International Journal of Heat and Mass Transfer 52 (2009) 2324–2334

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Marangoni condensation heat transfer of water–ethanol mixtures on a vertical surface with temperature gradients

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ARTICLE INFO

Article history:
Received 8 January 2008
Received in revised form 7 November 2008
Available online 7 January 2009

Keywords:
Marangoni condensation
Temperature gradients
Heat transfer coefficient
Concentration gradients

ABSTRACT

Marangoni condensation heat transfer of water–ethanol mixture vapours was investigated experimentally on a vertical surface with large and nonhomogeneous temperature gradients. The heat transfer investigation showed that the local heat transfer coefficients (HTCs) were varied along the surface for the nonhomogeneous temperature gradients on condensing surface. At the position with greater local temperature gradient, the HTC was higher. The highest HTC existed at the ethanol vapour concentration (EVC) of 1% and the HTC decreased with the increase of EVC when the EVC was more than 2%. Compared to the solutal Marangoni condensation, which was only driven by concentration gradients, owing to the effect of temperature gradients, the present heat transfer was enhanced by 25–100% for the mixture vapours ($C_V < 5\%$ and $C_V = 50\%$) and pure steam, and by 0–50% for the other mixture vapours ($5\% \leqslant C_V < 20\%$). In addition, the effect of vapour velocity and pressure was confirmed to be positive to condensation heat transfer. The preliminary analysis illustrated that, for a positive system with a volatile component, under the coaction of concentration and temperature gradients, the surface tension gradients on the saturated condensate surface became greater, leading to the Marangoni condensation heat transfer to be further enhanced. Meanwhile, the visual observations indicated that condensation modes greatly depended on EVC and vapour-to-surface temperature difference (ΔT).

1. Introduction

When the binary mixture vapours of a positive system, e.g., water–ethanol mixtures, condenses on a solid surface, irregular modes of condensate of uneven thickness appear, such as dropwise condensation. As Marangoni effect is responsible for the dropwise condensation, the phenomenon is called Marangoni condensation or Marangoni pseudo-dropwise condensation. In 1961 Mirkovich and Missen [1] firstly discovered this non-filmwise condensation phenomenon for binary vapours, and compared HTCs for the various types of binary vapours condensation in 1963 [2]. In 1968 Ford and Missen [3] demonstrated a criterion for film instability by an inequality, and established a sign convention $d\sigma/db$ by $d\sigma/db \leqslant 0$ for stable and $d\sigma/db > 0$ for unstable, where σ was the surface tension and b was film thickness. A positive system, where the surface tension of the highboiling-point component was larger than that of the lowboiling-point component, coagulated on a solid surface, the sign convention $d\sigma/db$ was positive and the condensation film would be unstable. Fujii et al. [4] presented an experimental study of condensation of water and ethanol mixtures on a horizontal tube. Their group reported five condensation modes: drop, streak, ring, smooth film and wavy film. For vapour mixtures having ethanol concentrations of 0–20%, the condensation HTC was less than that of pure steam. In 1994 Hijikata et al. [5] theoretically and experimentally investigated the condensation mechanisms of water–ethanol mixture on a flat plate by instability analysis, and found that the values of HTCs were relatively low. All the studies above reported that the HTC of binary vapours was less than or equal to that of pure steam.

On the other hand, in 1997 Morrison and Deans [6] studied the condensation of water–ammonia mixtures on the outside of a smooth horizontal tube. Their results showed that condensation heat transfer was enhanced by as much as 13% when the vapour concentration of ammonia in steam was in the range of 0.23–0.88%. The paper by Philpott and Deans in 2004 [7] reported that on the rates of condensation heat transfer for weak ammonia–water mixtures in a horizontal, shell and tube condenser, the average condensation heat transfer for the condenser was enhanced by up to 14%, for inlet ammonia concentrations in the range of 0.2–0.9%. Furthermore, local enhancement of the condensation heat transfer reached up to 34% when the local bulk vapour concentrations of ammonia ranged from 0.2% to 2%. In recent years Utaka and coworkers performed a series of experiments on Marangoni condensation for water–ethanol mixtures on a small vertical plane. They first achieved several times heat transfer enhancement and found the HTC revealed nonlinear characteristics with peak values with the increase of surface subcooling. They systematically

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doi:10.1016/j.ijheatmasstransfer.2008.11.011

Nomenclature

b	film thickness (μm)
C	ethanol mass concentration in solution (%)
C_V	ethanol vapour mass concentration in mixture vapour (%)
F	ratio of heat transfer coefficient
h	heat transfer coefficients (kW m^{-2} K^{-1})
$\bar{h}$	mean heat transfer coefficient (kW m^{-2} K^{-1})
l	distance (mm)
P	vapour pressure (kPa)
q	heat flux (kW m^{-2})
$\bar{q}$	mean heat flux (kW m^{-2})
r_e	latent heat of ethanol (kJ kg^{-1})
r_{mix}	latent heat of mixture (kJ kg^{-1})
r_w	latent heat of water (kJ kg^{-1})
T	temperature (K)
T_V	vapour temperature (K)
U	vapour velocity (m s^{-1})

Greek symbols

Δh	heat transfer coefficient difference (kW m^{-2} K^{-1})
ΔT	vapour-to-surface temperature difference (K)
Δt	local temperature difference (K)
$\overline{\Delta T}$	mean vapour-to-surface temperature difference (K)
$\Delta\sigma$	surface tension difference (mN m^{-1})
λ	thermal conductivity (kW m^{-1} K^{-1})
σ	surface tension (mN m^{-1})
τ	time (s)
ϕ	heat transfer rate (kW)

Subscript

a–f	different location in the plate
i, j	tab
max	peak points of condensation curves
sat	saturation
w, n, e, s	direction

investigated the dependence of HTCs on surface subcooling [8], vapour velocity [9] and EVC [10]. The HTC was found to be relatively low at small surface subcooling and subsequently to increase steeply before decreasing again. The effect of vapour velocity was to raise HTC. The maximum HTC in the condensation characteristic curves appeared at an ethanol vapour mass fraction of approximately 1% and then HTCs decreased with increasing EVCs. Compared to pure steam, the condensation heat transfer was enhanced approximately 2–8 times. Murase et al. [11] studied the Marangoni condensation using a horizontal condenser tube. The results showed the same trends as those found by Utaka for vertical surfaces. Differences in detail could be explained by geometry considerations and strong dependence of HTC on ΔT and vapour velocity, both of which varied around the perimeter of the horizontal tube. In addition, Yan et al. [12,13] investigated the effect of vapour pressure on Marangoni condensation for water–ethanol vapours. The condensation modes took different appearances under different vapour pressures. The data showed that the HTC increased with the increasing pressure and the promotion effect was significant at low EVCs.

The Marangoni effect is caused by surface tension gradients on the free surface. It can be the result of concentration and/or temperature gradients. In the case of concentration gradients, the effect is called the solutal Marangoni effect. When temperature gradients are responsible for the Marangoni effect, the effect is frequently called thermocapillarity. The previous condensation studies above almost only focused on the effect of concentration gradients, known as so-called solutal Marangoni condensation. In their studies, the experiments were carried out on flat plates or tubes, and the temperature of their condensing surfaces was uniform on macroscale. For the binary mixture vapours and the uniform temperature on the condensing surface, the original intention of the previous works was to use the solutal effect to obtain the pseudo-dropwise condensation. But in the current heat-exchanger field, in order to get more heat transfer, lots kinds of fins were adopted in the heat exchangers. The actual cooling surface was not always flat and the temperature field was always ununiform. It was necessary to study the condensation rules on a surface with temperature gradients. For the temperature gradients on the condensing surface in the binary mixture vapours condensation, the original intention of this condensation was to use the solutal effect and thermal effect to obtain the pseudo-dropwise condensation. There were only few references concerned with the condensation on a surface with temperature gradients for mixture vapours. Utaka and Kamiyama [14] studied the spontaneous movement of condensate drops by applying bulk temperature gradient on the heat transfer surface in Marangoni condensation. As a result of experiment using water–ethanol vapour mixture, the movement of droplets from low temperature-side to high temperature-side could be observed on the heat transfer surface arranged horizontally. Hu et al. [15] investigated the Marangoni condensation on an oblique plate and primarily studied the effect of temperature gradients on the heat transfer flux. The temperature gradients on condensing surface were thought to be small, continuous and homogeneous. The mean HTC could be augmented as much as 15% compared with the literature under similar experimental conditions. From this research it could be concluded that the magnitude of temperature gradient would affect the efficiency of heat transfer enhancement. In other words, greater temperature gradients may promote higher heat transfer. Also, the nonhomogeneous temperature gradients on the condensing surface may create stronger disorder and stronger Marangoni convection. The direct result may be a further heat transfer enhancement. So it is necessary to investigate the Marangoni condensation on surfaces with other style of temperature gradients. The purpose of this paper is to study the Marangoni condensation heat transfer characteristic on a vertical surface with larger and nonhomogeneous temperature gradients deeply.

2. Experimental apparatus and methods

2.1. Experiment apparatus

As mentioned in Section 1, in engineering application, many kinds of fins, such as taper fin and flat fin, have been designed in the heat exchangers to enhance heat transfer. The oblique plate in the Hu et al. [15] is just thought to be the application of taper fin. The application of flat fin has not been reported in Marangoni condensation researches. A copper plate, shown in Fig. 1(a), was devised specifically for getting a condensing surface with temperature gradients as described in Section 1, thought to be the application of flat fin. The condensing surface had an area of 25 mm × 40 mm. One typical temperature field of cross section is shown in Fig. 2(a), calculated by a numerical simulation. As seen in Fig. 2(a), the temperature field was serrated. The temperature of condensing surface was nonhomogeneous, but symmetrical. At