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Electric field effect on the bubble behavior and enhanced heat-transfer characteristic of a surface with rectangular microgrooves

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ABSTRACT

The effect of an electric field on the evaporation/boiling heat-transfer characteristic of an evaporation surface with rectangular microgrooves was experimentally investigated. R141b was used as the working fluid. The operating pressure was 1.01×10^5 Pa. Experimental results showed that electric field significantly affected the thermal performance of the evaporation/boiling surface. The heat-transfer enhancement effects increased with increased electric field strength. The heat-transfer coefficient enhancement factor could reach as high as 1.45 under the applied electric field. A visualization experimental study on the bubble behavior and nucleate site density was also conducted. Visualization experiment results indicated that the bubble departure time and nucleate site density decreased with increased electric field strength.

1. Introduction

Electrohydrodynamic (EHD) heat-transfer enhancement is an active method of promoting heat transfer that introduces the electric field theory to the heat-transfer area. When a dielectric fluid medium is applied by an electric field, the interaction between the temperature and flow fields in the fluid occurs, and the heat-transfer process in the fluid is enhanced. The electric heat-transfer enhancement technique has more advantages, such as simple equipment, convenient control, low power dissipation and significant effect. This technique also has large potential for practical applications in the energy, chemical, metallurgy, aerospace, and HAVC industries.

The physical basis of the electrically enhanced condensation and boiling is the EHD force, which is generated by an electric field and provided by the following equation [1]:

$$f_e = qE - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left\langle E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\rho\right\rangle \tag{1}$$

The first term on the right of Eq. (1) is the Coulomb force acting on the free charges in a fluid, which is called the electrophoretic force. An electrophoretic force exists once a net charge is created in the fluid and becomes dominant in applications where corona wind is utilized. The second term stands for the dielectrophoretic force, which is a consequence of inhomogeneity or a spatial change in the permittivity of the dielectric fluid because of non-uniform electric fields, temperature gradients, and phase differences. The third term called electrostriction stress represents the non-uniformity of electric permittivity.

Heat-transfer enhancement using the EHD technique in the phase change process has been studied by many researchers in recent years. Several experimental investigations have been made to understand the heat-transfer characteristics of vapor–liquid phase change heat transfer [2–15]. Many studies have focused on single isolated bubbles both for nucleate boiling from artificial nucleation sites and adiabatic gas injected bubble growth [17–20].

Ogata and Yabe [6,7] investigated experimentally the pool boiling heat-transfer characteristic under electric field strength. Results show that an enhancement factor with an applied electric field of approximately 8.5 times the maximum value obtained without an electric field and the boiling bubble number largely increased and were violently forced to move around on the heat-transfer surface. Zaghdoudi et al. [8] performed an experimental study on the influence of a DC uniform electric field on the nucleate boiling heat transfer for n-pentane, R113, and R123. The experimental results show a threefold increase in the nucleate pool boiling heat-transfer coefficient unlike that of the zero electric field strength. Chen et al. [9] experimentally and theoretically studied the nitrogen bubble deformation with various DC electric fields by visualizing with a high speed camera. The experimental results show that the bubble elongation increases along the direction

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Nomenclature

a	heat-transfer enhancement factor
q	heat flux density (W m^{-2})
l	distance between two thermocouples (m)
h	heat-transfer coefficient (W m^{-2} K^{-1})
h_{EHD}	heat-transfer coefficient with the applied electric field (W m^{-2} K^{-1})
h_0	heat-transfer coefficient without the applied electric field (W m^{-2} K^{-1})
T_t	temperature for the back of the copper plate with microgrooves (K)
T_s	saturation temperature of the working fluid (K)
T_1, T_2, T_3, T_4	temperature of the copper heater (K)

Greek symbols

λ	thermal conductivity of pure copper (W m^{-1} K^{-1})

parallel with increasing electric field strength. The electrostriction stress compresses the bubble, whereas the dielectrophoretic stress expands the bubble along the bubble surface. The electrohydrodynamic stress exerted on the bubble surface leads to the bubble elongation at departure. Quan et al. [10] experimentally investigated the microbubble growth from a rectangular Pt microheater. The experimental results show that with the increasing electric field strength, the heat flux required for boiling inception increases, boiling nucleation time is delayed, nucleation temperature decreases, and bubble growth is suppressed. Dong et al. [11] quantitatively studied the electric field characteristics around a bubble in a two-phase system and analyzed the dielectric permittivity effect of the working fluid on a single bubble. The numerical results indicate that the non-uniformity of the electric field around a bubble increases with increased dielectric permittivity of the working fluid. Both numerical analyses and experiments allowed Cho et al. [12] to conclude that an air bubble injected into a dielectric liquid through a 0.1 mm-diameter orifice is elongated in the direction of the applied uniform electric field. The elongation increased with the electric field magnitude, whereas the departure volume remained constant. Kweon et al. [13] studied the effect of DC and AC electric fields on an air bubble injected into cyclohexane in an experimental investigation. They analyzed three electrode geometries and found that the departure volume decreased in a non-uniform electric field when increasing the applied electric potential difference. Pascual et al. [14] conducted saturated nucleate boiling experiments of R123 along a 0.13 mm-diameter platinum wire with an applied uniform electric field. The experimental results show that the number of active nucleation sites and average bubble diameter decreased under the electric field strength. Darabi et al. [15] experimentally investigated an electric field on the falling film evaporation of refrigerant R134a on a vertical plate and three commercial tubes. Up to a fourfold enhancement in the heat-transfer coefficient was obtained with the plate configuration, which occurred at a heat flux of 10 kW/m^2. Gao et al. [16] experimentally investigated bubble nucleation and its growth dynamic under an applied electric field on a small heater in pool boiling. R113 was used as the working fluid. The experimental results show that with the increasing imposed electric filed strength, the bubble departure diameter and departure frequency decrease, whereas the bubble growth and bubble waiting times increase. Di Marco et al. [17] experimentally and numerically investigated the bubble shape under the electric force action. They studied the dynamics in adiabatic conditions to understand the fundamental physics ruling their interface evolution. Their results were utilized to simulate bubble behavior in zero and partial gravity for the preparation of microgravity experiments. Prediction shows that bubble microgravity elongation also occurs for the larger values of bubble volume and applied voltage. Di Bari et al. [18] investigated adiabatic bubble growth in uniform DC electric fields. The results show that the bubbles growing in electric fields became progressively more elongated in the vertical direction with increasing electric field strength compared with the field-free case. Schweizera et al. [19] experimentally investigated wall temperature and heat flux distribution during nucleate boiling in the presence of an electric field and in variable gravity. The bubbles were observed with a synchronized high speed camera. The experimental results show a significant influence of the electric field on the bubble shapes. The characteristic elongation of the bubble shapes could be observed. The bubble departure diameters are larger, and bubble frequency is lower than in normal gravity boiling in the present case. Siedel et al. [20] performed an experimental study of electric field effects during nucleate boiling from an artificial nucleation site. The results show that the bubbles are elongated because of the electrically induced stresses acting on the bubble interface during the growth stage. The growth characteristics are notably different compared with that of the field-free baseline cases. The measurements indicate that the rate of heat transfer/vapor generation is initially lower than the field-free cases, although it tends to be sustained for a large portion of the bubble lifetime. The vapor generation rate for the field-free case is initially almost twice as high as the cases with EHD, although it drops off quite early in the bubble life.

A literature review shows that most experimental studies are related to the EHD effects on heat-transfer enhancement and bubble behavior for pool boiling [3–9,11–20]. This study used R141b as the working fluid to study the evaporation/boiling phase change heat-transfer characteristic and bubble behavior for the capillary fluid flow on a vertical plate with rectangular microgrooves under a saturated vapor ambient at different electric field strengths. An experimental investigation was also performed to study the nfluence of an applied electric field on the nucleation density.

2. Experimental system and procedure

2.1. Experimental system

The experimental system is illustrated in Fig. 1. The experimental setup could be divided into three parts, namely, the experimental test unit, direct current high voltage power supply unit, and data acquisition unit. The data acquisition unit includes the computer, data acquisition, and high-speed camera. This experimental apparatus was designed to measure the heat-transfer coefficient and visualize bubble behavior on the microgroove surface.

A schematic of the test vessel is shown in Fig. 2. The test vessel is a rectangular vessel with dimensions of 70 × 60 × 125 mm. The four walls of the test vessel are made of 12.5 mm-thick stainless steel. The copper surface with rectangular microgrooves was placed vertically on one wall of the vessel. Glass windows were made on the three other side walls of the test vessel to facilitate visualization. The top surface of one copper block was attached symmetrically to the plate with microgrooves. The top surface of the copper block was a square area with dimensions of 10 × 10 mm. The copper block sides were insulated with a glass wool layer, and heat was supplied by four cartridge heaters that