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Flow condensation in a mini channel with serrated fins with jet impingement cooling: Experimental study and development of new correlation

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ABSTRACT

The present study experimentally investigated the heat transfer characteristics of flow condensation in a mini channel with serrated fins. The hydraulic diameter of the aluminum channel was 1.28 mm with 11 offset rectangular channels. The vapor of refrigerant R134a was cooled by cold water with jet impingement. After the calibration of jet impingement cooling, the influences of different parameters on condensation heat transfer were identified with the experimental conditions of vapor quality from 0 to 1, heat flux from 5 kW/m^2 to 52 kW/m^2, mass flux from 72 kg/(m^2·s) to 145 kg/(m^2·s) and saturation pressure from 0.38 MPa to 0.50 MPa. Flow patterns during condensation were also observed through the visualization design of test section. The experimental results reveal that the vapor quality and mass flux have insignificant influence on the local heat transfer coefficient. The heat transfer coefficient increases with the heat flux and decreases with the saturation pressure. Annular flow is dominant during the whole condensation process. As the existing empirical correlations fail to give reasonable prediction of the present experimental results, a new one is developed with the mean relative deviation and mean absolute relative deviation of 2.3% and 12.0%, respectively. The present work can provide valuable guidance for the design of mini channel condenser for engineering application.

1. Introduction

Flow condensation heat transfer has often occurred in various industries such as refrigeration, desalination and power station [1,2]. Particularly in the past few decades, benefited from the development of manufacturing technologies, thermal components, such as condenser and heat pipe, become smaller and lighter with higher heat transfer efficiency. Such tendency of component miniaturization has brought about development in various fields. For example, the micro reactor and heat exchanger could be used in electric devices for high heat flux dissipation and thermal control in satellite or spacecraft [1]. Due to the restriction of the mini or micro geometry, the flow condensation characteristic in such kind of channel may be different from that in conventional ones. As a result, a large variety of studies have been focused on the condensation heat transfer to uncover the flow and heat transfer characteristics in mini or micro channels.

As the size of mini or micro channel is much smaller than that of conventional ones, the behavior of forces, such as gravity, surface tension, inertia and buoyancy, differ from those in conventional ones [3]. But the flow pattern and condensation heat transfer performance are usually influenced by these forces. In fact, in previous investigations, the dimensionless numbers in the form of different forces were used to classify the types of channels. The numbers include Bond number *Bo* [4], Lapalce constant *L* [5], *Eötvös* number *Eö* [6] and confinement number *Co*. For example, the confinement number *Co* represents the ratio of surface tension and buoyancy, and the value of 0.5 is the threshold of conventional and mini or micro channel [7]. Differently, Kandlikar and Grande [8] used a certain channel diameter to classify various types of channels. They recommended the channel classification criterion as follows: conventional channel (diameter larger than 3.0 mm), mini channel (diameter 0.2–3.0 mm) and micro channel (diameter less than 0.2 mm). Mehendail et al. [9] adopted a similar criterion to distinguish the mini or micro channel from conventional ones. However, the values of channel diameter were not exactly the same with that adopted by Kandlikar and Grande [8]. To sum up, no univeral agreement has been reached on the classification of

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Nomenclature

A_c	cross-sectional flow area(m^2)
A_p	primary heat transfer area (m^2)
A_s	secondary heat transfer area (m^2)
Bo	Boiling number, $q/(Gh_{lg})$
Co	Convective number, $(1/x-1)^{0.8}(\rho_l/\rho_g)^{0.5}$
D_h	hydraulic diameter (m)
G	mass flow rate (kg/s)
h	enthalpy (J/kg)
h_{lg}	latent heat of vaporization (J/kg)
M	mass flux ($kg/m^2 \cdot s$)
MRD	mean relative deviation
$MARD$	mean absolute relative deviation
N	number of data points
P	pressure (MPa)
P_R	reduced pressure, P_{sat}/P_{crit}
P_{crit}	critical pressure (MPa))
Pr	Prandtl number
q	heat flux (W/m^2)
Re	Reynolds number,GD_h/μ
T	temperature (°C)
x	vapor quality

Greek symbols

α	heat transfer coefficient ($W/m^2 \cdot K$)
λ	thermal conductivity ($W/m \cdot K$)
μ	dynamic viscosity (Pa·s)
ρ	density (kg/m^3)
η_f	fin effectiveness

Subscripts

ave	average value
g	gas
i	inlet
j	jet impingement
k	the *kth* measurement point
local	local value
o	outlet
sat	saturation
t	total value
w	wall

different channels. However, one point that can be determined is that the channel with serated fins of equivalent diameter of 1.28 mm in present study belongs to the mini channel in terms of all the abovementioned criteria.

Due to its practicality in various areas, the flow condensation heat transfer has been widely investigated by the researchers. The circular channel was mostly investigated. Goss Jr. and Passos et al. [10] investigated the condensation heat transfer characteristics of refrigerant R134a in a micro tube with eight parallel circular channels with the diameter of 0.77 mm. Their experimental results indicated that the saturation temperature and heat flux had no obvious influence on the condensation heat transfer coefficient. However, it increased with both the mass flux and vapor quality of refrigerant. What was more, in the moderate range of vapor quality, the heat transfer coefficient tended to be constant. Kaew-on et al. [11] experimentally studied the flow condensation of R134a inside a mini circular and three flattened tubes severally. The equivalent diameters of these studied tubes ranged from 1.16 mm to 3.51 mm. They concluded that the heat transfer coefficient of flow condensation increased with mass flux, heat flux and vapor quality but showed little dependence on saturation pressure. By comparing the existing flow pattern maps, it revealed that most of the flow patterns in the tested channel belonged to the semi-annular and annular flow. Oh and Son [12] identified the flow condensation of R22, R134a and R410A in a single circular micro tube with the diameter of 1.77 mm. They stated that the local heat transfer coefficient had an ascending trend with the increase of both vapor quality and mass flux. The refrigerant R410A had the greatest condensation heat transfer coefficient and the other two kinds of refrigerants almost shared the same values in terms of heat transfer coefficient under comparable experimental conditions. The condensation heat transfer performance of R134a and R404A in circular mini channels with the diameters ranging from 0.31 mm to 3.3 mm was investigated by Bohdal et al. [13]. Their results indicated that the R134a had higher heat transfer coefficient than that of R404A. Sapali and Patil [14] also compared the condensation heat transfer performance of these two kinds of refrigerants in a smooth and micro-fin tube respectively. They also concluded that R134a showed better condensation heat transfer performance than R404A. What is more, the tube with micro-fins had greater heat transfer coefficient than that of the conventional one. The condensation heat transfer coefficient of R134a and R32 in a single circular channel with the diameter of 0.96 mm was compared by Matkovic et al. [15]. They concluded that the heat transfer coefficient increased with the mass flux of refrigerant. The correlation developed by Cavallini et al. [16] gave the most accurate prediction of condensation heat transfer coefficient. Five kinds of refrigerants were selected by Cavallini et al. [17] to investigate the condensation characteristics in a smooth tube. Their summarized that higher heat transfer coefficient was obtained at lower saturation pressure, greater mass flux and vapor quality. Experiments were also conducted by Charun [18], Zhang et al. [19] and Col et al. [20] to study the condensation heat transfer performance of R404A, R22, R410A and R1234yf in circular channels with the diameter ranging from 0.96 mm to 3.3 mm.

Except the widely used circular channel, the multiport rectangular channel was also studied by some researchers. Park et al. [21] compared the condensation heat transfer performance among R1234ze(E), R134a and R236fa in a multiport mini channel with the hydraulic diameter of 1.45 mm. They concluded that the heat transfer coefficient decreased with the decrease of vapor quality as condensation processed. And it also increased with the increase of mass flux and the decrease of saturation pressure. They developed a data processing method to evaluate the local heat flux and heat transfer coefficient based on single-phase experiments. However, they did not analyze the influence of local heat flux on heat transfer coefficient. Then López-Belchí et al. [22] adopted the above data processing method to evaluate the condensation heat transfer performance of propane in a multiport mini channel with the diameter of 1.16 mm. They only identified the influence of refrigerant mass flow rate and vapor quality on heat transfer characteristics. Derby et al. [23] adopted three kinds of multiport channels with the equivalent diameter of 1 mm, namely square, triangular and semi-circular, to study the condensation heat transfer performance of R134a. Their experimental results indicated that the heat transfer coefficient was mainly determined by the vapor quality and mass flux but hardly affected by heat flux, saturation pressure and channel configuration. Sakamatapan and Kaew-on et al. [24] also investigated the flow condensation of R134a in two multiport mini channels with the equivalent diame-