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Condensation heat transfer characteristics of carbon dioxide in a horizontal smooth tube

Chang-Hyo Son *, Hoo-Kyu Oh

Department of Refrigeration and Air-Conditioning Engineering, College of Engineering, Pukyong National University, San 100, Yongdang-dong, Nam-gu, Pusan 608-739, South Korea

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ABSTRACT

The condensation heat transfer characteristics for R744 flowing in a horizontal smooth tube were investigated experimentally. The test section consisted of 2400 mm length with horizontal copper tube of 4.95 mm inner diameter. The experiments were conducted at refrigerant mass fluxes of 400–800 kg/m^2 s, and saturation temperatures of 20–30 °C. The experimental results showed that the mass flux and saturation temperature have a strong effect on the condensation heat transfer coefficients of R744. The experimental data were compared against existing heat transfer correlations. Most of correlations failed to predict the experimental data. However, the correlation predicted by Kondou and Hrnjak showed relatively good agreement with experimental data within 20.7%. But this correlation was proposed for limited experimental conditions. Therefore, it is necessary to develop accurate and reliable correlation to predict the heat transfer coefficients of condensing R744 in the horizontal tube.

1. Introduction

From autumn to spring, outdoor units of commercial refrigeration systems using R744 spend most operating hours in a subcritical cycle. Although the operating condition of the summer season takes a transcritical cycle, it is necessary to understand the characteristics of the subcritical cycle to ensure reliable system performance and to evaluate the annual performance [1].

For conventional refrigerants, flow condensation inside smooth tubes was investigated by several researchers [2–5]. But, the characteristics of R744 flow condensation heat transfer in horizontal smooth tubes are not well known. However, in recent years, some researchers [6–8] have conducted for R744 condensation heat transfer inside tubes and channels.

As shown in Table 1, Park and Hrnjak [6] presented R744 flow condensation heat transfer coefficients and pressure drop in 0.89 mm microchannels. Their results were summarized as followings. Experimental flow patterns were predicted by two flow pattern maps of Akbar et al. [9] and the Breber et al. [10], and it could be predicted that annular flow patterns could exist in most of flow conditions except low mass flux and low vapor quality conditions. Akers et al. [11] could predict heat transfer coefficients within acceptable error range, and from this comparison, it could be inferred that the flow condensation mechanism in 0.89 mm channels should be similar to that in large tubes.

Hayes et al. [7] investigated experimentally for R744 condensation in three brazed plate heat exchangers with different geometry. An in-depth dimensional analysis was completed on the two-phase data yielding heat transfer correlations. Relationships of the two-phase heat transfer characteristics are presented, the data are compared with related studies, and conclusions are made from the two-phase data.

Jang and Hrnjak [8] carried out some experiments focusing on condensation of R744 at low temperatures of −15 and −25 °C, where the low stage of cascade systems operates. Their findings confirmed the applicability of Cavallini et al. [5] correlation in these conditions because of the similarity in thermophysical properties of R22 at high heat rejection temperatures (35 °C) and R744 at low temperatures (−15 to −30 °C).

Therefore, it is important to understand the characteristics of R744 condensation heat transfer in order to determine the proper size or to design circuits of condensers (gas coolers). Despite the importance of this, as shown literature reviews, very limited information about this heat transfer process has been reported. Most of the previous studies about flow condensation in tubes were performed at low temperatures below 0 °C. Also, R744 condensation heat transfer coefficient data in horizontal tubes have not been reported in any publication known to the authors. More experimental studies are necessary to develop R744 condensation heat transfer database and correlations in horizontal tubes.

Accordingly, the purpose of this study is to present new experimental data and search the suitable existing predictions which describe the present data and also analyze the experimental data to find condensation heat transfer characteristics in a single smooth

* Corresponding author.
E-mail address: sonch@pknu.ac.kr (C.-H. Son).

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Nomenclature

c_p	specific heat at constant pressure (kJ/(kg K))
d	diameter (m)
dp/dz	frictional pressure gradient along tube axis (kPa/m)
G	mass velocity (kg/m^2 s)
g	gravitational acceleration (m/s^2)
i_{fg}	latent heat (kJ/kg)
j	superficial velocity (m/s)
k_w	thermal conductivity (kW/mK)
m	mass flow rate (kg/s)
N	number of data
P	pressure (kPa)
Q	heat capacity (kW)
T	temperature (K or °C)
VCR	volumetric refrigeration capacity (kJ/m^3)
X	martinelli parameter
x	vapor quality
dz	length of test section (m)

Greek symbols

μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (mN/m), deviation
v	specific volume (m^3/kg)

Dimensionless groups

Pr	Prandtl number, $\mu c_p/\kappa$
Re	Reynolds number, $\rho v d_i/\mu$

Subscripts

avg	average
cal	calculated
cr	critical point
cs	source water
exp	experimental
i	inner, inside
in	inlet
l	liquid
out	outlet
pre	preheater
re	refrigerant
sat	saturation
sub	subsection
v	vapor
w	wall

tube. In this study, the condensation heat transfer characteristics of R744 flowing in the horizontal smooth tube were investigated experimentally. The present experimental results are compared with previous correlations proposed for smooth tubes.

2. Experimental apparatus and procedures

2.1. Test facility

The schematic of an experimental facility in this study is shown in Fig. 1. Basically, it consists of two independent loops: one is the R744 refrigerant loop and the other is the cooling water loop for the test section. Detailed descriptions for the two loops of the test facility are provided below. A schematic diagram of the test rig is shown in Fig. 2.

The refrigerant loop shown in Fig. 1 is composed of a magnetic gear pump, a mass flow meter, two preheaters, a condenser (test section for condensation heat transfer experiment), a subcooler and a receiver etc. The subcooled liquid R744 is charged in the receiver where it is further cooled to increase its density. The liquid in the receiver is pumped by a magnetic gear pump, and then flows through a flow meter. The liquid R744 enters the preheater, where it is heated up to the desired vapor quality at the inlet of the test section. Electrically insulated heating wires were wrapped around the surface of copper tubes in the preheater. The preheater was insulated with glass fibers and rubber. The amount of heat loss from the preheater was calibrated through pretests with water; this is correlated to the voltage input. In passing through the test section, the two-phase R744 is completely condensed and subcooled by cooling water.

Afterwards, the refrigerant is subcooled by the subcooler and goes into the liquid receiver. Finally, the subcooled refrigerant is recirculated through the refrigerant loop. The subcooler is a counterflow heat exchanger with refrigerant flowing in the inner tube and the water flowing in the annulus. It was used to condense the refrigerant leaving the test section. The mass flow rate of refrigerant into the test section was adjusted by changing the speed of the gear pump. The refrigerant flow rate was measured by the mass flow meter. The pressure of the cycle was controlled by the charged amount of refrigerant.

The cooling water loop is composed of a centrifugal pump, an in-line electric heater and a heat exchanger. The cooling water is pumped to the circular-tube annulus, where it absorbs the heat of the condensing refrigerant. The mass flow rate of cooling water was controlled by adjusting the metering valve and pump speed. The inlet temperature of the cooling water at the test section was controlled by both the electric heater and the refrigeration unit. The mass flow rate of cooling water was also measured by a turbine type flow meter.

2.2. Test section

Fig. 2 shows details of the test section which is a horizontal smooth tube-in-tube type heat exchanger. The refrigerant flows through the inside of copper tube and the cooling water flows through the annulus in the counterflow direction. The test sections are smooth tube having inside-diameters/outside-diameters of 4.95 mm/6.35 mm. The total length of the condenser is 2400 mm and contains 12 subsections along with 200 mm in length of one subsection. The test sections were well insulated by thermal

Table 1
Summary of previous studies on condensation heat transfer of R744.

Literature	Tube geometry	T_{sat} (°C), P_{sat} (MPa)	x (/), q_{re} (kW/m^2)	G_{re} (kg/m^2 s), Re (/)
Kondou and Hrnjak [1]	Smooth tube, d_i = 6.1 mm	P_{sat} = 5–7.5	0–1, q_{re} = 3–30	100–240
Park and Hrnjak [6]	Microchannel, d_i = 0.89 mm	−15, −25	0–1	200–800
Hayes et al. [7]	Chevron plate exhanger	−17.8–34.4	q_{re} = 2.5–15.7	Re = 1500–30,000
Jang and Hrnjak [8]	Smooth tube d_i = 6.1 mm	−15, −25	0.1–0.9	200–400