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Experimental study on time-series characteristics in Marangoni condensation for ethanol-water mixtures on a horizontal surface

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ABSTRACT

In this paper, an experimental system for condensation on a horizontal surface was designed and built to study the Marangoni condensation of ethanol-water mixtures. The time-series characteristics, including heat transfer characteristics and condensation modes, were experimentally studied herein. In the case of pure steam, the condensation mode was film-wise during the time-series process. As the condensation was processed, the heat transfer coefficient decreased first and then stayed stable. And the heat transfer coefficient increased with the increase both in the impinging cooling water temperature and vapor velocity. In the case of ethanol-water mixtures, the condensation modes at the starts of the time-series processes presented film-wise, film-wise with dropwise and dropwise under different conditions. As the impinging cooling water temperature and ethanol vapor concentration increased, the vapor-to-surface temperature difference and the heat transfer coefficient both showed smooth, periodic, fluctuated and slow variations during the time-series process. Increase in the vapor velocity promoted the transformation towards the periodic variation. Four typical condensation styles, including the filming style, periodic-dropwise style, irregular-dropwise style and slow-growth-dropwise style, were concluded based on the time-series characteristics, and the condensation styles distribution was obtained. As the impinging cooling water temperature increased, the condensation style presented filming, periodic-dropwise, irregular-dropwise and slow-growth-dropwise successively. The corresponding vapor-to-surface temperature difference, whose range was divided into four parts accordingly. As the ethanol vapor concentration increased, the ranges for the periodic-dropwise style increased first and then decreased. The ranges for the periodic-dropwise style increased with increasing the vapor velocity.

1. Introduction

When two-component vapor mixtures with positive system property, where the surface tension of the mixtures has a negative gradient with the mass fraction of the more volatile component, such as ethanol-water and ammonium-water mixtures etc., condensed on solid surface, the dropwise condensation mode appeared due to surface tension gradient, owning to the temperature and concentration gradient on the condensate surface. This phenomenon, first found by Mirkovich and Missen [1] in 1961, was usually called Marangoni condensation. It was a new way to achieve dropwise condensation mode which was mainly depended on the physical properties of the mixtures. Then the long duration of the dropwise mode and excellent heat transfer performance was obtained. Consequently, the interest of research on the Marangoni condensation was stimulated and the systematical studies were conducted by the scholars around the world.

The heat transfer characteristics of Marangoni condensation were the focus at beginning. Hijikata et al. [2,3] theoretically and experimentally studied the condensation heat transfer characteristics on the horizontal tubes and plate respectively. The results indicated that the heat transfer coefficients were lower or equal those of the pure steam. Fujii et al. [4] performed experiments outside the horizontal tubes and got the similar results, which were attributed to the large thermal resistance of the diffusion layer in the main vapor mixtures. Utaka et al. [5–8] experimentally studied the effects of ethanol vapor concentration, vapor-to-surface temperature difference and vapor velocity on the heat transfer characteristics on the vertical plate. The heat transfer coefficient had the maximum value at the ethanol concentration of 1.0% and varied non-monotonously with the increase in the vapor-to-surface temperature difference. Moreover, the increase in the vapor velocity intensified the heat transfer process. Furthermore, Yan's group experimentally studied the heat transfer characteristics on the

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Nomenclature

P	vapor pressure (kPa)
T	temperature (K)
ΔT	vapor-to-surface temperature difference (K)
U	vapor velocity ($m \cdot s^{-1}$)
W	concentration (%)
h	heat transfer coefficient ($kW \cdot m^{-2} \cdot K^{-1}$)
l	distance between thermocouple and the condensing surface (mm)
q	heat flux ($kW \cdot m^{-2}$)
t	time (s)
u	uncertainty

Greek symbols

λ	thermal conductivity ($kW \cdot m^{-1} \cdot K^{-1}$)
τ	response time (s)
$\Delta\tau$	response time difference (s)

Subscripts

1,2	row of the thermocouples
c	impinging cooling water
e	ethanol vapor
s	saturated vapor mixtures

vertical plate [9], vertical tubes [10] and vertical micro tubes [11]. The heat transfer coefficient was intensified most obviously at the relatively lower ethanol vapor concentration, increased with the increase in the vapor pressure and velocity, and varied a little and non-monotonously with the increase in the diameter in normal and microscale scale, respectively. In addition, Wang et al. [12] developed the research on the vertical plate with temperature gradients and found the heat transfer coefficient was enhanced by the temperature gradient.

The condensation mode is an important way to explain the variation of the heat transfer characteristics and reveal the condensation mechanism. Therefore, the study on the Marangoni condensation mode was meaningful. Fujii et al. [13] summarized the condensation modes of ethanol-water mixtures outside the horizontal tubes. The smooth-film condensation was found at the ethanol vapor mass concentration of 0–0.2 and 0.8–1.0, while the dropwise, drop and streak and ring-wise condensation were found at the other concentrations. Utaka and Wang [6] concluded the condensation modes on the vertical surface. The condensation mode presented smooth film, rivulet, dropwise, dropwise with rivulet and smooth film one by one with the increase in the vapor-to-surface temperature difference. Six condensation modes were observed by Yang et al. [14] including smooth film, drop, streak, drop-streak, wavy-streak and drop with tail. With the decrease in the vapor-to-surface temperature difference, the condensation mode changed from drop to drop-streak, then to steady streak, and finally to smooth film. Later, Wang et al. [15] made a further study on the vertical surface with microscopic temperature gradient. The condensation modes were irregular and rivulet mode usually appeared as a transition state when the dropwise mode changed to film mode. In addition, Chen et al. [11] observed four condensation modes on a vertical mini-tube, including smooth film, drop, drop-wavy, and waviness. Furthermore, Ma et al. [16] analyzed the effect of surface free energy difference on the condensation modes. As the surface free energy difference increased, the condensation modes transformed from film-wise to dropwise. Jiang et al. [17] experimentally studied the condensation flow patterns in the trapezoidal micro-channels. Annular, annular-streak, annular-streak-droplet, churn, injection, droplet-injection and bubble flow patterns were observed along the flow direction and flow patterns were closely related to the equivalent surface free energy differences.

A thorough understanding of the mechanism of Marangoni condensation and heat transfer characteristics requires the knowledge of the droplet size and its distribution. Therefore, it is worthy studying the condensation modes quantificationally. The maximum droplet diameters measured by Fujii et al. [13] were about 1.5–2.5 mm. Utaka et al. [18] measured the minimum initial drop distances and the maximum departing drop diameter, which were in the range of $0.03 \sim 0.15$ mm and with a minimal value of 1.5 mm, respectively. Utaka and Kobayashi [8] found the maximum heat transfer coefficient was in proportion to maximum departing droplet diameter with a power of −0.35. Moreover, Utaka and Nishikawa et al. [19,20] measured the liquid film thickness by a laser absorption method and the minimum thickness was less than 1 μm. Results achieved by Wang et al. [15] indicated drops with the diameter less than 1 mm was more than 70% in all drops and the peak values of the maximum departing diameters increased with the ethanol vapor concentration, which were about 1.5 mm to 5 mm.

The Marangoni condensation, similar to the dropwise condensation of pure vapor, is a dynamic process. However, the studies about the time-series process for the traditional dropwise condensation and Marangoni condensation were relative less. Tanaka [21] firstly studied the transient process during dropwise condensation for pure steam and obtained the droplet size distribution. Ma et al. [22] made an investigation on the size distribution of the initial droplet and the effect of the vapor pressure. Later, Wen et al. [23] studied the transient characteristics of initial droplet size distribution at lower and ultra-lower steam pressure. The initial nucleated droplets satisfied lognormal distribution, and then transformed to a bimodal distribution, finally revealed an exponential distribution during the process. Noriyuki et al. [24] also analyzed the time-series characteristics and geometric structures of drop-size distribution density in dropwise condensation. The research from Castillo et al. [25] revealed that droplet growth dynamics exhibited a strong dependency on relative humidity. Besides, Utaka and Kamiyama [26,27] studied the movement of the droplet on the condensing surface with temperature gradient. The droplet was observed moving from lower temperature part to the higher one, and the velocity, not affected by the droplet size, was proportionate to gradient in the temperature and surface tension. Chen and Utaka et al. [28] developed the study on the droplet movement. Results indicated that the velocity had a close connection with the initial distance and the surface tension gradient. Meanwhile, the growth period of the condensate droplet were observed and recorded during the experiments conducted by Ma et al. [29] and Lan et al. [30]. Wang et al. [15] also studied the period during Marangoni condensation. The cycle time, affected by vapor-to-surface temperature difference, ethanol concentration and vapor pressure, was approximate 0.2–2 s. Recently, Li et al. [31] performed preliminarily study on the time-series process on the horizontal surface. The characteristic time decreased with the increase in the initial vapor-to-surface temperature difference and increased slightly with the increase in the ethanol vapor concentration as a whole.

To sum up, previous studies about Marangoni condensation were mainly on the vertical surfaces, horizontal tubes and vertical tubes, where the gravity effect acted on the condensate with the same direction of the surface tension gradient. The essential reason