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R134a condensation flow regime and pressure drop in horizontal microchannels cooled symmetrically and asymmetrically

Ji Wang, Jin Wang, Jun Ming Li *

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

An experimental investigation was conducted for two-phase flow regimes and friction pressure drop during condensation of refrigerant R134a in oval parallel microchannels with a hydraulic diameter of 301.6 μm, an aspect ratio of 2.46 and a length of 50 mm. The effects of microchannel cooling methods, including asymmetric cooling and symmetric cooling, were studied. The flow regimes and pressure drops were recorded for qualities of 0.1–0.9 and mass flux of 60–250 kg/(m^2 s). The inlet saturation temperature of R134a is 31.3 °C. Film wavy flow, corner wavy flow, slug flow and bubbly flow were observed. The flow regimes were mapped and compared with 8 flow regime maps in the literature. Two flow regime criteria were given using vapor Weber number. The wavy-intermittent flow transition locations were measured and compared with the correlations in the literature. The transition location moves downstream with increasing refrigerant mass flux and inlet quality. The transition locations were more upstream for the condensation flow cooled symmetrically then that cooled asymmetrically. The friction pressure drop increases with increasing mass flux and quality. The pressure drop for microchannels with symmetric cooling is lower than asymmetric cooling. The pressure drop data was compared with the correlations in the literature.

1. Introduction

Microchannel condensers are increasingly used in HVAC and refrigeration equipment to increase system efficiency and reduce refrigerant inventory. The investigation of condensation heat transfer and pressure drop in microchannels is the foundation for microchannel condenser design. As condensation processes in a tube, the magnitudes of gravity, shear stress and surface tension changes, resulting in different two-phase flow regimes. The condensation heat transfer and pressure drop mechanisms vary among different flow regimes. Therefore, it is necessary for condensation heat transfer and pressure drop modelling to better understand the occurrence of, and transition between, different flow regimes.

Refrigerant condensation flow in channels with $D_h > 1.0$ mm was systematically studied due to the direct application of conventional condenser design. Researchers, such as Traviss and Rohsenow [1], Breber et al. [2], Soliman [3,4], Tandon et al. [5], Wang [6], Dobson and Chato [7], Coleman and Garimella [8,9], and Cavallini et al. [10] studied refrigerants condensing in tubes with $1.0 < D_h < 10$ mm and proposed condensation flow regime maps based on their data. The refrigerants used by those researchers include R12, R113, R22, R134a, R407C, R32, R125, n-pentane and steam. Nema et al. [11] proposed new flow regime transition criteria with dimensionless numbers using Coleman and Garimella's [8,9] data.

The condensation flow regimes in channels with $D_h < 1$ mm were studied recently because the development of micro electro mechanical system (MEMS) technology made it easier to fabricate microchannels on silicon wafer bond with Pyrex glass. However, most researchers used steam due to its low saturation pressure which facilitates the test section manufacture. One of the earlier investigations was conducted by An et al. [12], who studied steam condensation flow in a 468-μm circular tube and observed plug flow, annular flow and bubbly flow. Chen and Cheng [13] studied steam condensation flow in silicon microchannels with $D_h = 75$ μm. Wu and Cheng [14] and Wu et al. [15] investigated steam condensation flow regimes in trapezoidal silicon microchannels. They defined the periodic transition from annular to intermittent flow as "injection flow" and measured its occurrence locations and frequencies. Quan et al. [16] also studied injection flow characteristics for steam condensation flow in trapezoidal silicon microchannels with $90 < D_h < 128$ μm. They proposed a transition criterion for dividing smooth and wavy annular flow using condensation

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* Corresponding author.
E-mail address: lijm@tsinghua.edu.cn (J.M. Li).

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Nomenclature

Bo	Bond number
c_p	heat capacity (J/(kg K))
D_h	microchannel hydraulic diameter (m)
Fr	Froude number
Fr_{mod}	modified Froude number
Fr_{so}	Froude number for Dobson and Chato's (1998) flow regime map
g	gravitational acceleration (m/s^2)
G	refrigerant mass flux (kg/(m^2 s))
Gr	Grashof number
h	heat transfer coefficient (W/(m^2 K))
i_l	specific enthalpy of the saturated liquid (J/kg)
i_{in}	specific enthalpy at the evaporator inlet (J/kg)
i_{lv}	latent heat (J/kg)
I	current (A)
j_g^*	dimensionless vapor velocity
L	microchannel length (m)
m	mass flow rate (kg/s)
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Q_{loss}	test section heat loss to the ambient environment (W)
Re	cooling water Reynolds number
T	temperatures (K)
u	velocity (m/s)
U	voltage (V)
We	Weber number
x	test section average quality
x_{in}	R134a vapor quality at the test section inlet
x_{out}	R134a vapor quality at the test section outlet
X_{tt}	Martinelli parameter
z	axial position (m)

Greek symbols

α	void fraction
γ	contraction area ratio
δ	the water jacket thickness (mm)
ρ	density (kg/m^3)
σ	surface tension (N/m)
λ	the water jacket thermal conductivity (W/(m K))
ψ_s	separated flow multiplier

Subscripts

ave	average
de	deceleration
exp	experimental
f	frictional
i	inside
in	inlet
l	liquid
o	outside
out	outlet
pre	predicted
r	refrigerant
t	total
v	vapor
w	water

number and mass flux. Ma et al. [17] proposed a dimensionless criterion for annular-intermittent transition based on their data of steam condensing in trapezoidal silicon microchannels with $D_h = 138.72$, 165.87 and 134.52 μm. Zhang et al. [18,19] conducted visualization experiments of steam condensing in wide rectangular silicon microchannels ($D_h = 578.3$ μm) with a high aspect ratio of 26.7. They characterized the periodic bubble emission phenomena and the multi-channel effect on the bubble motions due to Marangoni effect. Wu et al. [20] also studied steam condensation flow in wide rectangular silicon microchannels ($D_h = 90.6$ μm) with a aspect ratio of 9.668, and observed droplet-annular compound flow, injection flow and slug-babbly flow. They claimed that channel shape has a significant influence on flow pattern transition. Fang et al. [21] measured the liquid film thickness variation during steam condensation flow in a rectangular silicon microchannel ($100 < D_h < 300$ μm) using optical interferometry method, and compared their data with theoretical prediction proposed by Zhao and Liao [22], Wang and Rose [23] and Wu et al. [24]. Only qualitative agreement was obtained due to the different thermal boundaries. Fang et al. [25] studied the effect of wall hydrophobicity on steam condensation flow regimes in rectangular silicon microchannels ($D_h = 286$ μm) and observed dropwise flow in the hydrophobic channel. Chen et al. [26] also studied steam condensation flow in hydrophobic rectangular silicon microhannels ($D_h = 150$ μm) and found droplet existed in most flow patterns. Refrigerant condensation flow regime in microchannels with hydraulic diameters smaller than 1 mm was studied by few researchers. Médéric et al. [27] studied the condensation flow patterns of n-pentane in single glass tubes with $D_h = 10$, 1.1 and 0.56 mm, and found that the surface tension effect started to dominate the gravitational effect as the D_h decreased below 1 mm.

Pressure drops of condensation flow in channels with $D_h <$ 1 mm were measured by several researchers. Garimella et al. [28] measured R134a condensation pressure drop in circular and noncircular microchannels and developed a multi-regime pressure drop model for R134a condensing in microchannels with $0.4 < D_h < 4.9$ mm and $150 < G < 750$ kg/(m^2 s). Quan et al. [29] and Wu et al. [30] studied steam condensation pressure drop in trapezoidal silicon microchannels with $D_h = 109$, 142, 151 and 259 μm and $D_h = 77.5$, 93.0 and 128.5 μm, respectively. They all demonstrated that the hydraulic diameter has significant effects on condensation pressured drop in microchannels. Kim et al. [31] measured pressure drop of FC-72 in parallel square channels with $D_h = 1$ mm and presented a detailed pressure drop model. Liu et al. [32–34] measured R32, R152a, R22, R290 and R1234ze(E) condensation pressure drop in circular and square channels with $D_h \approx 1$ mm. They found the channel shape starts to affect pressure drop when refrigerant mass flux are higher than 400 kg/(m^2 s).

Most condensation flow regime research in channels with $D_h < 1$ mm was for steam condensation flow, whose results are not directly applicable to predict refrigerant condensation flow regimes. On the other hand, the silicon microchannels were cooled only from silicon side. This asymmetric cooling is not consistent with practical application, such as integrated microchannel heat exchanger. In our previous research [35], R134a and R1234ze(E) flow pattern transition during condensation in microchannel arrays ($D_h = 301.6$ μm) was studied for low mass flux ($6 < G < 50$ kg/(m^2 s)). Moreover, the refrigerant condensation flow regimes in microchannel arrays with various vapor qualities and higher mass fluxes should be further studied for the application of integrated microchannel heat exchanger design.

The present study addresses these deficiencies in the literature by investigating flow regimes and pressure drop during condensation of R134a in mircochannels made of borosilicate glass. High speed imaging was used for flow regime visualization. Flow regimes and flow pattern transition locations for condensation