International Journal of Thermal Sciences 134 (2018) 140–159

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Condensation flow patterns and model assessment for R1234ze(E) in horizontal mini/macro-channels

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ARTICLE INFO

Keywords:
Condensation
R1234ze(E)
Mini/macro-channels
Heat transfer coefficient
Pressure gradient

ABSTRACT

Knowledge regarding the condensation flow patterns of environment friendly refrigerant R1234ze(E) in mini/macro-channels was important for alternative industrial applications. In this paper, the condensation heat transfer and pressure drop characteristic of R1234ze(E) in horizontal circular channels with diameter ranged from 0.493 to 4.57 mm were numerically investigated and compared with that of R134a. The detailed liquid film distribution, local film thickness and velocity field were presented for better understanding the condensation process. Both the heat transfer coefficients and pressure gradients increased with the mass flux, vapor quality and the decrease of the tube diameter. The heat transfer coefficients of R1234ze(E) were smaller than that of R134a, but the pressure gradients of R1234ze(E) were larger than that of R134a. The difference in heat transfer and pressure drop performance was found to be smaller in macro-channels. The effects of surface tension and gravity on liquid film distribution are significantly influenced by the tube diameter. The liquid film distribution was very close for R1234ze(E) and R134a for their similar physical properties. The average film thickness of R1234ze(E) was thinner than that of R134a. The axial velocity of the vapor phase decreased with the vapor quality, while the variation of the liquid phase velocity was associated with the circumferential position for the gravity effect. The simulated heat transfer coefficients and pressure gradients were compared with predicted values from the available well-known correlations. A new pressure drop correlation was proposed for practical application.

1. Introduction

The utilization of energy and the global climate change are the important issues concerned increasingly by the international community. The mini-channel heat exchangers which showed great performance in terms of heat transfer efficiency, compactness, less refrigerant charge and strong pressure endurement [1], have been widely applied in many applications, such as refrigeration industries, microelectronic system and space systems. Many researchers [2,3] agree that the combination of mini-channel and low GWP refrigerants was an effective way to improve both the energy efficiency and the environment impact.

The mini-channel technology has a wide range of applications, and their most important use is in compact condensers for air conditioning systems [4,5]. The following studies proved that the usage of mini-channel heat exchangers was exactly beneficial to improving the system efficiency and environmental performance. Park and Hrnjak [5] compared the performance of R410A residential air-conditioning systems by separately adopting a round-tube condenser and a micro-channel condenser when the other components were identical. They found that in all conditions there was an improvement in the COP and cooling capacity of the system when using the micro-channel condenser. Gómez et al. [2] experimentally and numerically investigated the performance of an air/water chiller when replacing a conventional fin-and-tube condenser with a mini-channel condenser. Their results showed that using a mini-channel condenser could either reduce the refrigerant mass or increase the efficiency and cooling capacity. Wang and Peterson [6] compared the performance of a thermally activated cooling system using conventional plate heat exchangers and micro-channel heat exchangers as the boiler and recuperator. A significant improvement in heat transfer effectiveness was observed when using microchannel heat exchangers. García-Cascales et al. [7] separately tested the performance of an air/water heat pump when using a mini-

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https://doi.org/10.1016/j.ijthermalsci.2018.08.006
Received 4 May 2018; Received in revised form 17 July 2018; Accepted 3 August 2018
1290-0729/

channel heat exchanger and a fin-and-tube heat exchanger as the evaporator. It was found that there was a 0.64%–11.69% reduction in refrigerant charge when using a mini-channel coil.

There is plenty of research work about dealing with the condensation flow inside mini-channels and many well-known heat transfer and pressure drop correlations have been proposed. A comprehensive review of the literature concerning condensation flows inside mini-channels can be found in Awad et al. [8,9] and Cavallini et al. [10]. It should be noted that many earlier investigations concerning condensation flow in tubes mainly focused on hydrofluorocarbon refrigerants (HFCs) such as R134a and R410A. As the substitute of chloroflurocarbon (CFCs), HFCs do not contain the chlorine element and then the ozone depleting potential (ODP) is zero. However, the global warming potential (GWP) of HFCs was high, which was still a threat to the climate on the earth. In 1997, the Kyoto Protocol limited greenhouse gas emissions in the form of regulation. Recently, according to the new Regulation (No 517/2014) drafted by the European Union (EU), the emissions of greenhouse F-gases by year 2030 should be reduced to a third of the current amount in the EU. It was believed that HFCs would be eventually be phased out even though they are the most widely used refrigerant today. As the substitute of HFCs, halogenated olefins (HFOs) such as R1234ze(E) and R1234yf were considered to be a good option in refrigeration systems for their very low GWP values, short atmospheric lifetimes, low flammability and non-toxic.

Recently, Mota-Babiloni et al. [11] published a review concerning the most relevant research on R1234ze(E). A number of researches focused on investigating the thermophysical properties, compatibility and flammability and system performance of vapor compression systems, while few studies focused on investigating the in-tube two-phase heat transfer coefficient and pressure drop of R1234ze(E), which plays an important role in design and optimization of vapor compression systems. Diani et al. [12] experimentally measured the condensation heat transfer coefficients and pressure drops of R134a, R1234yf and R1234ze(E) inside a microfin tube with the hydraulic diameter of 2.4 mm. The heat transfer coefficients of R1234ze(E) was similar with that of R134a, but the frictional pressure drops were 30% higher than that of R134a. The heat transfer coefficients of R1234yf was slightly lower than that of R134a, while the frictional pressure drops were similar to that of R134a. Liu et al. [13] measured the condensation heat transfer coefficients and pressure drop of propane, R1234ze(E) and R22 in both circular and square horizontal mini-channels. Both the heat transfer coefficients and the pressure gradients of the propane were larger than that of R1234ze(E) which were larger than that of R22. Jige et al. [14] measured the condensation heat transfer coefficients and pressure drop of R32, R134a, R410A and R1234ze(E) in a horizontal rectangular multiport tube. It was found that the pressure gradient of R1234ze(E) was higher than that of R32, R134a and R410A. Two new correlations for predicting the frictional pressure gradients and heat transfer coefficients in rectangular channels were developed. Del Col et al. [15] compared the condensation characteristic of R1234ze(E), R32, R134a and R1234yf in a single horizontal mini-channel. The heat transfer coefficients of R1234ze(E) were lower than that of R32 and R134a, but higher than that of R1234yf. However, the pressure gradient of R1234ze(E) was higher than that of R134a, R1234yf and R32 at the same condition. Based on the criteria developed by Cavallini et al. [16], under the same thermal power, the condensing heat transfer area requested for R1234ze(E) and R1234yf were respectively 25% and 15% higher than that needed for R134a. Agarwal and Hrnjak [17] experimentally investigated the condensation process of refrigerants R134a, R1234ze(E) and R32 in a horizontal circular tube. The results showed R32 got higher heat transfer coefficients and lower pressure gradients than that of R1234ze(E) and R134a. Anowar Hossain et al. [18] measured heat transfer and pressure drop data of R1234ze(E), R32 and R410A in a horizontal circular tube. They found that the heat transfer coefficients of R1234ze(E) was 20–45% lower than that of R32, but 10–30% higher than that of R410A. Sempértegui-Tapia and Ribatski [19] experimentally measured two-phase frictional pressure drop of R134a, R1234ze(E), R1234yf and R600a in horizontal circular, square and triangular mini-channels. At the same condition, the pressure gradients of R600a was the largest and then the R1234ze(E), R134a and R1234yf. Highest pressure gradients can be observed for the triangular channel and then the square and circular channels.

Except the experimental research, the condensation flow inside mini/macro-channels can be predicted successfully by numerical simulation applying liquid-vapor interface track methods and heat mass transfer models. The team of Da Riva and Del Col [20–22] numerically investigated the condensation heat transfer process of R134a in horizontal/vertical circular/non-circular tubes using the volume of fluid (VOF) method at steady state. They pointed out that at the lower flow rates, the condensation flow was considered to be gravity-dominated while the shear stress became the prevailing force when increasing the mass velocity. The surface tension force may improve heat transfer performance and the gravity had a smaller effect in the square mini-channel. The turbulence of liquid film played a great role in generating high thermal performance at high flow rates. Besides, Wei Li's group [23–25] numerically studied heat transfer and pressure drop characteristics of R410A condensation in horizontal circular mini/micro-tubes. They found that the condensation heat transfer coefficients and pressure gradients increased with the mass flux and vapor quality but decreased with the increase of tube diameter and saturation temperature. The gravity would increase the local heat transfer coefficients for decreasing the film thickness at the top of the tube, which was more noticeable at a larger diameter tube, lower vapor quality and mass flux. With respect to R1234ze(E), Wen et al. [26] numerically investigated the condensation heat transfer and pressure drop characteristic of R1234ze(E), R134a and Propane in a horizontal mini-channel. The available correlations tended to underestimate their simulated pressure gradients of R1234ze(E). They [27] also explored the relative role of surface tension, gravity and shear stress in mini/macro-channels during condensation of R1234ze(E).

As a conclusion, the previous studies provided some valuable information concerning in-tube condensation of R1234ze(E). However, researches on this issue were still limited and the available studies were almost all conducted through the method of experimentation, which failed to capture more detailed information about the two-phase behavior in tubes. In this paper, the condensation heat transfer and pressure drop characteristic of R1234ze(E) inside mini/macro-channels was numerically investigated. The effects of mass flux, vapor quality and tube diameter on local heat transfer coefficients and pressure gradients were discussed. Furthermore, a detailed analysis of the liquid film distribution, film thickness and condensation flow field was presented.

2. Numerical model

A schematic diagram of the geometric model adopted in this paper was shown in Fig. 1. The steady-state condensation process of R1234ze (E) and R134a inside single horizontal circular tubes were simulated. The diameter ranged from 0.493 to 4.57 mm and the mass flux covered from 400 to 800 kg m^{-2}s^{-1}. Both the vapor phase and liquid phase of each refrigerant were considered to be incompressible. The inlet velocity profile of the saturated vapor (T_{sat} = 313 K) including the turbulent kinetic energy and its dissipation rate was obtained by the well-developed single phase flow. A pressure boundary condition was applied at the outlet. The wall was considered to be a smooth non-thickness surface and a no slip wall boundary condition was given. Since in practical application the condensing refrigerant was usually cooled by a secondary fluid, the wall temperature was assumed to be a constant, which was 10 K lower than the saturation temperature. The effect of pressure drop along the tube length on saturation temperature was also neglected. The fluid properties of each refrigerant which were considered to be a function of temperature were derived from the REFPROP 9.0