The Enhancement of Pool Boiling Heat Transfer by Passive Technique using Rotating Blades Applied on the Nucleation Sites

A. Suriyawong, S. Saisorn, A. Kawahara, S. Wongwises

1 Department of Mechanical Engineering, Faculty of Engineering, King Mongkut’s Institute of Technology Ladkrabang, Bangkok 10520, Thailand
2 Department of Engineering, King Mongkut’s Institute of Technology Ladkrabang Prince of Chumphon Campus, Pathiu District, Chumphon 86160, Thailand
3 Faculty of Advanced Science and Technology, Kumamoto University, Kumamoto, Japan
4 Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab. (FUTURE), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut’s University of Technology Thonburi, Bangmod, Bangkok 10140, Thailand

E-mail: adirek.su@kmitl.ac.th

Abstract. This paper was aimed to investigate the nucleate boiling phenomena with the presence of the rotating blades above the heat transfer surface. The boiling process at 1 atm was carried out by allowing heat transferred from a copper surface to distilled water. The 4-blade rotor made from copper was vertically installed at different distances above the heat transfer surface (Lsb). The flow visualization during phase-change phenomena under heat flux values of 160-610 kW/m² was feasible by high-speed camera. The results showed that pool boiling at the heat flux of 160 kW/m² corresponded to isolated bubble regime, and at the value of 610 kW/m², the column regime was observed. In addition to the two-phase flow pattern, the heat transfer coefficient data was reported in this work. The heat transfer results were found to depend on the distance at which the rotor was installed.

1. Introduction

The pool boiling is a sort of heat transfer with the processes of phase changing between liquid and gas under vaporization. The investigation of nucleate pool boiling has been needed to develop and control the steam generation process. The major techniques, i.e., passive method and active method, applied on boiling process to enhance heat transfer have been investigated by different researchers in the past years. The tasks dealing with improved heat transfer surface, different working fluids, and secondary motion over the heat transfer surface have been proposed. The following are the discussions based on different previous works available for nucleate boiling phenomena.

Jaikumar and Kandlikar [1] reported the pool boiling behaviors affected by sintered open micro-channel. The heating surfaces which were improved based on nano-technology were presented by Shi et al [2] and Kruse et al [3]. They pointed that the nano-coated surfaces were able to significantly improve the heat transfer performance.

Peng et al [4], Heris [5] and Amiri et al [6] investigated the effect of nanofluids on the nucleate boiling phenomena. It was reported that nanofluids resulted in significant heat transfer enhancement.
Kim et al. [7] and Bartoli and Baffigi [8] studied the enhancement of pool boiling heat transfer with installation of the ultrasonic vibration on the heating surface. The results indicated that an ultrasonic vibration was major factor enhancing heat transfer rate. Sheikhbahai et al. [9] studies the pool boiling heat transfer on the heating surface under the electrohydrodynamic conditions. Although the electric field has advantages for the electrohydrodynamic technique producing agitation near the heat transfer surface, it needs the external power source to support the system. In this work, the passive technique using the rotating blades without external energy was applied to enhance the heat transfer performance. The pool boiling curves as well as heat transfer results are reported in the present paper.

2. Experimental arrangement
The experimental method is briefly presented in this section. It should be noted that the detailed apparatus can be found in Suriyawong et al. [10]. The apparatus was designed in order to study two-phase flow pattern and heat transfer phenomena. In this work, the 4-blade rotor was employed to induce a commotion of the water near the heat transfer surface. The copper rotor was machined to have a diameter of 30 mm, a length of 50 mm, an angle of 90°, and a core of 5 mm. It was adjusted to be vertically installed at different distances ($L_{SB}$) above the heating surface, i.e., 5 mm, 15 mm, and 25 mm, respectively. The experimental conditions were controlled under a pressure of 1 atm and heat flux values ranging from 160 to 610 kW/m$^2$.

3. Data reduction
Experimental studies were carried out, based on the flat plate heating surface, to observe the pool boiling heat transfer characteristics. The heat fluxes, $q''$ (W/m$^2$), can be calculated from the following equation:

$$ q'' = \frac{4VI}{\pi D^2} $$

(1)

where $V$ is the voltage (V), $I$ is the direct current (A), and $D$ is the heating surface diameter. The average boiling heat transfer coefficient, $h_b$ (W/m$^2$·ºC), is calculated from the equation below:

$$ h_b = \frac{q''}{T_s - T_{sat}} $$

(2)

where $T_{sat}$ is the saturation temperature of water (ºC), and $T_s$ is the average heater surface temperature (ºC) calculated from

$$ T_s = \frac{\sum_{i=1}^{4} T_i \sum_{i=1}^{4} x_i^2 - \sum_{i=1}^{4} T_i \sum_{i=1}^{4} x_i}{4 \sum_{i=1}^{4} x_i^2 - \sum_{i=1}^{4} x_i^2} $$

(3)

where $x_i$ is the position (m) and $T_i$ is the local temperature (ºC) which is measured at the test section. Equation (3) was obtained by the linear least squares method using the four thermocouple installed in the test section with their respective points and considering the origin ($x = 0$) at the heating surface. The uncertainty of heat flux $\delta q''$ (W/m$^2$) can be calculated from the following equation:

$$ \frac{\delta q''}{q''} = \sqrt{\left(\frac{\delta V}{V}\right)^2 + \left(\frac{\delta I}{I}\right)^2 + \left(\frac{2\delta D}{D}\right)^2} $$

(4)

where $\delta V$ is uncertainty of voltage (V), $\delta I$ is uncertainty of direct current (A) and $\delta D$ is uncertainty of heating surface diameter (m). The uncertainty of heat transfer coefficient $\delta h_b$ (W/m$^2$·ºC) can be calculated from the following equation:
\[ \frac{\partial h_b}{h_b} = \sqrt{\left(\frac{\delta q}{q}\right)^2 + \left(\frac{\delta T_s}{T_s - T_{sat}}\right)^2 + \left(\frac{\delta T_{sat}}{T_s - T_{sat}}\right)^2} \]  

(5)

where \( \delta T_{sat} \) is uncertainty of liquid saturation temperature (ºC) and \( \delta T_s \) is uncertainty of surface temperature (ºC) can be calculated from the following equation:

\[ \frac{\delta T_s}{T_s} = \frac{1}{T_s} \sqrt{\sum_{i=1}^{4} \left( \frac{\partial T_s}{\partial T_i} \delta T_i \right)^2 + \sum_{i=1}^{4} \left( \frac{\partial T_s}{\partial \delta x_i} \delta x_i \right)^2} \]  

(6)

where \( \delta T_i \) is uncertainty of local temperature (ºC) and \( \delta x_i \) is uncertainty of position of temperature measurement (m).

The uncertainties of the heating surface temperature, heat flux and heat transfer coefficient are ±0.6%, ±2.6%, and ±7.8% respectively.

4. Results and discussion

In this research, the effects of the \( L_{SB} \) on the nucleate pool boiling curve, heat transfer coefficient and boiling phenomenon of distilled water at atmospheric pressure were studied. The horizontal circular plate heating surface was made from copper with surface roughness of 0.2 µm.

The pool boiling curve was developed and presented with the nucleate pool boiling phenomena induced by the presence of the 4-blade rotor rotating above the heat transfer surface. The \( L_{SB} \) varied between 5, 15 and 25 mm, while the number of blade was kept at 4 blades. It was found from the results that, the increase in the \( L_{SB} \) caused an increase in the \( T_s - T_{sat} \) when compared to the non-blade configuration. The corresponding pool boiling curves are illustrated in figure 1.

Figure 2 represents the dependence of heat transfer coefficient on the heat flux. It was found that the increase in heat flux resulted in the increased heat transfer coefficient. Moreover, the decrease in \( L_{SB} \) also caused the heat transfer coefficient increased. The heat transfer enhancements corresponded to 6.35 %, 9.45%, and 13.01%, for the \( L_{SB} \) at 25 mm, 15 mm, 5 mm, respectively.

![Figure 1. Distilled water pool boiling curves with different \( L_{SB} \) configurations.](image)

![Figure 2. Heat transfer data for different \( L_{SB} \) configurations.](image)

Figure 3 shows images of bubble formation on heating surface for the different \( L_{SB} \) during saturated nucleate pool boiling with three different heat flux conditions (167, 385 and 610 kW/m²). The heat flux of 610 kW/m² induced larger bubbles than that of 385 and 167 kW/m². In this work, the \( L_{SB} \) with 5 mm tended to be strongly driven by the bubbles. The kinetic energy seems to decrease with increasing the \( L_{SB} \).
The images of nucleate pool boiling behaviors taken at various time points by an Aos Promon Studio camera are shown in figures 4 and 5. The video frames of nucleate pool boiling heat transfer of distilled water at atmospheric pressure in the apparatus without the rotating blades are shown in figures 4. The observations showed that the bubble nucleates on the heating surface, grew in size, and eventually departed from the heating surface. The bubble size for the heat flux of 167 kW/m$^2$ was smaller than that obtained from the heat flux values of 385 and 610 kW/m$^2$, respectively. Figure 5 showed the video frames of nucleate pool boiling heat transfer of distilled water at atmospheric pressure in the apparatus installed with rotating blades with the $L_{SB}$ of 5 mm. The $L_{SB}$ with 5 mm was experimented during saturated nucleate pool boiling under three different heat flux conditions (167, 385 and 610 kW/m$^2$). The heat flux of 167 kW/m$^2$ resulted in the vapor bubbles smaller than those generated by the heat flux values of 385 and 610 kW/m$^2$. In addition, the heat flux of 610 kW/m$^2$ seemed to cause the bubbles transmitting more energy to the rotating blades, and hence, the secondary motion of the distilled water near the heating surface was highly disordered. The higher the heat flux, the stronger is the secondary motion caused by the rotating blades.
5. Conclusions
The experimental investigation was carried out to explore the nucleate boiling behaviors with the presence of the rotating blades positioned at different locations above the heat transfer surface. Isolated bubble regime was observed at low heat flux, and was developed to be the column regime when heat flux became higher. With the presence of the 4-blade rotor vertically installed above the surface at a distance of 5 mm, the heat transfer enhancement was up to 13.01% when compared to the case without the rotor.

References
[1] Jaikumar A and Kandlikar S G 2015 Int. J. Heat Mass Transfer 88 652-61
[2] Shi B, Wang Y and Chen K 2015 Appl. Therm. Eng. 75 115-21
[3] Kruse C M, Anderson T, Wilson C, Zuhlke C, Alexander D, Gogos G and Ndao S 2015 Int. J. Heat Mass Transfer 82 109-16
[4] Peng H, Ding G, Hua H, Jiang W, Zhuang D and Wang K 2010 Int. J. Refrigeration 33 347-58.
[5] Heris S Z 2011 Int. Commun. Heat Mass Transfer 38 1470-3
[6] Amiri A, Shanbedi M, Amiri H, Heris S Z, Kazi S N, Chew B T and Eshghi H 2014 Appl. Therm. Eng. 71 450-9
[7] Kim H Y, Kim Y G and Kang B H 2004 Int. J. Heat Mass Transfer 47 2831-40
[8] Bartoli C and Baffigi F 2011 Exp. Thermal Fluid Sci. 35 423-32
[9] Sheikhbahai M, Esfahany M N and Etesami N 2012 Int. J. Thermal Sciences 62 149-53
[10] Suriyawong A, Saisorn S and Wongwises S 2017 Exp. Thermal Fluid Sci. 87 109-16

Acknowledgement
The research is financially supported by King Mongkut’s Institute of Technology Ladkrabang and King Mongkut’s University of Technology Thonburi.