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Condensation heat transfer and pressure drop characteristics of CO_2 in a microchannel

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ABSTRACT

The condensation heat transfer coefficient and pressure drop of CO_2 in a multiport microchannel with a hydraulic diameter of 1.5 mm was investigated with variation of the mass flux from 400 to 1000 $kgm^{-2}s^{-1}$ and of the condensation temperature from −5 to 5 °C. The heat transfer coefficient and pressure drop increased with the decrease of condensation temperature and the increase of mass flux. However, the rate of increase of the heat transfer coefficient was retarded by these changes. The gradient of the pressure drop with respect to vapor quality is significant with the increase of mass flux. The existing models for heat transfer coefficient overpredicted the experimental data, and the deviation increased at high vapor quality and at high heat transfer coefficient. The smallest mean deviation of ±51.8% was found by the Thome et al. model. For the pressure drop, the Mishima and Hibiki model showed mean deviation of 29.1%.

Transfert de chaleur lors de la condensation et caractéristiques de chute de pression du CO_2 à l'intérieur d'un microcanal

Mots clés : condensation ; transfert de chaleur ; dioxyde de carbone ; coefficient de transfert de chaleur ; chute de pression ; complexité de l'écoulement ; microcanal

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Nomenclature

A	area, m^2
C_C	vena-contraction coefficient
C_p	specific heat, $kJkg^{-1}K^{-1}$
c	convective film constant
D_h	hydraulic diameters, mm
f_i	interfacial roughness factor
G	mass flux, $kgm^{-2}s^{-1}$
h	heat transfer coefficient, $Wm^{-2}K^{-1}$
ID	inner diameter, mm
j	superficial velocity, ms^{-1}
Nu	Nusselt number, hDk^{-1}
Pr	Prandtl number, $C_p\mu\ k^{-1}$
Re	Reynolds number, $GD\mu^{-1}$
Re_{Lo}	Reynolds number with only liquid
r	internal radius of tube, m
U	Overall heat transfer coefficient, $Wm^{-2}\ K^{-1}$
k	thermal conductivity, $Wm^{-1}K^{-1}$
T	temperature, °C
x	vapor quality

Greek symbols

α	void fraction
Δ	difference
μ	viscosity, m^2s^{-1}
θ	upper angle of the tube not wetted by stratified liquid, rad
ρ	density, kgm^{-3}
σ	surface tension, Nm^{-1}

Subscripts

acc	accelerational
aux	auxiliary
c	contractional, convective
cond	condensation
e	expansional
fric	fricational
i	internal
l	liquid
lm	log mean temperature difference
o	external
tot	total
tp	two-phase
v	vapor

1. Introduction

CO_2 has been utilized as a representative natural refrigerant in various refrigeration systems, from domestic to commercial applications. When CO_2 is applied to a water heater, heat pump, or vending machine working under ambient temperature conditions, the refrigeration cycle undergoes a transcritical process due to its relatively low critical temperature. Recently, CO_2 refrigeration systems have been extended in application to food storage facilities and industrial food processing, in which the evaporation temperatures are less than −25 °C. Bansal (2012) showed that CO_2 has favorable thermophysical properties as a refrigerant at low temperature, such as relatively high liquid and vapor thermal conductivities, and low liquid viscosity and surface tension. In low-temperature applications, CO_2 refrigeration systems with a condensation process in the cycle, such as cascade systems, have been widely applied. In the case of CO_2/NH_3 cascade system, the maximum COP was found at condensation temperature of CO_2 from −10 to 10 °C, which are dependent on the evaporation temperature of CO_2. In the present study, the condensation temperature was determined from −5 to 5 °C. The cascade system has shown benefits regarding coefficient of performance (COP) compared to when the transcritical cycle of a multi-stage compression system is used (Sawalha, 2008). Because most studies on CO_2 systems have focused on the design of the gas cooler, the research on CO_2 condensation has been relatively limited, and proper design for CO_2 condensers is needed. Considering the relatively low pressure drop of CO_2 in a tube compared to that of conventional refrigerants, the application of microchannels to the CO_2 condensers is promising as a compact heat exchanger. It should be noted that microchannel condenser showed high heat transfer coefficient too.

Many studies on the convective condensation in mini and microchannels have been conducted, and the latest studies with channels less than 3 mm are summarized in Table 1. Wang and Rose (2006) theoretically analyzed the effect of channel shape on condensation in horizontal microchannels. The existence of a thin condensate film region around channel determines the effect of channel shapes on the condensation heat transfer. The heat transfer coefficient was the highest at square channels, followed in order by rectangle, triangle, and circle channels in the high vapor quality region. Shin and Kim (2005) studied the condensation heat transfer inside circular and rectangular mini-channels. In low mass flux conditions, rectangular channels showed slightly higher heat transfer coefficients than circular channels due to the effect of the gutter flow of the liquid at the corners induced by surface tension in the rectangular channels. As the mass flux increased, the heat transfer coefficients of the circular channels were higher than those of the rectangular channels. Zhang et al. (2012) and Del Col et al. (2010) investigated condensation heat transfer with alternative refrigerants in single circular tubes with inner diameters between 0.96 and 1.289 mm. Zhang et al. (2012) utilized R22, R410A, and R407C as working fluids. They determined that the interface shear stress was the most dominant factor at high vapor quality, and conduction in the liquid layer was dominant at low vapor quality in condensation heat transfer. Existing correlations showed substantial discrepancies with experimental data. Del Col et al. (2010) compared the heat transfer coefficient of R1234yf with that of R134a. They showed that the heat transfer coefficient of R1234yf was lower than that of R134a by 15–30% in the vapor quality region ranging from 0.4 to 0.8. This was explained by the high thermal resistance of R1234yf by relatively low thermal conductivity. The prediction of the heat transfer coefficient by the model of Cavallini et al.