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Pressure drop characteristics of R134a during flow boiling in a single rectangular micro-channel☆

Chanyoot Keepaiboon [a], Phubate Thiangtham [a], Omid Mahian [b], Ahmet Selim Dalkılıç [c], Somchai Wongwises [a,*]

[a] Fluid Mechanics, Thermal Engineering and Multiphase Flow Research Lab. (FUTURE), Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangmod, Bangkok, Thailand

[b] Young Researchers and Elite Club, Mashhad Branch, Islamic Azad University, Mashhad, Iran

[c] Heat and Thermodynamics Division, Department of Mechanical Engineering, Mechanical Engineering Faculty, Yildiz Technical University, Yildiz, Besiktas, Istanbul 34349, Turkey

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ABSTRACT

The pressure-drop characteristics during flow boiling in a single rectangular micro-channel with hydraulic diameter of 0.68 mm are presented. In the present study, pressure drop was studied at heat flux range of 7.63–49.46 kW/m^2, mass flux range of 600–1400 kg/m^2 s, and saturation temperature of 23, 27 and 31 °C. Experimental results indicated that the total pressure was dominated by frictional pressure drop. The increase of mass flux also increased the frictional pressure gradient, whereas the increase of saturation temperature reduced the frictional pressure gradient. In addition, heat flux also had an insignificant effect on the frictional the pressure gradient. A new correlation was also proposed for effective design of micro-channel heat exchanger.

1. Introduction

Micro-channel heat exchangers and heat sinks had received more interest in the past few years. Their advantages include high heat-transfer coefficient, compact size, and lower required fluid mass. However, despite the many advantages of applying micro-channel heat exchangers in micro-scale devices, they still have flaw in the increase of pressure drop, when compared to conventional-sized flow channel. Therefore, understanding characteristics of pressure drop occurring in micro channel is essential for the design of compact heat exchangers. Revision of past researches about flow-boiling pressure drop of refrigerant in mini–microchannel is discussed in the following section.

Hwang and Kim [1] studied the characteristics of pressure-drop of R-134a in circular stainless steel ducts with inner diameters of 0.244, 0.430, and 0.792 mm. They concluded that the pressure drop became higher with the increase of the Reynolds number, which was similar to the occurrence of conventional-sized tubes in single-phase flow. Moreover, the two-phase pressure drop increased with increasing quality and mass flux, and increased with decreasing inner diameter.

Choi et al. [2] studied convective boiling-pressure drop of refrigerant (R-410A) in horizontal mini-channels with inner diameters of 1.5 and 3.0 mm. Their results showed that the increase of quality lead to the increase of pressure drop which, in turn, reduced the density while evaporation and average velocity of refrigerant increased. The higher mass flux caused the pressure drop to be high due to the friction between fluid and pipe wall.

Pamitran et al. [3] studied pressure drop during flow boiling for CO_2 in stainless steel tubes with inner diameters of 1.5 and 3.0 mm and with lengths of 2000 and 3000 mm. They concluded that the pressure drop increased with smaller inner-tube diameter, lower saturation temperature, and higher mass and heat fluxes. Furthermore, pressure drop was also a function of mass flux, inner-tube diameter, surface tension, density, and viscosity. A new correlation based on the Lockhart–Martinelli method was developed as a function of the Weber number, We_{tp}, and the Reynolds number, Re_{tp}.

Agostini et al. [4] studied two-phase pressure drop for R236fa during flow boiling in a silicon multi micro-channel heat sink. The results showed that the increase of vapor quality and mass velocity lead to the increase of total pressure drop. On the contrary, the increase of saturation temperature reduced the total pressure drop.

Lie et al. [5] studied frictional pressure-drop characteristics of R-134a and R-407C during evaporation in horizontal small tubes with the same inside diameter of 0.83 mm or 2.0 mm. Their results indicated that R-134a had higher frictional pressure drop than R-407C. Moreover, the heat flux had minimal effect on frictional pressure drop, but the increase of refrigerant mass flux increased frictional pressure drop.

Choi et al. [6] studied two-phase pressure drop during flow boiling of propane in stainless steel tubes with inner diameters of 1.5 mm and 3.0 mm. Results of their work showed that the increase in heat flux made the pressure drop higher due to the increase of vaporization. Additionally, pressure gradient in the 1.5 mm tube was higher than in the 3.0 mm tube. Also, the decrease in saturation temperature increased the

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* Corresponding author.
E-mail address: somchai.won@kmutt.ac.th (S. Wongwises).

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Nomenclature

A	cross sectional area (m^2)
c_p	specific heat at constant pressure (kJ kg^{-1} K^{-1})
D_h	hydraulic diameter (mm)
G	mass flux (kg m^{-2} s^{-1})
H	depth (m)
i	enthalpy (kJ kg^{-1})
I	current (A)
k	thermal conductivity (W m^{-1} K^{-1})
L	length (m)
$\dot{m}$	total mass flow rate (kg s^{-1})
N	number of channels
ΔP	pressure drop (kPa)
Q	heat transfer rate (kW)
q''	heat flux (kW m^{-2})
Re	Reynolds number, $\mathrm{Re} = \frac{Gd}{\mu}$
T	temperature (°C)
V	voltage (V)
W	width (m)
x	vapor quality

Greek letters

μ	dynamic viscosity (Pa-s)
α	void fraction
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})

Subscripts

ch	channel
con	contraction
exp	expansion
f	friction
in	inlet
l	liquid
v	vapor
out	outlet
ref	refrigerant
sat	saturation
tot	total
tp	two phase
TS	test section
w	wall

pressure drop due to the effect of physical properties of density and viscosity on pressure drop at different temperatures.

Revellin and Haberschill [7] had compared frictional pressure drop gained from their experiment with four well-known correlations (Gronnerud [8], Friedel [9], Muller-Steinhagen and Heck [10], and Jung and Radermacher [11]) and the model proposed by Quibem and Thome [12]. They found that the Gronnerud [8] correlation and the model of Quiben and Thome [12] yielded the best prediction.

Soupremanien et al. [13] studied the influence of aspect ratio during flow boiling in two single rectangular mini-channels of the same hydraulic diameter of 1.4 mm. Results indicated that C2 (W = 2.3 mm, H = 1 mm, AR2 = 0.43) had higher pressure drop than C1 (W = 5.6 mm, H = 0.8 mm, AR1 = 0.143). Concerning cross-sectional shape, the width had a stronger influence on pressure drop than the height. In fact, these results could be explained by the confinement of bubbles, which was stronger in the width direction for C2 (W = 2.3 mm, H = 1 mm, AR2 = 0.43) than for C1 (W = 5.6 mm, H = 0.8 mm, AR1 = 0.143).

Saisorn et al. [14] studied the flow patterns and heat transfer of R134a during flow boiling in a 1.75 mm diameter tube. The experimental data were compared with a three-zone flow boiling model. The prediction gave fair agreement with the experimental results.

Maqbool et al. [15] studied two phase pressure drops of test conditions in two sizes of vertical mini channels for ammonia at a wide range. The test sections were made of stainless steel (AISI 316) tubes with an internal diameter of 1.70 and 1.224 mm. Results concluded that the increase of vapor quality and the decrease of saturation temperatures gave higher frictional pressure drop. Furthermore, the decrease of tube diameter also increased the pressure drop.

Park et al. [16] studied two-phase pressure drop and heat-transfer coefficients of C_6F_{14} in two multi-ported rectangular micro-channels with hydraulic diameters of 61 and 278 μm. Their results showed that the increase of vapor quality and mass flux gave higher pressure drop. The heat flux did not have any effect on the pressure drop. For the flow in horizontal microchannels, the two-phase pressure drop mainly arose from friction.

Kim and Jeong [17] studied pressure-drop characteristics of CO_2 in a mini-channel tube with and without micro-rectangular grooves. They concluded that pressure drop of the grooved channel was higher than that of smooth channel in the two-phase experiments. Except at very high quality (0.9–1.0), the pressure drop increases with increasing quality. The pressure drop decreases as the saturation temperature increases.

Maqbool et al. [18] studied heat transfer and pressure drop during flow boiling for propane in a vertical circular mini-channel having an internal diameter of 1.70 mm. They concluded that the increase of mass flux and vapor quality indicated the increase of two-phase frictional pressure drops. Furthermore, the decrease of saturation temperature increased the two-phase frictional pressure drop. The two-phase frictional pressure drop is higher for higher exit vapor quality. This is because higher vapor fraction causes the specific volume and average velocity to be high.

Yang et al. [19] studied flow-boiling phenomena in a single annular flow regime in SiNW micro-channels and in smooth wall micro-channels. Their results showed that the entrainment droplets were reduced by flattening the profile of the liquid–vapor interfaces using the high capillary pressure generated by SiNWs. These two factors – flow separation and reduced entrainment droplets – led to a dramatic reduction of frictional pressure drop.

Revision of this past research obviously shows that most researchers studied pressure drop characteristics in mini-/micro-circular tube. It also shows that the pressure-drop characteristics during flow-boiling in a single rectangular micro-channel using refrigerant as working fluid has received comparatively little attention in literature. As a result, in this study, the researchers present a study about pressure-drop characteristics of R134a refrigerant during flow boiling in a single rectangular micro-channel with hydraulic diameter of 0.68 mm. This paper is a continuation of the authors' previous work [20] on the characteristics of R134a refrigerant during flow boiling in a single rectangular micro-channel. In addition, the experimental test-section was also specifically designed with epoxy-coated casting method in order to prevent leakage of the refrigerant. The proposed test-section is considered as an innovation in the field of micro-channel heat sink research. This study also presents a correlation which can be applied in designing micro-scale multi-channel heat exchangers in the future.

2. Experimental apparatus

In this section, important components of the experimental test loop and the test section are discussed as follows.

2.1. Description of the experimental test loop

A schematic diagram of the experimental apparatus is presented in Fig. 1. The refrigerant was pumped by a magnetic micro gear pump, which is controlled by an inverter, into the test-section through a series of filter and dryer, Coriolis-type mass flow meter, pre-heater, sight glass,