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Boiling heat transfer of co- and counter-current microchannel heat exchangers with gas heating

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In this paper, we present an experimental study on a two-phase boiling heat transfer of liquid methanol in co- and counter-current microchannel heat exchangers (MCHEs) with gas heating. The silicon-based MCHE with dimensions of $20 \times 20 \times 2$ mm is designed with 18 microchannels. The working fluids on the hot and cold sides of the MCHE are helium and liquid methanol, respectively. During the study, the helium fluid inlet temperature is varied from 40 to 250 °C, while the mass flux is fixed at 10 kg/m^{2}s; additionally, the mass flux of the liquid methanol is varied from 3 to 9 kg/m^{2}s, and the inlet temperature is varied from room temperature to the saturation temperature of methanol, depending on the hot-side heat flux. The results demonstrate that the convective boiling heat transfer increases with the mean vapor quality until approaching the critical heat flux (CHF) condition. The counter-current MCHE exhibits a higher CHF due to a higher inlet subcooling temperature than the co-current MCHE. The single-phase and convective boiling heat transfer coefficients are measured and compared with the existing correlations. Moreover, two empirical correlations for the two-phase boiling heat transfer coefficient for the MCHEs are proposed in this study.

1. Introduction

Heat exchangers are an important component in the field of energy conservation and recovery systems. With the increasing energy demands and the decreasing dimensions of heat exchangers, the microchannels represent the next step in heat exchanger development [1]. Recently, MCHEs have been widely applied to micro-reactors for hydrogen production [2–8], micro-evaporator/condensers [9–12], and air-conditioning systems [13–14]. Compared to traditional heat exchangers, MCHEs have the advantages of a high heat-transfer area density, a low thermal resistance, and the miniaturization of the equipment. Hence, the heat transfer efficiency of MCHEs is more often investigated in the literature. Schubert et al. [15] developed metallic cross-flow and counter-flow MCHEs with microchannels or microcolumn structures. The water throughput is in the range of 0.19 kg/s and per passage pressure drops is up to 6 bar. The maximum overall coefficient reached with the microcolumn device was 54.5 kW/m^{2}K at a water mass flow of 0.1 kg/s, while the coefficient was significantly lower, i.e., 18.2 kW/m^{2}K, for a microchannel heat exchanger. Brandner et al. [16] studied various cross-flow heat exchangers with microchannel and microcolumn arrays (aligned and staggered) and compared their thermal performances. They found that decreasing the hydraulic diameter of the microchannels can enhance the heat transfer, and the staggered array of microcolumns exhibited the best performance in their study. Hasan et al. [17] studied the effect of channel geometry on the performance of a counter-flow MCHE. The influences of channel shapes such as circular, square, rectangular, isotriangular, and trapezoidal were evaluated by numerical simulations. In their studies, decreasing the volume of each channel or increasing the number of channels increased the heat transfer, but the required pumping power and pressure drop were also increased. The channel with a circular shape resulted in the best overall performance.

For a detailed understanding of the thermal and hydrodynamic phenomena of an MCHE, Kang and Tseng [18] developed a theoretical model to illustrate the fluidic and thermal characteristics of a cross-current MCHE. The model was validated by comparing it with experiment data from literature. Their results showed that the heat transfer rate and pressure drop were influenced significantly by the average fluid temperature on both the hot and cold sides. They also examined the effect of different materials—copper and silicon—on the performance and found that the material exerts a small influence only on the efficiency due to the thinness of the

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Nomenclature

A	area (m^2)
Bo	boiling number $\left(\frac{q''_{me}}{G_{me}h_{fg}}\right)$, dimensionless
C_p	specific heat (J/kg K)
D	hydraulic diameter of channel (m)
G	mass flux (kg/m^2s)
K	thermal conductivity (W/mK)
Ja	Jakob number $\left(Ja = \frac{\rho_l Cp_l (T_{he,m} - T_{me,sat})}{\rho_v i_{fg}}\right)$, dimensionless
$\dot{m}$	mass flow rate (kg/s)
$\dot{Q}$	heat transfer rate (W)
q''	heat flux (W/m^2)
Re	Reynolds number ($\rho VD/\mu$), dimensionless
$Re_{2\varphi}$	two-phase Reynolds number $\left(\frac{G(1-x_m)D}{\mu_l}\right)$, dimensionless
T	temperature (°C)
X	vapor quality

Greek symbols

β	constant in Eq. (4) (W/K)
δ	thickness (m)
ε	efficiency
γ	ratio of $\dot{Q}_{trans,v}$ to $\dot{Q}_{me,v}$
ξ	ratio of hot-side heat loss to total heat loss

Subscripts

A	ambient
exp	experiment
He	helium
In	inlet
l	liquid
$loss$	heat loss
m	mean
me	methanol
out	outlet
pre	predicted
sh	superheat
si	silicon
sp	single-phase
sys	test section average
t	two-phase
$trans$	heat transfer from hot side to cold side of MCHE
v	vapor

fins. García- Hernando et al. [19] experimentally studied the hydrodynamic and heat transfer performance of MCHEs with 100×100-μm and 200×200-μm square cross-sections with a single-phase flow. Their experimental results were well predicted by classical theories of viscous flow and heat transfer. Their study revealed no effects of heat transfer enhancement or pressure drop increase as a consequence of the small scale of the microchannels. However, the plate thickness and material were found to be critical in the design of an MCHE because the convection coefficients are extremely large on a small scale. Dang and Teng [20] experimentally studied the influences of flow plate configurations on the performance of an MCHE. The parameters of substrate thickness, channel hydraulic diameter, and inlet/outlet locations were considered by two categorized fluid flow conditions, i.e., varying the inlet temperature of the hot side and varying the mass flow rate of the cold side. Their results showed that the effect of the channel hydraulic diameter is more significant than that of the substrate thickness. Moreover, a smaller hydraulic diameter was demonstrated to lead to a higher heat transfer rate and pressure drop. Cao et al. [21–22] investigated the pressure drop and heat transfer of three types of MCHEs, i.e., co-flow, counter-flow, and cross-flow MCHEs, with two or ten 0.4-mm-thick stainless steel plates. They then developed the correlations of the average Nusselt number and pressure drop as a function of the Reynolds number in the microchannels based on their own data.

Studies on MCHEs with boiling or condensation two-phase flows are significantly more limited than that of single-phase flows. Hsieh and Lin [23] studied the saturated-flow boiling heat transfer and frictional pressure drop of the refrigerant R-410A flowing in a vertical plate heat exchanger (PHE). They used water to heat the R-410A. The results indicated that the heat transfer coefficient and frictional pressure drop of R-410A increased almost linearly with the heat flux. Furthermore, a significant effect of the refrigerant mass flux on the boiling heat transfer appeared only in the high heat-flux region. They proposed the empirical correlations for the saturated boiling heat transfer coefficients and friction factor based on their own data. Longo and Gasparella [24] investigated the effect of heat flux, mass flux, saturation temperature, outlet conditions, and fluids properties on the heat transfer and pressure drop for the vaporization of HFC-134a, HFC-410A, and HFC-236fa inside a small brazed-plate heat exchanger. Their results showed that the HFC-410A exhibits the highest heat transfer coefficient and lowest frictional pressure drop. Furthermore, the experimental heat transfer coefficients were compared with literature and a correlation for frictional pressure drop was proposed. Furberg et al. [25] studied the performance of a standard PHE evaporator, both with and without a novel nano- and microporous copper structure that is used to enhance the boiling heat transfer mechanism in the refrigerant channel. The results showed that the refrigerant channel with the enhancement structure improved the overall heat transfer coefficient by more than 100%.

Fernando et al. [26–28] developed a minichannel, aluminum tube heat exchanger to minimize the refrigerant charge in a small system. The study covered both single-phase (liquid-to-liquid) conditions, and two-phase conditions (serving as an evaporator and condenser). Their experimental heat transfer coefficients were compared with predictions from correlations in literature. Their results showed that the shell-side Nusselt numbers for single-phase flows were considerably higher than those predicted by the correlations from literature, and the two-phase heat transfer coefficients are higher than the predictions from the correlations in literature.

In the present study, we experimentally measure the single-phase and two-phase boiling heat-transfer characteristics associated with a custom-made gas-to-liquid MCHE. Such a MCHE is studied to design a methanol evaporator as a component of a reformed methanol fuel cell (RMFC). The heat transfer is from the high-temperature gas product of a methanol reformer to the cold liquid methanol. Hence, the reformed gases can be cooled via a heat exchange in an MCHE and then enter the fuel cell at an appropriate temperature. Meanwhile, the liquid methanol can be vaporized using the heat from the reformed gases for use in the methanol reformer. This can increase the heat transfer efficiency and benefit the environment by converting the exhaust heat to evaporate liquid methanol. In our previous study [29], we investigated into the two-phase flow patterns and the efficiency of the co- and counter-current MCHEs. In the present study, the effects of the flow arrangement on the heat transfer characteristics of MCHEs in both single- and two-phase flow regions are explored. The two-phase boiling heat transfer coefficient of the co- and counter-current MCHEs is compared with existing correlations in literature, and empirical correlations are proposed for co- and counter-current MCHEs.