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A study of transcritical carbon dioxide flow through diabatic capillary tubes

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ABSTRACT

An experimental and theoretical study of the diabatic flow of carbon dioxide through lateral capillary tube suction line heat exchangers is outlined. The influence of both operating conditions (capillary tube inlet and outlet pressures, capillary tube inlet temperature and suction line inlet temperature) and tube geometry (heat exchanger length and position, suction line diameter and capillary tube length) on the heat and mass flow rates was experimentally evaluated using a purpose-built testing facility. In total, 75 tests were carried out with heat fluxes spanning from 1 to 11 kW m^{-2} and refrigerant mass flow rates ranging from 12 to 26 kg h^{-1}. In addition, the mathematical model of Hermes et al. (2008) was adapted to run with carbon dioxide as working fluid. The model was validated against experimental data, and a good agreement between the experimental and calculated mass flow rates was achieved with 85% and 98% of the data points being within ±5% and ±10% error bounds, respectively.

Etude sur l'écoulement du dioxyde de carbone transcritique à l'intérieur de tubes capillaires diabatiques

Mots clés : dioxyde de carbone ; détente ; tube capillaire ; échangeur de chaleur

1. Introduction

The steadily increasing international environmental concern (IPCC, 2007) has revived the carbon dioxide as a working fluid for applications such as air-source heat pumps and vehicle air-conditioners. In spite of the growing use of capillary tubes in CO_2-based refrigeration systems, very few related publications have been found in the open literature (Chen and Gu, 2005; Madsen et al., 2005; Cao and Yu, 2007; Agrawal and Bhattacharyya, 2008). These studies are limited by the lack of experimental data covering the typical operating conditions of light commercial refrigerating appliances, an important niche for CO_2 application. In addition, the literature review revealed that an experimentally validated model for carbon dioxide flows through capillary tube suction line heat exchangers is still to be developed.

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Nomenclature

Roman

A	heat transfer surface area, m^2
c_p	specific heat, $J\,kg^{-1}\,K^{-1}$
D	inner diameter, m
D_o	suction line outer diameter, m
f	Darcy's friction factor
G	mass flux, $kg\,m^{-2}\,s^{-1}$
h	specific enthalpy, $J\,kg^{-1}$
L	length, m
NTU	number of transfer units
m	mass flow rate, $kg\,s^{-1}$
p	pressure, Pa
q	heat flux, $W\,m^{-2}$
t	temperature, K
U	overall heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
v	specific volume, $m^3\,kg^{-1}$
z	axial coordinate, m

Greek

α	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
ϵ	heat exchanger effectiveness
η	viscosity, Pa s
λ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
τ	shear stress, Pa

Subscripts

c	capillary tube
e	evaporator
hx	heat exchanger
i	inlet
l	saturated liquid
max	maximum
o	outlet
s	suction line
sup	superheating
v	saturated vapor

In a prior work (Da Silva et al., 2009), the influence of both operating conditions (inlet pressure and temperature) and tube geometry (capillary tube diameter and length) on the CO_2 mass flow rate through adiabatic capillary tube flows was experimentally explored. A dataset comprising 66 experimental data points was gathered and used to validate a mathematical model for a broad range of operating conditions and capillary tube geometries. An excellent agreement between the experimental and calculated mass flow rates was achieved, with 95% of all data predicted by the numerical model being within ±10% error bands. The model was also used to advance the knowledge about the transcritical carbon dioxide expansion through adiabatic capillary tubes.

However, in most light commercial refrigeration applications, the capillary tube instead of being adiabatic is brazed tangentially to the suction line forming a lateral counter-flow heat exchanger (see Fig. 1), thereby increasing the evaporator capacity and avoiding the liquid carryover to the compressor. This has motivated most researchers and model developers to put forward mathematical models for CO_2 flows through diabatic capillary tubes.

For instance, Chen and Gu (2005) developed a model for simulating the R-744 flow through diabatic capillary tubes, but their results have not been compared with experimental data. In the same year, Madsen et al. (2005) investigated the high-side pressure control of CO_2 refrigeration systems using capillary tubes. They carried out experimental and theoretical studies when a reasonable level of agreement between measured data and model predictions was achieved. However, the validation exercise was limited by the narrow range of geometries and operating conditions considered. More recently, Agrawal and Bhattacharyya (2008) proposed a numerical model for predicting the transcritical carbon dioxide capillary tube flow for heat pump applications. The results were compared with the numerical results of Chen and Gu (2005) and the experimental results of Madsen et al. (2005), showing a good level of agreement.

Nonetheless, it is worth noting that all the previous works are limited to some extent by the lack of experimental data to enable a proper validation exercise. Moreover, the literature review showed a clear indication that an experimentally validated model for carbon dioxide capillary tube suction line heat exchangers is still to be developed. Therefore, this work is focused on the development and validation of a numerical model for simulating the transcritical carbon dioxide flow through *lateral* capillary tube suction line heat exchangers.

2. Experimental work

2.1. Experimental facility

The experimental study was carried out using a purpose-built test facility that reproduces a transcritical refrigeration cycle while controlling and recording all the relevant parameters (pressures, temperatures and mass flow rate). The test section,

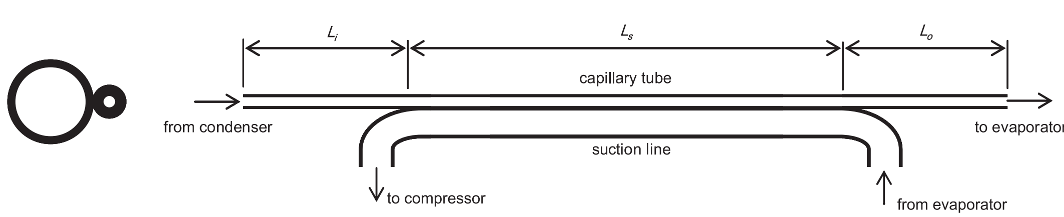

Fig. 1 – Schematic representation of a lateral type capillary tube suction line heat exchanger.