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Experimentation and modeling of refrigerant flow through coiled capillary tubes

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Abstract

Air-conditioners use spirally coiled capillary tubes as an expansion device to enhance compactness of the unit. However, most empirical correlations for predicting refrigerant flow rate through capillary tubes were developed for straight capillary tubes without consideration of coiled effects. The objectives of this study are to investigate the flow characteristics of the coiled capillary tubes and to develop a generalized correlation for the mass flow rate through the coiled capillary tubes. The mass flow rate of R22 through the coiled capillary tubes and straight capillary tubes was measured for various operating conditions and tube geometries. The mass flow rates of the coiled capillary tubes decreased by 5–16% more than those of the straight capillary tubes at the same operating conditions. A generalized correlation for predicting refrigerant mass flow rate through coiled capillary tubes was developed by introducing the parameter of capillary equivalent length. The present correlation showed good predictions with the present database for R22, R407C and R410A in the straight and coiled capillary tubes, yielding average and standard deviations of 0.24% and 4.4%, respectively.

Keywords: Air conditioning; Air conditioner; Experiment; Modelling; Expansion device; Capillary tube; Coiled tube; Correlation; Flow

Expérimentation et modélisation de l'écoulement du frigorigène dans les capillaires en spirale

Mots clés : Conditionnement d'air ; Conditionneur d'air ; Expérimentation ; Modélisation ; Détendeur ; Capillaire ; Tube hélicoïdal ; Corrélation ; Débit

1. Introduction

A capillary tube has been used as an expansion device in small refrigeration and air-conditioning systems. It controls the refrigerant mass flow and balances the system pressure in the refrigeration cycle. It is simple and low cost and has a low starting torque. Generally, refrigeration systems use a spirally coiled capillary tube to construct a compact unit.

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Nomenclature

D	coil diameter (mm)
De	Dean number
d	capillary inner diameter (mm)
f_{sc}	single-phase friction factor
f_{tp}	two-phase friction factor
h_{fg}	heat of vaporization (kJ/kg)
L	capillary overall length (mm)
L_e	capillary equivalent length (mm)
$\dot{m}$	mass flow rate (kg/h)
n	semi-circumference numbers of coiled tubes
P_{in}	inlet pressure (kPa)
P_c	critical pressure (kPa)
P_{sat}	saturated pressure (kPa)
Re	Reynolds number
T	temperature (°C)
T_c	critical temperature (°C)
x	vapor quality
ΔT_{sub}	subcooling (°C)

Greek letters

ε	absolute roughness (mm)
μ	dynamic viscosity (kg/ms)
ν	kinematic viscosity (m^2/s)
π	dimensionless parameter group
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

cond	condenser
evap	evaporator
f	saturated liquid
g	saturated vapor
meas	measured
pred	predicted

The shape of the coiled capillary tube can considerably affect the mass flow rate in the refrigeration cycle because the flow resistance from the secondary flow varies with the coiled shape [1]. Since an improperly sized capillary tube can significantly reduce the performance of a refrigeration system [2,3], an appropriate tool for the optimal design of the coiled capillary tube is essential. Although there have been many studies on the flow characteristics and modeling of straight capillary tubes, studies on the spirally coiled capillary tube have been very limited.

Capillary tube models can be classified into two categories, which are a numerical model and an empirical correlation. The determination of the friction factor in the capillary tube was the major part of the numerical modeling. Most theoretical models modified the friction factor based on measured data [4–6]. Ito [1] reported that the pressure drop of a coiled tube increased because of the secondary flow generated by a centrifugal force. He represented the friction factor as a function of the dimensionless parameter of $Re\sqrt{d/D}$. The friction factor proposed by Ito [1] increased with the reduction of the coil diameter D, yielding greater resistance to the refrigerant flow. Yufeng et al. [7] developed a numerical model to calculate the mass flow rate of coiled capillary tubes by modifying the correlation of the friction factor obtained from the literature.

Empirical correlations for frictional pressure drop, mass flow rate, and delay of vaporization were developed to predict the flow characteristics of refrigerants passing through capillary tubes [8–11]. However, most existing correlations in the open literature focused on straight capillary tubes. The effects of the coiled shape on the mass flow rate through the coiled capillary tubes have been hardly investigated. Kim et al. [11] compared the mass flow rates of the coiled capillary tubes with those of the straight capillary tubes. Guobing and Yufeng [12] investigated the mass flow rate hysteresis of R22 in a coiled adiabatic capillary tube. They found that the measured mass flow rate in the coiled adiabatic capillary was more dispersive than those in a straight one. It was suggested that for the coiled capillary tube, the secondary flow effect caused by the centrifugal force increased the uncertainty of the flash point location. Guobing and Yufeng [13] simulated the performance of coiled capillary tubes and verified their model by using the experimental data. They showed that the mass flow rate of the coiled capillary tube with the coil diameter of 40 mm was approximately 10% less than that of the straight capillary tube and the variation of the mass flow rate was negligible beyond the coil diameter of 300 mm. Garcia-Valladares [14] simulated the performance of coiled capillary tubes by using the separated flow model. However, the experimental data for the coiled geometry were very limited, so the effects of the coiled shape were difficult to generalize. In addition, they did not consider the number of coils in their correlation, which changes the straight section length in the overall tube length.

The objectives of this study are to investigate the mass flow characteristics of coiled capillary tubes and to develop an empirical correlation for predicting mass flow rate through the coiled capillary tubes. The present correlation was designed to cover both the straight and coiled capillary tubes with R22, R407C, and R410A. The capillary equivalent length L_e was introduced into the present correlation to consider the coiled effects of the capillary tube. In addition, a numerical model was developed to simulate the performance of the coiled capillary tubes. The predicted results using the proposed numerical model were compared with the measured data in this study.