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In-tube condensation heat transfer of CO_2 at low temperatures in a horizontal smooth tube

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This paper presents the experimental investigation of CO_2 condensation in a horizontal smooth tube at saturation temperatures between 0 and −15 °C with mass fluxes between 50 and 200 kg m^{-2} s^{-1} and for various vapour qualities. One tube-in-tube counter flow heat exchanger was designed together with an open-loop CO_2 cycle to make up an experimental rig that condenses CO_2 at these conditions. The inner test tube, with internal diameter of 6.52 mm, is cooled using Glycol Water flowing in the outer tube. Experimental trends show that the heat transfer coefficient decreases with increasing saturation temperatures. Decrease in heat transfer coefficients is also observed for lower mass fluxes and lower vapour qualities in two-phase. Based on the experimental data collected, a new empirical correlation was developed to improve CO_2 heat transfer coefficient prediction. The new correlation agreed well with experimental and data from the literature, with an average deviation of −4.4%.

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Transfert de chaleur lors de la condensation du CO2 à l'intérieur d'un tube lisse horizontal

Mots clés : Dioxyde de carbone ; R744 ; Condensation ; Transfert de chaleur ; Tube horizontal ; Tasse température ; Écoulement diphasique

1. Introduction

The use of CO_2 (R744) refrigerant is becoming increasingly popular in cascade refrigeration systems to achieve very low temperatures in the food and refrigeration industry. Low contribution to global warming and ozone depletion along with its unique thermo physical properties makes it a promising environmentally friendly refrigerant. Majority of refrigeration and air conditioning industry around the world currently use synthetic chemical fluorocarbon refrigerants (such as R134, R404A, R410A, etc.), which have a high global warming potential (GWP) and ozone depletion potential (ODP) (Heaney et al., 2009).

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Nomenclature

A	Cross-sectional area (m^2)
Cp	Specific heat ($J\,Kg^{-1}\,K^{-1}$)
d	Tube diameter (m)
d_i	Internal diameter, inner tube (m)
d_o	External diameter, inner tube (m)
G	Mass flux ($kg\,m^{-2}\,s^{-1}$)
H	Enthalpy ($J\,kg^{-1}$)
HTC	Heat transfer coefficient (–)
k	Thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	Length (m)
$\dot{m}$	Mass flowrate ($kg\,s^{-1}$)
Nu	Nusselt number (–)
P	Pressure (kPa)
Pr	Prandlt number (–)
$\dot{Q}$	Heat transfer rate (W)
Re	Reynolds number (–)
S_i	Internal diameter, outer tube (m)
T	Temperature (°C, K)
w	Uncertainty (–)
x	Vapour quality (–)
X_{tt}	Martinelli parameter (–)

Greek symbols

α	Heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
μ	Dynamic viscosity ($N\,s\,m^{-2}$)

Subscripts

ele	Electrical
G	Vapour phase
gw	Glycol water fluid
hyd	Hydraulic
L, l	Liquid phase
tp	Two-phase

A good understanding of the heat transfer mechanisms of the working fluid is required to design compact heat exchangers and refrigeration units in large systems. However, very limited information is available in the open literature for condensation heat transfer of CO_2. This study focuses on establishing a database of HTC and a consequent correlation specifically for CO_2 at low temperatures.

2. Literature review

The working fluid in a condenser is generally single phase at the inlet (vapour) and outlet (liquid) and two-phase along its length with varying vapour quality. Factors that strongly influence in-tube condensation include: tube orientation, mass flux, tube diameter and the type of fluid flowing in the tube (El Hajal et al., 2003). Flow through a vertical is symmetrical, whereas in horizontal tubes the orientation of gravity is such that it causes the flow to become asymmetrical. As presented by Cheng et al. (2008), Thome (2005) and El Hajal et al. (2003), the flow patterns observed during condensation inside a horizontal tube can be universally classified as annular, stratified, slug, plug and bubbly.

One of the first proposed correlations for two-phase flow heat transfer inside horizontal tubes was by Ackers et al. (1959). Since then, two-phase condensation heat transfer inside a tube has been investigated by many researchers, from empirical and semi-empirical methods. Park and Hrnjak (2009) explored HTCs and pressure drops for CO_2 at saturation temperatures −15 °C and −25 °C. Their study involved horizontal microchannels of diameter 0.89 mm, with mass fluxes ranging from 200 to 800 $kg\,m^{-2}\,s^{-1}$. Under the same conditions, Kim et al. (2009) presented data for 3.48 mm inner diameter tube and a 3.51 mm micro-fin tube and found that most correlations tend to over predict HTC for CO_2. Similar trends were observed by Iqbal and Bansal (2010). Kim et al. (2009) and Zhao and Bansal (2010) stated that a possible reason for this discrepancy is the different thermal and transport characteristics of carbon dioxide.

3. Experimental rig design and data reduction

The schematic for the rig is shown in Fig. 1; an open-loop system designed to collect data of the low temperature condensation of CO_2 inside a horizontal tube. The open-loop design offers a fundamental approach in determining heat transfer without the addition of unnecessary components.

CO_2 in a liquid form, stored at 99.9% purity in industrial bottles (A), enters the system at ambient temperature as a saturated liquid, thus has a relatively large pressure of 5.5 MPa. To avoid two-phase discrepancies on flowrate measurements, the first of the two-stage sub-cooler (B) ensures CO_2 is in liquid state through the mass flow meter (C). The fluid is then throttled down to low temperatures through a needle value (D) enabling two-phase flow at low temperatures. The second stage of the sub-cooler (B) further removes heat and ensures CO_2 is in liquid state before it enters the pre-heater (E). Single-phase temperature and pressure measurements at the inlet of the pre-heater will establish its enthalpy, a known amount of electrical heat is inputted into the pre-heater (E) through a transformer, from which a desired exit vapour quality can be obtained. In-tube condensation of CO_2 takes place in the test section (F), where the temperatures of CO_2 and the glycol water are recorded, from which the amount of heat transfer between the two fluids can be calculated. A post-condenser heater (G) is used to heat CO_2 into vapour phase before the pressure regulator (H) expels it into the ambient. A hose pipe is used to vent the vapour CO_2 outside the test laboratory.

3.1. *Test section*

The test section ((F) in Fig. 1) is a 0.5 m long tube-in-tube counter flow heat exchanger designed to allow the exchange of heat between the primary fluid (CO_2) and the secondary fluid (glycol water). CO_2 flows through the central tube while glycol water flows through the annular area created by the two tubes. The glycol water is diverted from an existing rig into the heat

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