International Journal of Heat and Mass Transfer 90 (2015) 339–349

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Visualization study of condensation of ethanol–water mixtures in trapezoidal microchannels

Rui Jiang, Xuehu Ma *, Zhong Lan, Yuxiao Bai, Tao Bai

Institute of Chemical Engineering, Dalian University of Technology, Dalian, Liaoning Province 116024, China

ARTICLE INFO

Article history:
Received 8 January 2015
Received in revised form 6 June 2015
Accepted 9 June 2015
Available online 9 July 2015

Keywords:
Microchannels
Condensation
Two phase flow
Ethanol-water mixture
Surface free energy difference

ABSTRACT

A visualization experiment is carried out to investigate the ethanol–water vapor mixtures condensation flow patterns in an array of microchannels under a wide range of concentration (2–60%). The text microchannel is a trapezoidal silicon channel with a hydraulic diameter of 165.87 μm and a length of 50 mm. Along the flow direction, annular, annular-streak, annular-streak-droplet, churn, injection, droplet-injection and bubble flow patterns are observed in the vapor mixtures condensation under different inlet ethanol mass concentration (60%, 31%, 20%, 6%, 4% and 2%), which is obviously different from pure steam condensation. The equivalent surface free energy differences under various vapor conditions and vapor–surface temperature differences are calculated quantitatively. The experimental results show that flow patterns are closely related to the equivalent surface free energy differences. A correlation based on the critical quality is proposed to indicate the injection two-phase flow patterns transition.

1. Introduction

With advancement in modern science and technology, equipments are moving towards miniaturization. Condensation in the minichannels or microchannels attracts many researchers' attention. There are many applications with binary mixture condensation, such as Kalina power generation, condensation heat exchanger, distillation, refrigeration etc. [1–3]. Various flow regimes in condensation are observed resulting from changes in the relative magnitudes of forces acting upon the two phases, such as gravity dominated regimes (e.g. stratified flow) and shear stress dominated (e.g. annular flow) regimes. The flow regimes have great influence in the mechanisms of heat and mass transfer during two phase flow [4]. Different from the flow in the conventional tubes, surface tension and shear force instead of the body force are dominate in microchannel, which also results in different flow patterns for condensation in microchannels [5].

Cheng and Wu [6] classified the microchannel by introducing dimensionless parameter Bo, which is defined as:

$$\mathrm{Bo} = \frac{(\rho_L - \rho_V) \cdot g \cdot D^2}{\sigma} \qquad (1)$$

where g, ρ_l, ρ_v, D, and σ are gravity, liquid density, vapor density, hydraulic diameter of microchannel, and surface tension respectively. It is determined that if the Bo < 0.05, where the gravity effect can be neglected.

Wu et al. [7,8] and Quan et al. [9,10] have carried out visualization and measurement experiments on flow condensation of steam in trapezoidal silicon microchannels. The droplet, annular injection and bubble flow patterns during the condensation were observed in microchannels and the effect of inlet mass flux and microchannel diameters on the flow regimes were investigated. Chen et al. [11–13] have conducted several experiments on the condensation of steam in triangular, trapezoidal, and rectangular microchannels and investigated the different cross sections influence of the injection location and frequency in microchannels. Ma et al. [14] investigated the two-phase flow patterns and transition characteristics for steam condensation in silicon microchannels with different cross-sectional geometries and the flow regime maps for different microchannels during condensation were established in terms of steam mass flux and steam quality. Kim et al. [15] studied the flow pattern and pressure drop of FC-72 condensation in square microchannels experimentally and smooth-annular, wavy-annular, transition, slug, and bubbly flow regimes were identified. Nema et al. [16] developed different dimensionless transition criteria to distinguish transition point of the flow regimes of R134a condensation in minichannels.

It is well known that condensation mode is closely related to surface wettability of the compensating surface. Fang et al. [17] and Chen [18] deposited different functional coatings on silicon microchannels to form a hydrophobic surface and showed the

---

* Corresponding author. Tel.: +86 0411 84707892.
E-mail address: xuehuma@dlut.edu.cn (X. Ma).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.06.020
0017-9310/

Nomenclature

A	area, m^2
Bo	Bond number
Ca	capillary number
c_p	the specific heat, J kg^{-1} K^{-1}
D	hydraulic diameter, µm
g	gravitational acceleration, m s^{-2}
G	steam mass flux, kg m^{-2} s^{-1}
h_{f}	latent heat, kJ kg^{-1}
L	length mm
L_{Cu}	width of the cooler m
P	pressure
q	heat flux, kW m^{-2}
Q	heat transfer rate, W
Re	Reynolds number
T	temperature, K
W	ethanol weight concentration
We	Weber number
x	steam quality
X	distance, m
z	axial location, mm

Greek symbols

σ	surface tension, N m^{-1}
μ	viscosity Pa s
λ	thermal conductivity, W m^{-1} K^{-1}
ρ	density, kg m^{-3}
δ	thickness of the chip m

Subscript

c	condensate drop
Cu	copper
e	ethanol
f	film
in	inlet
l	liquid
m	mixture
out	outlet
p	plenum
sec	section
sg	silicon grease
si	silicon
v	vapor
w	water
W	wall

droplet flow pattern in the microchannel. However, for the confined space, it is difficult to modify inner surface of microchannels. Due to the surface tension gradient caused by the binary vapor condensation, a pseudo-dropwise condensation [19] would appear in the condensation process and lead to a special droplet-film combined condensation mode, which is known as Marangoni condensation or pseudo-dropwise condensation.

Murase et al. [20] investigated the steam–ethanol mixture condensation and found that Marangoni condensation may occur in condensation of binary mixtures for the more volatile constituent having smaller surface tension. Wang et al. [21] tested ethanol–water condensation under a wide range of concentration of the ethanol in a vertical surface, the visual observations showed that the condensation modes were dependent on the concentration of the ethanol and the temperature difference between vapor-to-surface. Utaka et al. [22,23] confirmed that there is an ultra-thin film with a thickness of 1 µm on the condensate surface during steam–ethanol condensation. They conducted an experiment about condensate drop movement by applying bulk temperature gradient on heat transfer surface. The surface tension gradient of this film due to temperature gradient drives the condensate drop to move from the low-temperature side to the high-temperature side. Lan and Ma et al. [24] conducted a visualization study on the ethanol–water mixture condensation with different ethanol concentration at atmospheric pressure. The ultra-thin liquid film, instead of the solid heat transfer surface, was considered as the real condensing surface. They measured that the condensation mode alternated from filmwise to transition state and finally to dropwise condensation with the increase of the vapor–surface temperature difference.

In this paper, visualization study was conducted to investigate flow regimes of ethanol-steam mixtures condensation in microchannels. The surface tension difference caused by the phase equilibrium in binary mixtures condensation was taken into consideration to reveal the influence on those flow patterns. Based on the experimental data, a correlation of injection flow pattern was established by various dimensionless parameters, to predict the correlation of steam quality.

2. Experimental setup

The experimental setup is shown in Fig. 1. The ethanol–water steam is generated from boiler, flows through filter, pre-heater, test section, post-condenser and finally into the condensate accumulator. All the pipelines are fully insulated to ensure the vapor is at the saturation state into the microchannels. The condensate is collected in the condensate accumulator and weighed in the electronic balance (±0.01 g) to calculate the steam mass flux. The system is vacuumed at the beginning of the experiment to discharge the noncondensable gas. The experimental system was keeping stable for 10 min as the criterion to detect the noncondensable gas is completely discharged.

Fig. 2 shows the schematic diagram of the experimental set up which is consisted of two principal subsystems: the microchannels and the test section. The cooler is manufactured by copper. The cooling water is flowing through the pathway (64 mm × 20 mm × 1.5 mm, length × width × height) in the bottom of the cooler. The thermal conductive silicon grease is used to maintain good thermal contact between the microchannel and the cooler. 14 parallel trapezoidal silicon microchannels is prepared by microfabrication in a chip via silicon wet etching and anodic bonded with Pyrex glass for flow visualization. The width of the microchannel top and bottom surface are 440.57 µm and 276.69 µm respectively. The height and hydraulic diameter are 115.73 and 165.87 µm. Fig. 2 illustrates the structure and dimension of microchannels tested by surface profiler and the microchannels photos. In our experiment, Bo number is approximately 0.01.

An inlet vapor plenum and an outlet vapor plenum are on the front and back of microchannels. In order to detect the local heat transfer rate of the microchannels, 20 T-type thermocouples (±0.05 °C) are equally divided into 5 group in the cooler. The distance between two adjacent thermocouples is 3 mm in the vertical direction and 12 mm in the axial direction, which is shown in Fig. 3.

A camera system (PHOTRON, FASTCAM APX-RS) mounted with a set of microscope lenses (HIROX, CX10C) is used to record the