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Experimental study on flow condensation of mixture in a hydrophobic microchannel

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ABSTRACT

The condensation flow patterns of ethanol–water mixture in a wide range of ethanol mass concentration inside a hydrophobic microchannel is experimentally studied via a high speed imaging system. The effects of channel surface wettability and ethanol concentration on flow condensation are compared and discussed. The experimental results indicate that the surface hydrophobic modification and ethanol concentration play a significant role in the flow condensation of mixture in a microchannel. The droplet condensation appears almost the whole two-phase flow region when the water steam is the main component, in which the droplet flow, droplet-streak flow, droplet-annular flow, droplet-injection flow and droplet-slug/bubble flow occur sequentially in a hydrophobic microchannel. With increasing ethanol concentration, the droplet-slug/bubble flow after droplet-injection flow disappears and is replaced by the pure slug/bubble flow. When the ethanol vapor is the main component, the droplet condensation almost disappears, and the annular-streak flow, annular flow, injection flow and slug/bubble flow appear sequentially along the flow direction. Both an increase in vapor Reynolds number and a decrease in ethanol concentration cause the injection location move toward the channel outlet. In addition, the surface hydrophobic modification introduces the droplet condensation, which is beneficial for the flow condensation heat transfer.

1. Introduction

Miniaturization is a notable feature of the modern devices due to the rapid development of microfluidic science and technology. As a typical physical process, the microscale flow condensation widely exists in miniaturized systems, including micro heat pipes, micro fuel cells, and micro coolers. The flow condensation in a microchannel involves the gas–liquid two-phase flow, phase change heat transfer, flow instability as well as the coupled heat and mass transfer. The flow regimes are the result of comprehensive effects of channel scale, surface wettability and fluid properties. Either the hydrophobically-modified surface or the introduction of binary miscible mixture is beneficial to the enhancement of flow condensation heat transfer. However, it is not properly known how the mixture concentration affects the flow condensation regime in a hydrophobic microchannel. In this particular situation, it is of considerable significance to understand the two-phase flow condensation of mixture in a hydrophobic microchannel.

In a microchannel, the small dimension highlights the importance of surface forces, causing the flow condensation regime to be significantly different from the conventional channels [1]. The surface tension and shear force, rather than the gravity and buoyancy, are dominant the two-phase flow condensation regimes under microscales [2–6]. The flow patterns along the flow stream in microchannels are usually the droplet flow, annular flow, injection flow and slug/bubble flow, which are related to the mass flux [7–11], channel size [7], steam quality [8,9] and cooling rates [10,11]. Owing to the microscale effect, the injection flow is the characteristic condensation flow pattern in microchannels [7–13]. Several special flow patterns are observed in microchannels, including the droplet-annular flow in a wide rectangular silicon microchannel [14], and droplet-injection flow in a hydrophobic microchannel [15]. In addition, the hydrophobically-modified surface could make the droplet condensation occupy the whole gas–liquid two-phase flow region in a microchannel [15,16], which is beneficial to the enhancement of condensation heat transfer.

It is generally accepted that the condensation heat transfer can be improved by adding a miscible additive to the vapor. By this

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Nomenclature

A_{cr}	cross-sectional area of channel, m^2
D	hydraulic diameter, m
L	effective length of microchannel, m
l	distance between the channel inlet and view point, m
m_l	flow rate, kg s^{-1}
n	channel number
Re_v	vapor Reynolds number
t	temperature, K
W	ethanol weight concentration, %
X	dimensionless location

Greek symbols

υ_v	vapor mixture viscosity, $m^2\ s^{-1}$
ρ_v	vapor mixture density, kg m^{-3}

Subscripts

p	injection flow
in	channel inlet

mean, even on a wettable surface, the condensate does not always occur as a liquid film. In the binary vapor condensation, owing to the presence of surface tension gradient, any disturbance on the vapor-condensate interface causes the so-called pseudo-droplet condensation [17,18]. The previous experimental investigation indicates that the condensation performance of a vapor mixture is dependent on the mixture composition [19–22], vapor-to-surface temperature difference and vapor velocity [23]; the condensation modes on a solid surface mainly includes the film condensation, transition state and dropwise condensation [24]. Considering that the mixture and microscale are two approaches to enhance condensation heat transfer performance, it is a great potential for practical applications to combine the advantages of microscale condensation and vapor mixture condensation. Recently, Jiang et al. [25] have taken a visualization experiment to study the condensation flow regimes of ethanol–water mixtures in a trapezoidal microchannel. They have observed several special flow patterns under different ethanol concentrations which are not observed for the pure vapor condensation in microchannels.

Despite several experimental efforts have been conducted to explore the vapor–liquid two-phase flow behaviors of flow condensation in a microchannel [7–16], conventional condensation of a mixture on a solid surface [17–24] and even vapor mixture condensation in a microchannel [25], few studies have focused on flow condensation of mixture in a hydrophobic microchannel. Especially, it is unclear what the relation is between the condensation flow patterns and the mixture concentration in a hydrophobic microchannel. To gain a further insight into the microscale flow condensation regimes, an experimental investigation is conducted to explore the flow condensation in a hydrophobic microchannel by using ethanol–water mixtures in a wide range of ethanol concentration. The observed flow patterns of vapor mixture condensation in a hydrophobic microchannel are presented and analyzed. In addition, the effects of channel surface wettability and ethanol mass concentration on condensation flow patterns are compared and discussed.

2. Descriptions of the experiment

2.1. Experimental setup

In order to elucidate the flow condensation regimes of a mixture in a hydrophobic microchannel, the ethanol–water mixtures in a wide range of ethanol mass concentration are applied. The experimental setup for the observation of condensation flow patterns in a microchannel is designed and assembled. Fig. 1 shows the experimental setup of flow condensation in a microchannel, which is mainly composed of the test section, pipeline system, thermostatic water bath and high speed imaging system.

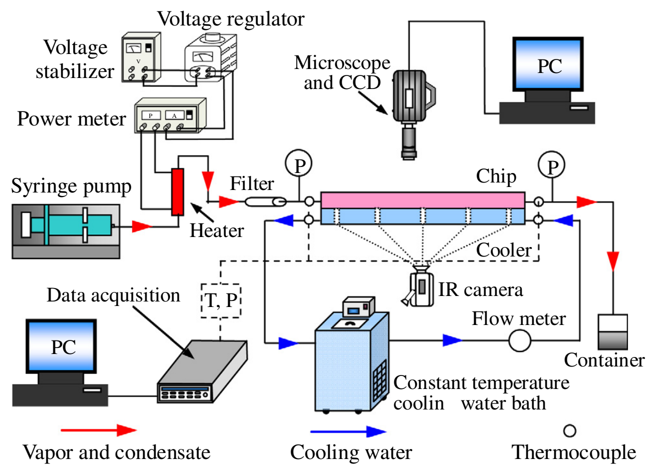

Fig. 1. Schematic of experimental setup.

The test section, which is fixed on a Teflon base, contains the experimental chip and aluminum cooler. The experimental chip is made of 10 parallel microchannels with a rectangular cross-section (width: 300 μm, height: 100 μm, effective length L = 56 mm), as shown in Fig. 2. The microchannel is fabricated by the use of deep reactive ion etching (DRIE) on ⟨1 0 0⟩ silicon wafers. Pyrex glass is anodically bonded to the silicon wafer to form the parallel microchannels. The microchannel wall is treated to be hydrophobic by using thin Au film and the equilibrium contact angle of water is 96° (see W = 0% in Fig. 3). The contact angles of ethanol–water mixtures with different ethanol mass concentrations on the channel wall is measured and shown in Fig. 3. The contact angle of ethanol–water mixtures is much smaller than 96°. The circulation fluid supplied by a thermostatic waterbath is used to control the temperature of aluminum cooler for the regulation of flow condensation in a microchannel.

Ethanol–water mixtures with different ethanol concentrations (W = 2%, 10%, 20%, 40%, 60% and 80%) in the syringe are injected by syringe pump (LSP01-1BH with the flow accuracy of 0.5%.) into a heater where the saturated vapor is generated. In the experiment, a long vertical upward minitube with electric heating is utilized as a heater to generate the vapor. The heat power as measured by power meter is changed by adjusting the voltage according to the flow rate of ethanol–water mixtures. For all the experimental cases, no temperature jump is observed for the wall temperature at the downstream of vertical upward minitube. This implies that the generated vapor is saturated at the microchannel inlet. Fig. 4 presents the relationship between the saturated temperature and pressure under different mass concentrations of ethanol. After flow