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Experimental investigation and development of new correlation for flow boiling heat transfer in mini-channel

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ABSTRACT

The flow boiling heat transfer of refrigerant R134a in horizontal multiport mini-channel was experimentally investigated in this paper. Two kinds of mini-channels made of aluminum alloy with the hydraulic diameter of 0.63 mm for 23 rectangular channels and 0.72 mm for 14 rectangular channels were studied. Electric heating film was adopted to provide direct uniform heat flux. The experimental results were obtained with the vapor quality between 0 and 1, the heat flux ranging from 10 to 60 kW/m^2, the mass flux ranging from 128 to 560 kg/(m^2.s) and the saturation pressure from 0.22 to 0.58 MPa. It was found that nucleate boiling dominates in the low vapor quality region and the heat transfer coefficients of mini-channel are higher than those in conventional channel. The heat transfer coefficients increase with the increasing of both heat flux and saturation pressure but have little dependence with the mass flux. In the high vapor quality region, connective boiling is the main contributor. Heat flux and saturation pressure have little influence on the heat transfer coefficients, but the influence of mass flux is obvious. There is a small increase in heat transfer coefficient with an increase of mass flux. Accordingly, a new correlation for flow boiling heat transfer in mini-channel of R134a was proposed based on Gungor and Winterton correlation. The mean relation deviation is −1.76% and the mean absolute relation deviation is 19.0% respectively. This new correlation is proved to have an obvious accuracy improvement in predicting the flow boiling heat transfer coefficient of R134a in mini-channel. The present work can provide a guidance to the design of mini-channel heat exchanger.

1. Introduction

The miniaturization of electronic devices caused significant increase in heat dissipating rate per unit device area, and electronics cooling, especially for high heat flux micro-electronics components, such as micro-chips and avionics devices, has been attracting increasing research interests in the last decades. In recent years, the flow boiling heat transfer in mini- or micro-channel is considered to be an alternative to replace the conventional cooling methods based on the forced convective single-phase heat transfer, and the mini- or micro-channel has compact structure which leads to considerably large heat transfer area naturally and also has excellent heat transfer performance. Moreover, the flow boiling heat transfer mainly takes advantage of refrigerant's latent heat to absorb larger amount of heat compared with single-phase scheme while maintaining satisfactory low heat transfer temperature difference.

The characteristics and mechanisms of flow boiling heat transfer in mini- or micro-channel were studied but not clearly examined yet. Kandlikar and Grande [1] proposed a channel size classification criterion based on the manufacturing techniques and mean free path of molecules. Different from the classification method proposed by Kandlikar and Grande [1], a lot of other researchers' approaches were based on the forces acting during flow boiling, for example: surface tension, inertia, buoyancy [2–4]. Dimensionless numbers, such like Confinement number (*Co*), *Eötvös*number (*Eö*), Bond number (*Bo*), were adopted to weight their interactions and served as the threshold between different kinds of channels. According to these criteria, the two adopted multiport channels with the inner hydraulic diameters of 0.63 mm and 0.72 mm all belong to mini-channel. Jabardo and Bandarra Filho [5] experimentally investigated the convective boiling in a 12.7 mm internal diameter horizontal copper tube with R134a, and tape electrical resistors were adopted to provide heat flux. They found that the heat transfer coefficient increased with the increasing of heat flux and mass flux when vapor quality of refrigerant was less than 0.9. Saturation pressure's effect on heat transfer coefficient was related with heat flux. For low heat flux, the heat transfer coefficient rose with heat flux, but this phenomenon disappeared in high vapor quality region. Choi et al. [6] took two stainless steel tubes with hydraulic diameters of

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Nomenclature

A	heat transfer surface(m^2)
A_c	cross-sectional flow area(m^2)
Bo	Boiling number, $q/(Gh_{lg})$
C	dimensionless factor
cosh	Hyperbolic cosine function
D_h	hydraulic diameter(m)
dT	Micro element of temperature(°C)
dx	Micro element of distance(m)
G	mass flux($kg/m^2.\ s$)
h	enthalpy(J/kg)
h_{lg}	latent heat of vaporization(J/kg)
L	length(m)
$\dot{m}$	mass flow rate(kg/s)
mH	Parameter of the fin
N	number of data points
Nu	Nusselt number
P	pressure(MPa)
P_{cr}	reduced pressure, P_{sat}/P_{crit}
P_{crit}	critical pressure(MPa)
Pr	Prandtl number
Q	heating power(W)
q	heat flux(W/m^2)
Re	Reynolds numberGD_h/μ
T	temperature(°C)
We	Webber number, $G^2D_h/(\sigma\rho)$

Greek symbols

α	heat transfer coefficient ($W/m^2.\ K$)
λ	thermal conductivity($W/m.\ K$)
μ	dynamic viscosity($Pa.\ s$)
ρ	density(kg/m^3)
σ	surface tension(N/m)
η_f	Fin effectiveness

Subscripts

eff	Effectiveness
exp	experiment
g	gas
i	inlet
inner	Inner side of the wall
k	the k_{th}measurement point
l	liquid
lo	liquid only
o	outlet
pre	prediction
sat	saturation
tp	two phase
up	Upper wall of the tube
w	wall

1.5 mm and 3.0 mm as test sections. The refrigerant was heated directly by applying an electric current to the tube. At low quality region (vapor quality less than 0.15), the mass flux had an insignificant effect on the heat transfer coefficient. At relative high quality region (vapor quality ranges from 0.15 to 0.6), the heat transfer coefficient increased with the mass flux. Cartridge heater was used to evaporate the refrigerant at uniform heat flux by Bertsch et al. [7,8], but different conclusions were obtained from these two papers: the heat transfer coefficient had positive relationship with mass flux but showed little dependence with saturation pressure in Ref. [7]; while in the other paper, the influence of mass flux on heat transfer coefficient was almost negligible, and the saturation pressure's increment led to a slight increase in the heat transfer coefficient at moderate vapor quality region. Recent experiments conducted by Thiangtham et al. [9] revealed that at high heat flux conditions, the heat transfer coefficients increased with the increase of mass flux, which is similar to the result in Ref. [7]. And the mass flux's influence on heat transfer coefficients became more significant at high vapor quality even at low heat fluxes.

In addition to R134a, other refrigerants, such as R22 and R410a, are also always considered as common-used working fluid. Kim et al. [10] designed a test section with a flat tube for refrigerant R22 and an annular channel for hot water, and R22 was heated by hot water. It was found that the heat transfer coefficient increased as the mass flux increased. However, at low quality region, the effect of mass flux seemed to vanish. The saturation pressure had a complicated influence on heat transfer coefficient which related with heat flux: high pressure brought about great heat transfer coefficient at high heat flux, but the effects could not be observed at low heat flux. Yun et al. [11] used R410a to conduct a series of experiments and found that the heat transfer coefficient was closely affected by the mass flux but not by the saturation pressure.

A number of empirical correlations for R134a flow boiling heat transfer have been proposed based on experimental data analysis [12] and theoretical analysis [13]. However, most of them cannot show satisfactory prediction accuracy for other experimental data. The theoretical derivation one has very complex formation [13] and is difficult to give a predictable coefficient quickly for engineering applications. Fang et al. [12] collected 1158 data points for flow boiling heat transfer of R134a from nine previous papers, and 18 existing correlations were evaluated. The results showed that even the best Gungor and Winterton correlation [14] has a poor performance with the mean absolute relation deviation of 36.6%. A lot of attempts have been made for the purpose of developing an acceptable predicting correlation for flow boiling heat transfer in mini-channel [9,15]. However, no existing correlation has been reported with satisfactory prediction accuracy so far.

In the present work, two kinds of multiport mini-channels were selected as the test channels because of their compact structures and promising application prospects. The effects of hydraulic diameter, heat flux, mass flux and also saturation pressure on the heat transfer coefficients were analyzed by the experimental results, and the mechanisms underlying these effects were also explained. In addition, a new correlation was developed based on the data points from both present work and other papers.

2. Experimental method

2.1. Experimental apparatus

An experimental set-up was designed to study the flow boiling heat transfer in multiport mini-channel, as shown in Fig. 1. The system consists of a refrigerant loop subsystem and a data measurement subsystem.

The refrigerant loop includes the following parts: gear pump, Coriolis mass flow meter, preheater, test section, receiver, tube-fin condenser and several valves. The refrigerant R134a is driven by the gear pump to cycle in the loop and its mass flow rate can be regulated continuously by changing the speed of gear pump, and the accurate mass flow rate in the loop is measured by high-precision Coriolis mass flow meter. In order to obtain the desired inlet vapor quality, a preheater is adopted. By adjusting the input power of preheater, the inlet state of refrigerant can be controlled. The receiver is used to reserve