where D and L are test case diameter and length, respectively.

$$q'' = \frac{VI}{A} \tag{4}$$

$$A = \pi DL \tag{5}$$

The temperature difference is determined by Eq. (6) where T_p is pool temperature and $T_{s,a}$ is an average surface temperature which is calculated by Eq. (7). In this equation, T_{upper} and T_{lower} are the temperatures of upper and lower sides of the test case.

$$\Delta T = T_{s,a} - T_p \tag{6}$$

$$T_{s,a} = \frac{1}{2}\left(T_{upper} + T_{lower}\right) \tag{7}$$

4- Results and Discussions

Experimental conditions for studying the effect of subcooling degree on the pool boiling heat transfer and temperature distribution are provided in Table 1.

Table 1. Experimental conditions

Parameter	Range
Average surface roughness	0.794 µm
Subcooling degree	0°C ~ 45.5°C
Heat flux, q''	0.31 kW/m^2 ~ 125.62 kW/m^2

Typical photographs taken from the boiling process are shown in Fig. 7. The side view of bubble formation over the surface is depicted in Fig. 7a, and the top view of bubble detach and departure to the upper portion of the test case is indicated in Fig. 7b.

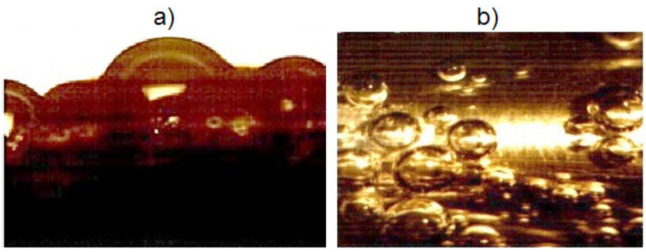


Fig. 7. Photographs from boiling process, (a) Side view of bubble formation, (b) Top view of bubble departure

4- 1- Repeatability

Repeatability is one of the major keys to investigate the accuracy of the experimental studies and is a criterion to evaluate the reliability of the experimental data. In this study, to evaluate the repeatability, one of the tests is selected and repeated. In this test, pool water is in the saturation temperature (T_p = 95.5°C) and surface temperature is used as the criterion parameter. Based on Fig. 8, repeatability of the tests is excellent and data of experiments have high accuracy and reliability. The maximum difference between the measured data is about 1%.

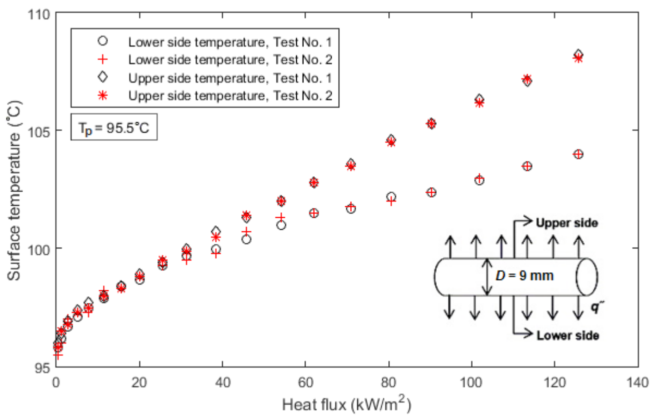


Fig. 8. Repeatability of experimental measurements

4- 2- Natural convection and nucleate boiling

Figs. 9 and 10 illustrate the comparison between experimental data and results obtained by Eq. (1) which is presented by Churchill and Chu [4] to predict heat transfer from a horizontal cylinder during natural convection.

Based on Figs. 9 and 10, heat transfer process could be separated into three regions; 1- When the surface temperature is less than saturation temperature (95.5°C), free convection is the major mechanism of heat transfer. 2- By increasing surface temperature, transition region takes place. In this region, mechanism of heat transfer gradually changes from natural convection to nucleate boiling. Based on the references such as [1, 3], the transition region may be continued up to excess temperature of 3-5°C. In this study, according to the results, the upper bound of the transition region is considered 3°C. Note that it is hard to find the exact range of transition region due to the uncertainty of the results. 3- With more increase in the surface temperature, heat transfer mechanism changes to boiling and based on the temperature of the pool water, it could be saturated or subcooled boiling.

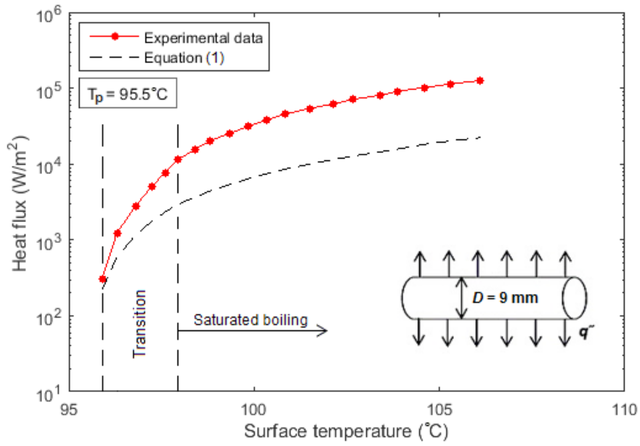
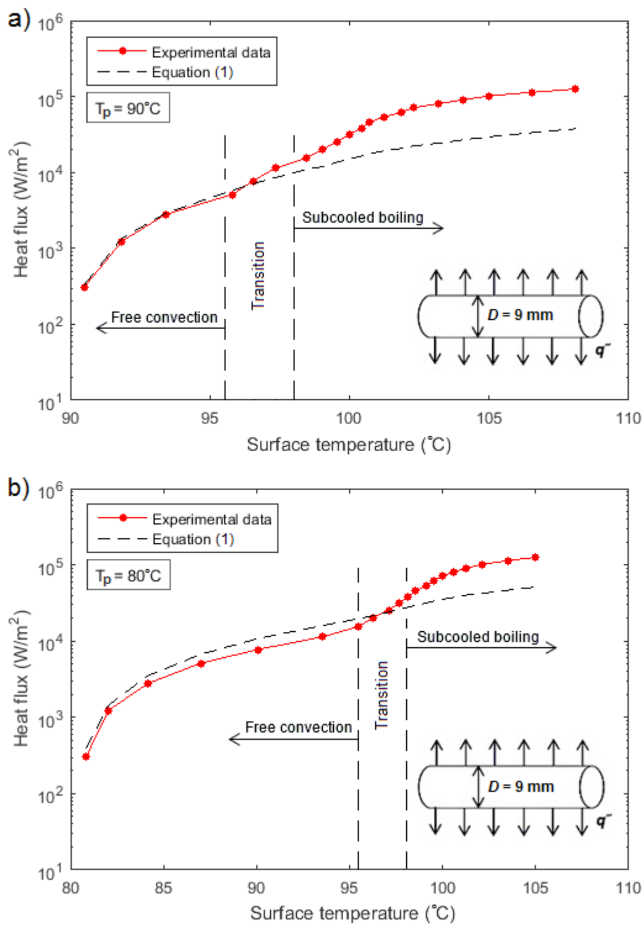
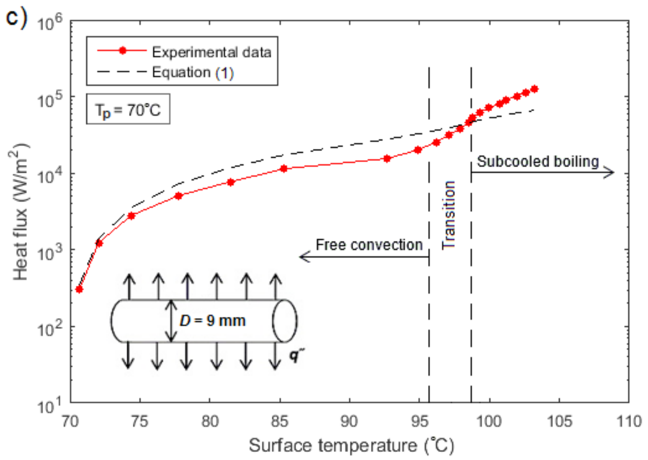


Fig. 9. Comparison between saturated boiling and natural convection





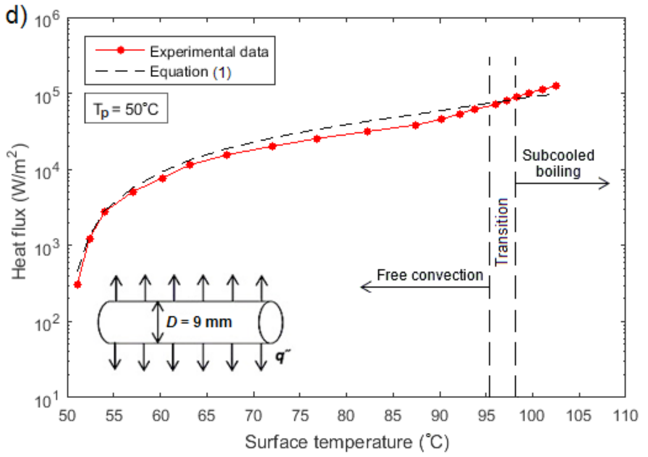


Fig. 10. Comparison between subcooled boiling and natural convection for various subcooling degrees

Fig. 9 shows that in the saturated boiling, when heating the surface begins, surface temperature increases up to saturation temperature and hence, transition region and then boiling occurs and in this condition, natural convection region does not exist. Therefore, the difference between the two curves in Fig. 9 is large and due to phase change during the boiling process, the heat flux is more than natural convection. By increasing surface temperature and intensification of the boiling process, the difference of the curves increases. This trend is similar to that of observed between natural convection and boiling curves in Fig. 1. Note that natural convection curve (dashed line) in Fig. 1 is determined by Eq. (1).

According to Fig. 10, when pool temperature is less than the saturation temperature, natural convection region exists and this region becomes larger by increasing the water subcooling degree. In this region, the difference between natural convection and boiling curves is small. When surface temperature increases and it becomes more than the saturation temperature, transition and then subcooled boiling occur. In these two regions, the difference between the curves gradually increases and by increasing the subcooling degree, this difference becomes smaller.

In Fig. 11, experimental data for saturated boiling are compared with Eq. (2) which is presented by Rohsenow [5] to predict heat flux during the saturated boiling process.

Fig. 11 shows that the difference between the two curves is large when the surface temperature is near the saturation temperature. This difference could even reach to 97%,

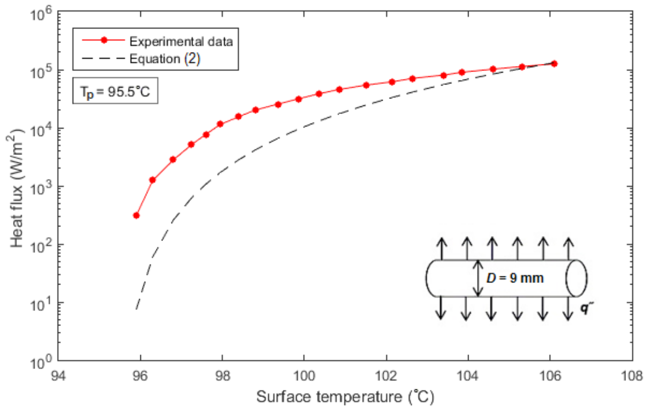


Fig. 11. Comparison between saturated boiling and Rohsenow correlation [5]

which is justified according to the limitations for the use of Eq. (2). Rohsenow correlation is applicable to clean and relatively smooth surfaces and the results obtained using this equation for real surfaces can be in error by ±100% [3, 21]. By increasing the surface temperature and consequently, the intensification of boiling process, the difference between the two curves reduces by about 5%.

4- 3- Temperature distribution

The variation of surface temperature in upper and lower sides with respect to the heat flux for saturated and subcooled boiling is shown in Figs. 12 and 13. As can be seen, when the surface temperature is less than saturation temperature, the upper side temperature is a little higher than the lower side temperature. By increasing the surface temperature up to saturation temperature, the difference between the temperature of upper and lower sides becomes larger. For heat fluxes more than 100 kW/m^2, this difference reaches to 6°C.

When surface temperature is less than the saturation temperature, major heat transfer mechanism is natural convection and due to the formation and growth of boundary layer around the test case, heat transfer coefficient in lower side of the cylinder is more than the upper side and consequently, lower side temperature is less than the upper side temperature.

When surface temperature is more than saturation temperature, boiling process takes place and bubbles form on the surface. The departure of the bubbles around the surface and accumulation on top of the test case as shown in Fig. 7 leads to a reduction of heat transfer coefficient at the upper side compared to the lower side. Hence, the temperature of the upper side of the test case becomes more than the lower side. Furthermore, the temperature difference between upper and lower sides in transition and boiling regions is more than natural convection region. Kang [8] and Gupta et al. [22] mentioned similar results.

4- 4- Effect of subcooling degree

In order to investigate the effect of subcooling degree on heat transfer coefficient in pool boiling, experiments are conducted for saturated and subcooled conditions. In this study, subcooling degrees of 5.5, 15.5, 25.5 and 45.5°C are investigated. Fig. 14 shows the variation of heat transfer coefficient with respect to the heat flux for above conditions.

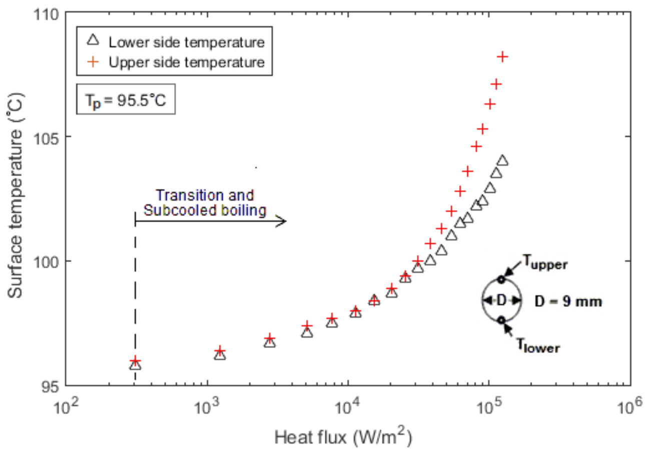
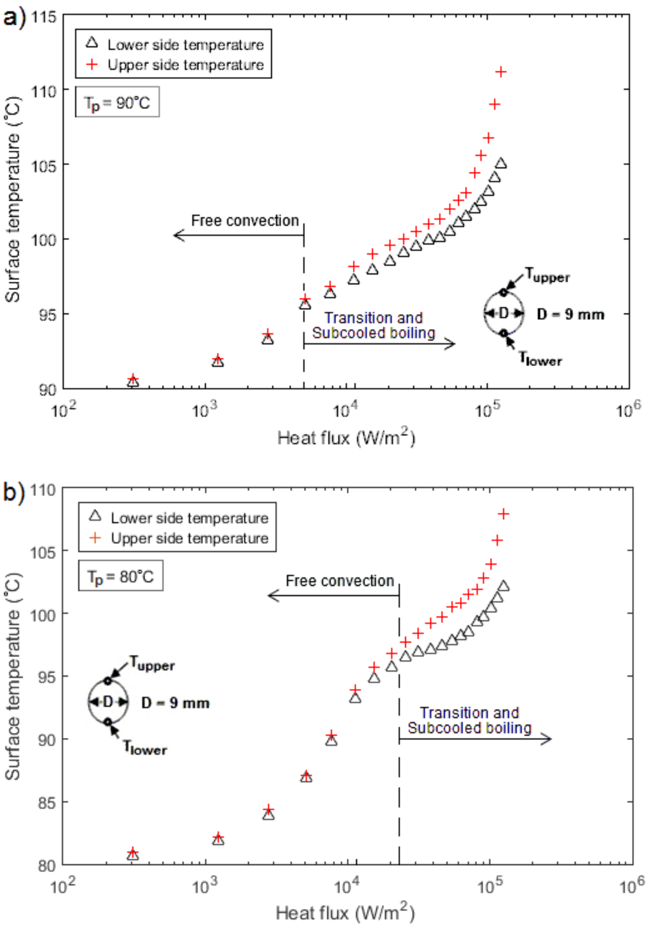


Fig. 12. Variation of surface temperature with respect to the heat flux in saturated boiling

Based on this figure, by increasing subcooling degree, heat transfer coefficient decreases which is similar to the results of experimental study of Kang [12]. Also, for subcooled boiling conditions and for heat fluxes less than 5 kW/m² where the major heat transfer mechanism is natural convection, the effect of subcooling degree on heat transfer coefficient is insignificant. By increasing heat flux and initiating boiling process, the effect of subcooling is considerable.

Variation of average surface temperature ($T_{s,a}$) which is defined by Eq. (7) with heat flux for various subcooling degrees is shown in Fig. 15. According to this figure, rises of subcooling degree leads to the reduction of average surface



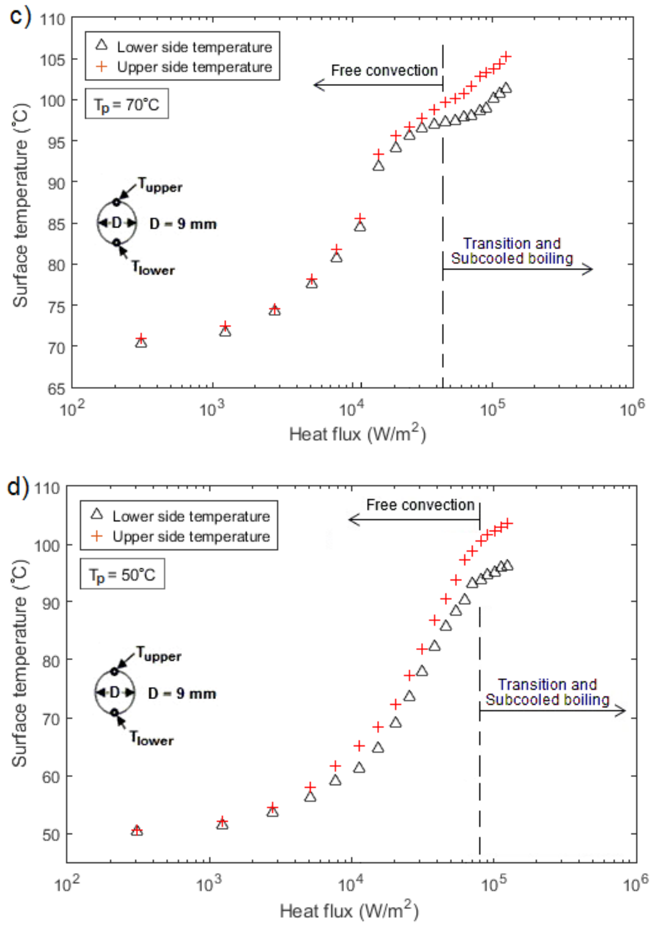


Fig. 13. Variation of surface temperature with respect to the heat flux in subcooled boiling

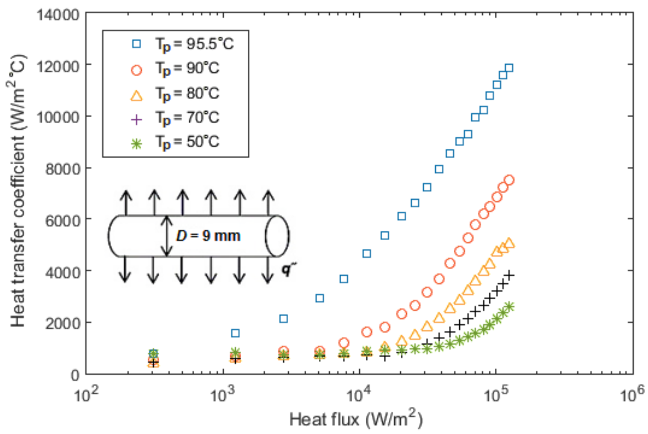


Fig. 14. Effect of subcooling degree on heat transfer coefficient

temperature. A decrease in the subcooling degree means that pool temperature decreases and since this reduction is more than that of surface temperature, the difference between the pool temperature and surface temperature increases and consequently, heat transfer coefficient in a specific heat flux decreases.

Fig. 15 also indicates that for heat fluxes less than 5 kW/m², subcooling degree strongly affects the surface temperature. This effect decreases with increase in heat flux so that for heat fluxes more than 70 kW/m², surface temperature tends to be the same value for all conditions. This trend could be due

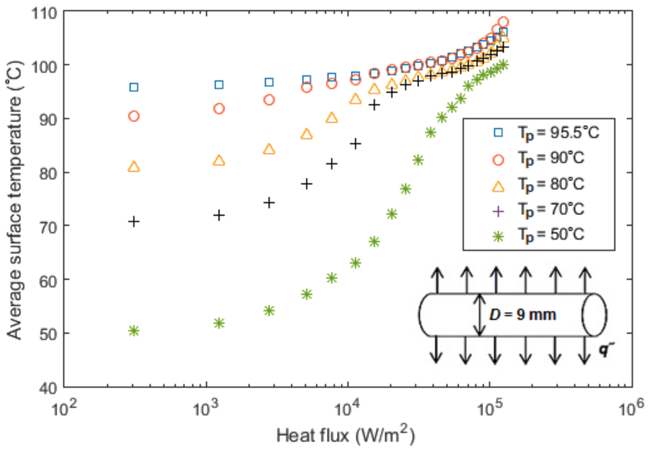


Fig. 15. Effect of subcooling degree on average surface temperature

to the same mechanism of pool boiling (nucleate boiling) for high heat fluxes and for all experimental conditions.

5- Uncertainty Analysis

Measuring data in an experimental study might have an uncertainty because of the limitation of the measuring instruments. In this study, to determine the uncertainty of each parameter, the method of Kline and McClintock [23] is used. In this method, when one variable such as R is a function of several measuring parameters such as $x_1, x_2,\ldots$ as Eq. (8), then the uncertainty of the variable, w_R, is calculated with that of the measuring data, w_1, w_2,…, and by using Eq. (9). The accuracy of the measuring devices in this research is tabulated in Table 2. Based on calculations, maximum uncertainty for the conducted experiments is about 14% and 17% for heat flux and heat transfer coefficient, respectively.

$$R = R(x_1, x_2, \ldots, x_n) \quad (8)$$

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \quad (9)$$

Table 2. Accuracy of the measuring devices

Instrument	Accuracy
Caliper	±0.02 mm
Multimeter	±0.01 A or ±5%
Voltmeter	±0. 1 V
Thermocouple	±0.1°C
Perthometer	±0.001 μm

6- Conclusions

Based on the measurements of pool boiling heat transfer from a horizontal circular cylinder with a specific surface roughness for various subcooling degrees and heat fluxes, it is concluded that:

- Increasing subcooling degree leads to major changes in the mechanism of heat transfer from nucleate boiling to natural convection.
- For low heat fluxes (less than 5 kW/m²) that natural convection is dominant, the temperature difference between upper and lower sides of the test case is less than 1°C but it increases for higher heat fluxes to more than 5°C.
- Heat transfer coefficient for pool boiling depends on the subcooling degree and for a specific heat flux, it decreases with increasing the subcooling degree due to the enhancement of temperature difference between the surface and pool water.
- The sensitivity of the heat transfer coefficient to subcooling degree increases with an increase in heat flux so that it changes from less than 30% for minimum heat flux (310 W/m²) to more than 40% for maximum heat flux (125 kW/m²).
- Average surface temperature depends on subcooling degree and it decreases by increasing subcooling degree.
- The sensitivity of average surface temperature to the degree of subcooling depends on heat flux and it decreases with an increase in heat flux so that for higher heat fluxes (more than 70 kW/m²), the variation of the surface temperature of different subcooling degrees is insignificant.

Acknowledgment

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Nomenclature

A	Surface area, m²
C_p	Specific heat at constant pressure, J/kg.°C
C_{sf}	Experimental constant that depends on surface – fluid combination
D	Diameter, m
g	Gravitational acceleration, m/s²
h	Heat transfer coefficient, W/m².°C
h_{fg}	Latent heat of vaporization, J/kg
I	Electric current, A
k	Thermal conductivity, W/m.°C
L	Length, m
n	Experimental constant that depends on the fluid
Nu_D	Nusselt number = $h.D/k$
Pr	Prandtl number
q''	Heat flux, W/m²
Ra_D	Rayleigh number = $g.\beta.\Delta T.D^3/\nu.\alpha$
T	Temperature, °C
ΔT	Temperature difference, °C
V	Electric potential difference, V

Greek symbols

α	Thermal diffusivity, m²/s
β	Volumetric thermal expansion coefficient, 1/°C
μ	Viscosity, kg/s.m
ν	Kinematic viscosity, m²/s
ρ	Mass density, kg/m³
σ	Surface tension, N/m

Subscripts

l	Liquid

p	Pool
s	Surface
sat	Saturation
v	Vapor

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