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Experimental study on flow boiling heat transfer for pure and zeotropic refrigerants in multi-microchannels with segmented configurations

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ABSTRACT

In this paper, the flow boiling heat transfer characteristics for pure refrigerants of R134a, R245fa and their binary zeotropic mixtures with three blending ratios (R134a/R245fa: 10/90, 30/70 and 70/30 by wt%) were experimentally investigated in the aluminum multi-microchannels with segmented configuration. Each multi-microchannel test plate consisted of seven parallel channel passages with the same total length of 110 mm and cross-sectional area of 2 mm × 1 mm (width × height), while the 10 mm-long interconnected area was arranged every 30 mm along the channel length in segmented one. For each refrigerant working fluid, the experiments were performed at the same inlet evaporating temperature of 26 °C under conditions of the heat flux and mass flux ranging from 20 to 350 kW/m^2 and 300 to 400 kg/m^2 s, respectively. According to the comparative study, R134a working fluid presented higher heat transfer coefficient than R245fa, but it was more prone to local dry out spots in advance. The small addition of volatile component of R134a was found to be beneficial for improving the heat transfer coefficient at higher heat flux as well as the flow boiling CHF, despite the common feature of degraded heat transfer coefficient for test zeotropic mixtures in most conditions. Compared with continuous microchannels, the heat transfer performance was enhanced for pure refrigerants but suppressed for zeotropic mixtures in segmented microchannels, however, in which the interconnected area was helpful to delay the occurrence of the transfer deterioration and improve the flow boiling CHF regardless of pure or zeotropic refrigerants.

1. Introduction

Flow boiling heat transfer in microchannels has been widely recognized as a highly efficient thermal management technology to meet the increasing cooling demands of high power and high heat flux electronic components. Due to the advantages of large specific surface area and utilization of latent heat of vaporization, microchannel heat sinks not only present considerable heat transfer performance with less coolant charge, but also maintain better uniformity of temperature distribution. However, the critical issues of vapor clogging and rapid bubble growth caused by the bubble confinement effect usually lead to the chocking flow or even reverse flow in channel passages, resulting in unfavorable two phase flow instabilities as well as premature dry out phenomenon in partial channels, which directly affects the flow boiling heat transfer performance in multi-microchannels [1,2]. Besides, taking into account the reasonable operating temperature range (lower than 80 °C) of relevant devices and equipment, refrigerants have played an important role in the selection of electronic coolants, especially for zeotropic mixtures, which can obviously delay or even avoid drying out and increase the critical heat flux (CHF) during the boiling process according to recent studies [3]. Therefore, it is of great significance to investigate the flow boiling heat transfer and enhancement mechanism of zeotropic mixtures in multi-microchannels.

In recent years, some extensive studies have been carried out to elucidate the flow boiling characteristics for pure refrigerants in multi-microchannels. Agostini et al. [4,5] explored the flow boiling heat transfer performance of R236fa and R245fa in silicon multi-microchannels and found that the heat transfer coefficient as a function of vapor quality reached the peak value at high heat flux and then decreased with further increase of heat flux, besides, the three-zone model [6] provided better prediction accuracy for the experimental data. Through the flow boiling tests of R134a in a multi-microchannel copper plate, Bertscha et al. [7] pointed out

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Nomenclature

A_{eff}	effective heat transfer area (m^2)
A_o	footprint heat transfer area (m^2)
$c_{p,l}$	liquid specific heat at constant pressure (J/kg K)
H	height of each channel passage (m)
h_{exp}	heat transfer coefficient (W/m^2 K)
h_{lv}	latent heat of vaporization (J/kg)
L	length of the multi-microchannels (m)
M	mass flow rate (kg/s)
m	fin parameter
N	number of channel passages
NP	normalized thermophysical properties
P_{cr}	critical pressure (Pa)
Q	heating power (W)
q_{eff}	effective heat flux (W/m^2)
q_o	footprint heat flux (W/m^2)
T	temperature (K)
ΔT_{db}	temperature difference between dew point and bubble point (K)
W	width of each channel passage (m)
X	perpendicular distance between the position and the bottom wall of microchannels
x	vapor quality

Greek symbols

α	fin efficiency
η	heat loss ratio
λ	thermal conductivity
φ	mass fraction of volatile component (R134a)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
σ	surface tension (N/m)

Subscripts

al	aluminum material
b	bottom wall
es	effective side
eva	evaporation
in	inlet
out	outlet
sat	saturation
sub	subcooled
tc	thermocouple
w	wall

that the heat transfer coefficient varied significantly with inlet vapor quality as well as mass velocity, but slightly with saturation temperature. Considering CPU cooling applications, Madhour et al. [8] learned that the flow boiling heat transfer coefficient of R134a inside a copper multi-microchannel heat sink reached as high as 270000 W/m^2 K relative to the base area, keeping the chip under 85 °C with a maximum pressure drop of 94 kPa. Similar experiments were also performed by Nascimento et al. [9] and presented that the boiling curves displaying heat flux versus average heat sink superheat were shifted to the right hand side with increasing mass velocity and inlet subcooling. Besides, Costa-Patry et al. [10] and Chang et al. [11] found that the pressure drop of R245fa, R236fa and FC-72 in microchannels increased with the increase of vapor quality and mass velocity, but the effect of heat flux was negligible since most of the pressure drop was caused by friction. Some other scholars also attempted to explored the flow boiling characteristics of new refrigerants (e.g. R1234yf and R1234ze(E)) in microchannels to expand the coolant choices and refrigerant applications [12,13].

As for zeotropic refrigerants at this research point, most of the related literatures only referred to the flow boiling characteristics in a single normal size tube or channel. For instance, Kondou et al. [14] investigated the flow boiling of R32/R1234ze(E) mixture in a horizontal microfin tube with 5.21 mm inner diameter and discovered that the heat transfer coefficient of mixtures was significantly degraded and minimized at the blending ratio of 20/80 by mass, where the temperature glide and the mass fraction distribution were maximized. According to Guo et al. [15], the R134a/R245fa zeotropic mixture (82/18 by wt%) presented less pressure drop, but higher heat transfer coefficient than that of the pure R245fa. A modified correlation was then developed based on existing correlations with the experimental data. The different flow patterns of R134a/R245fa mixtures were also identified by Abadi et al. [16] based on the visualized flow boiling tests in a circular glass tube.

Recently, several scholars began to focus on the single microtube/channel flow boiling phenomena of zeotropic mixture. Azzolin et al. [17,18] discussed the flow boiling heat transfer performance of R32/R1234ze(E) zeotropic mixture (50/50 by wt%) inside a 0.96 mm diameter circular microchannel and found that the heat transfer coefficient was less dependent on heat flux compared with pure components, and the heat transfer degradation of zeotropic mixture followed a linear behavior for 50% of all test conditions. With the consideration of additional mass transfer resistance, they extended the correlations developed from pure fluids to the cases of flow boiling of zeotropic mixtures in microchannels. Dang et al. [19] proposed that the hysteresis of flow pattern transition for zeotropic mixtures was strongly affected by both of the temperature glide and blending ratio through the visualized flow boiling experiments of R134a/R245fa zeotropic mixtures in a single rectangular micro-channel. The heat transfer prediction method was then developed taking into account the capillary and Marangoni effect. However, few publications have so far reported the flow boiling characteristics of zeotropic mixtures in multi microchannels.

For the heat transfer enhancement, some scholars have taken the lead in exploration of geometrical modification for microchannels, since the approaches of surface structure and modification as well as change of coolants indicated poor effectiveness in addressing the critical issues of vapor clogging and rapid bubble growth occurred in channel passages [20–22]. According to Wang et al. [23] and Szczukiewicz et al. [24], the undesired phenomena, such as reverse flow, parallel channel flow maldistribution and instabilities, were prevented by employing the inlet constrictions (micro-orifices) to each channel and then the temperature and pressure fluctuations could be obviously suppressed. Prajapati et al. [25] compared the bubble growth and flow instabilities in uniform, diverging and segmented finned microchannels during flow boiling process, and the bubble patterns were characterized with multiple growing interfaces and suppressed growth along the upstream for the segmented finned structure, which proved to reduce the reverse flow and subsequent instabilities, and then enhanced the heat transfer performance. Law and Lee [26] presented that increasing the width of secondary channel passages for segmented finned microchannels had adverse effect on heat transfer performance as well as CHF and pressure drop due to the less suppression of flow boiling instability and greater amount of flow diversion. Besides, Li et al. [27,28] set the structures of auxiliary channels and multiple nozzles in microchannels intending to induce self-excited and self-sustained high frequency two-phase