Number of blades of rotating blades affecting the boiling heat transfer enhancement of distilled water

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Abstract. This study examined the nucleate pool boiling characteristics of distilled water attached to a heating surface with a horizontal circular plate above which the rotating blades were installed. The experiments were performed to explore the effects of number of blades as well as the visualization of pool boiling phenomena on nucleate boiling heat transfer characteristics. The rotating blades were made from copper material, with the number of blade of 2, 3 and 4 blades. The results showed that, the rotor with 4 blades yielded a higher heat transfer coefficient than those with 2 or 3 blades. This is because the increased number of blade provided more chance for the bubbles to strike the rotating blades. Hence, the rotating blades did create a commotion of the working fluid above the heating surface. Camera frames were captured using an Aos Promon Studio at the heat fluxes of about 160-610 kW/m² to identify the location of bubble nucleation for each configuration. The photographic observations showed that, the pool boiling phenomenon with the heat flux value of about 160 kW/m² corresponded to the isolated bubble, and the boiling characteristic with the heat flux value of about 610 kW/m² were based on the column regime.

1. Introduction

The pool boiling is a sort of heat transfer with the processes of phase changes between liquid and gas under vaporization. A systematic investigation to improve heat transfer performance for pool boiling is necessary for several agricultural processes. In the past years, the pool boiling characteristics have been widely studied by different researchers. The heat transfer enhancement techniques contain different methods: (1) improved heating surface; (2) improved working fluid; and (3) improved disturbance near the surface. The followings are a brief survey of the experimental work based on nucleate boiling phenomena.

Jaikumar and Kandlikar [1] investigated the pool boiling phenomena for selectively sintered open micro-channel. The heat transfer performance was dependent on the channel configurations. Shi et al [2], Tang et al [3], Seo et al [4], Patil and Kandlikar [5] and Dong et al [6] experimentally studied pool boiling heat transfer on the heating surface coated with nanotubes and nanoparticles. The results indicated the nano-coated surface causing effectively improved heat transfer performance. The boiling
heat transfer of deionized water on the 304 stainless steel heating surface was experimentally studied by Kruse et al [7]. It was found that the improvements of the heat transfer coefficient as well as critical heat flux were accomplished when compared to the polished stainless steel surfaces.

Peng et al [8,9], Heris [10], Yang and Liu [11], Kole and Dey [12,13], Shoghl and Bahrami [14], Tang et al [15], Diao et al [16], Vazquez and Kumar [17] and Amiri et al [18] employed nanofluids in their experiments. The experimental results indicated the significant heat transfer enhancement obtained by using nanofluids.

Kim et al. [19] and Bartoli an and Baffigi [20, 21] 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 [22] and Quan et al [23] studied 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, however, the passive technique using the rotating blades without external energy was applied to enhance the heat transfer performance. Boiling curves and heat transfer coefficient data are presented in this paper.

2. Experimental arrangement
This investigation is a continuation of the authors’ previous work associated with pool boiling phenomena [24]. The rotating copper blades were designed to have a diameter of 30 mm, a length of 50 mm, a core diameter of 5 mm and a blade angle of 90 degree. The number of blades in the present work ranged between 2 and 4. The stainless steel downrod of the blades is 450 mm in length and 9.5 mm in diameter. The downrod was needed to hang the rotating copper blades.

3. Data reduction
This work was experimentally conducted to observe nucleate boiling characteristics on the flat plate heating surface. A heat fluxes, \( q'' \), is obtained from equation (1):

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

where \( V, I \) and \( D \) refer to voltage, direct current and diameter of heating surface, respectively. \( h_b \) or average heat transfer coefficient is given by the following equation:

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

where \( T_{sat} \) represents saturation temperature, and \( T_s \) stands for the average surface temperature which can be estimated based on the measurements of four thermocouples along the test section:

\[
T_s = \frac{\sum_{i=1}^{4} T_i \sum_{i=1}^{4} x_i^2 - \sum_{i=1}^{4} x_i \sum_{i=1}^{4} T_i x_i}{4 \sum_{i=1}^{4} x_i^2 - (\sum_{i=1}^{4} x_i)^2}
\]

where \( x_i \) and \( T_i \) presented in equation (3) are respectively the position and the local temperature at the test section. The uncertainty of heat flux \( \delta q'' \) can be calculated from the following equation:

\[
\frac{\delta q''}{q''} = \sqrt{(\frac{\delta V}{V})^2 + (\frac{\delta I}{I})^2 + (\frac{2\delta D}{D})^2}
\]

where \( \delta V \) is uncertainty of voltage, \( \delta I \) is uncertainty of direct current and \( \delta D \) is uncertainty of diameter of heating surface. The uncertainty of heat transfer coefficient \( \delta h_b \) is estimated from the following equation:
\[
\Delta T_h \leq \frac{1}{h_b} \left( \frac{\Delta q^2}{q} + \left( \frac{\Delta T_i}{T_i - T_{sat}} \right)^2 + \left( \frac{\Delta T_{sat}}{T_s - T_{sat}} \right)^2 \right)^{1/2}
\]

where \( \Delta T_{sat} \) is uncertainty of liquid saturation temperature and \( \Delta T_i \) is uncertainty of surface temperature which can be obtained by

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

where \( \Delta T_i \) is uncertainty of local temperature and \( \Delta x_i \) denotes uncertainty of the position for measuring the temperature.

The uncertainty of the surface temperature is ±0.6% whereas those for heat flux and heat transfer coefficient correspond respectively to ±2.6% and ±7.8%.

4. Results and discussion

In this research, the dependence of the nucleate boiling heat transfer characteristics on the number of blades was experimentally carried out, using distilled water as working fluid under a pressure of 1 atm. The heating surface was a copper plate having a roughness of 0.2 µm.

The pool boiling curves with different rotating blade configurations were illustrated in the form of heat flux and \( T_s - T_{sat} \). The 2-blade, 3-blade and 4-blade configurations were used in the experiment while the blade tip was vertically arranged in order to keep a distance of 5 mm measured from the heating surface. It was found from the results that, the increase in the number of blades caused a decrease in the \( T_s - T_{sat} \) when compared to the non-blade configuration. The corresponding pool boiling curves are shown in figure 1.

A heat transfer coefficient for different heat flux values are presented in figure 2. The figures indicate the dependence of heat transfer coefficient on the heat flux. Moreover, the increase of blade number resulted in the average heat transfer coefficient increased by 13.0%, 19.8%, and 29.7%, for the 2-blade, 3-blade and 4-blade configurations, respectively.

Figure 1. Distilled water pool boiling curves with different rotating blades configurations.

Figure 2. Heat transfer data for different rotating blades configurations.

Figure 3 shows images of bubble formation on heating surface for different rotating blades, 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 rotor with 4 blades tended to be strongly driven by the bubbles. The kinetic energy seems to increase with the number of blades.
Figures 4 and 5 show the images of nucleate pool boiling behaviors taken at various time points by an Aos Promon Studio camera. Figure 4 shows the video frames of water pool boiling heat transfer without rotating blades. The observations showed that the vapor bubble nucleate on the surface, grew in size, and finally departed from the surface. The bubble size for the heat flux of 610 kW/m$^2$ was larger than that obtained from the heat flux values of 385 and 167 kW/m$^2$, respectively.

Figure 5 shows the video frames of pool boiling behaviors influenced by the 4-blade configuration. The rotor with 4 blades was tested during saturated nucleate pool boiling under three different heat flux conditions (167, 385 and 610 kW/m$^2$). The heat flux of 610 kW/m$^2$ resulted in the bubbles bigger than those generated by the heat flux values of 385 and 167 kW/m$^2$. Furthermore, 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 water near the heating surface was highly developed. The higher the heat flux, the stronger was the secondary motion induced by the rotating blades.

5. Conclusions
The experimental study of the distilled water pool boiling phenomena was presented. The effect of the rotating blades on the heat transfer characteristics was discussed. The number of blades ranged between 2 and 4. The experimental results revealed that with increasing the number of blades, the heat
transfer performance tended to be enhanced. The improvements corresponding to 2, 3 and 4 blades were 13.0%, 19.8% and 29.7%, respectively.

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