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Experimental investigation and numerical simulation of choked refrigerant flow through helical adiabatic capillary tube

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HIGHLIGHTS

- The results confirm average error of about 5.5% for pressure.
- Drift flux model was applied for choked flow in coiled capillary tube.
- Under the same conditions, critical mass flux through helical tube with coil diameter of 40 mm is about 16% less than of straight one.
- The mass flux in steady and choked conditions through coiled capillary tube are equal approximately.
- The present model can be used as a suitable tool for design and optimization VCRC using helical capillary tubes.

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ABSTRACT

This paper presents a drift flux model and experimental study of choked refrigerant flow through both straight and helical adiabatic capillary tubes. The conservation equations of mass, energy, and momentum are solved using the fourth order Runge-Kutta method. This model is validated by previously published experimental data and also by test results performed and presented in this work for R-134a with average error of 5.5%. The effect of capillary tube inner diameter, length, relative roughness and coil diameter, and also various test conditions such as inlet pressure, inlet temperature, and sub-cooling degree of refrigerants are investigated. Critical mass flux variation, pressure distribution and temperature variation are obtained experimentally as well as vapor quality, vapor velocity and void fraction variation by numerical simulation. The results show that mass flux reaches a maximum amount at a specific value of evaporator pressure in choked conditions and also it is decreased by increasing the length of capillary tube. Moreover, critical mass flux increases by increasing of the tube inner diameter, condensation temperature and refrigerant degree of sub-cooling.

1. Introduction

Capillary tubes are used as refrigerant controlling devices, expansion devices and also as heart of a small vapor compression refrigeration cycle [1–3]. It connects outlet condenser to the inlet evaporator and balances the refrigeration cycle pressure and controls the refrigerant mass flux [1–9]. Because capillary tube has no moving parts, it cannot be adjusted to varying load conditions, resulting in extensive implementations therefore such as simple expansion devices in small household refrigerators and freezers with nearly constant refrigeration load [2,3]. In general, the inner diameter and length of a capillary tube ranges are from 0.5 to 2.0 mm, and 2–6 m, respectively [1–8].

In some vapor compression refrigeration cycle applications (VCRC), capillary tubes are coiled to minimize the space [4–8]. The fluid flow in coiled capillary tubes is subjected to the centrifugal force which causes secondary flow effect. Some researchers have referred to Dean effect to describe this secondary flow [1]. Dean Number is defined as $De = Re\,(d/D)^{0.5}$ that affects the amount of heat transfer, momentum, and mass flux in both kinds of coiled tubes [1].

Since in a capillary tube, the flow temperature reduces as it flashes into vapor phase, the flow analysis is complicated. Subcooled refrigerant enters the capillary tube and flows as a single phase up to the point where the pressure reaches the saturation pressure of refrigerant at flow temperature [1–5]. In a single-phase flow region, pressure gradient is almost constant [1–3]. Although it

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is expected that flashing to the vapor phase starts at the end of single-phase region, it happens with some delay at a point where flow pressure is slightly less than its saturation pressure. This region is called metastable flow region [10–12] which is often ignored in numerical simulations. By decreasing the pressure at the end of the tube, mass flux increases up to the "*critical condition*" in which mass flux remains stable and "*choked phenomenon*" happens at the end of the capillary tube. At this point, the pressure drops with a sharp gradient, in the other hands, dp/dz approaches to infinity and as a result fluid rapidly flashes to vapor phase [2,3]. Then, velocity of refrigerant flow increase due to increase in specific volume of the fluid until Mach number (local velocity of sound) reaches to 1.0 [2]. The condition dp/dz approaching infinity is a criterion for critical conditions [12–14]. Once the entropy reaches the maximum amount, the refrigerant velocity is equal to the velocity corresponding to Mach number 1.0, and then choked condition is happened [15–17]. Since, refrigeration systems are designed to work with critical condition of their capillary tube, analysis of the flow through these tubes is a vital step in the design and optimization of the refrigeration systems.

Bansal and Wang [2] proposed a homogenous flow model for R134a and R600a choked flow through adiabatic straight capillary tube. This numerical simulation is established based on first law of thermodynamics, empirical relations and a fresh look of fluid mechanics problem, known as "Fanno flow". The point of negative entropy change is a criterion for choked flow. In addition, their numerical modeling showed that critical mass flux increases as capillary tube diameter, condensation temperature and degree of sub-cooling increases.

Zhou and Zhang [5,8] have conducted numerical simulations and experimental validation for R22 refrigerant flow through coiled capillary tubes. They also used a homogenous two-phase flow model and three different friction factor correlations. They found that the mass flux through a capillary tube with coil diameter of 40 mm is reduced about 10% in comparison with a straight tube for the same test conditions.

Zhou and Zhang [7] have also conducted experimental investigation on the hysteresis effect of the coiled adiabatic capillary tube performance. The reported results indicate that the hysteresis effect decreases, as the coil diameter increases.

An experimental investigation and a homogenous numerical simulation were performed by Park et al. [9] for R22 flow through a straight and coiled capillary tube. They found that under the same test conditions, the mass flux through the coiled capillary tubes is decreased by about 5–16% compared to the straight capillary tubes.

The effects of sub-cooling degree for R22 flow through the coiled capillary tube were studied by Garcia–Valladares et al. [12,13]. They used a separated two-phase flow model for simulation of refrigerant flow through coiled tube. Their results indicated that the mass flux of capillary tube increases with increases in degree of sub-cooling as well as condensation pressure. Moreover, the entropy equations were used for detecting critical flow conditions.

Melo et al. [18] performed an experimental study on adiabatic straight capillary tubes with three refrigerants, namely HFC-134a, CFC-12 and HC-600a, under choked flow conditions in order to investigate the effect of tube diameter, length, degree of sub-cooling and condensation pressure. In addition, they reported a dimensional analysis for predicting the mass flux for different refrigerants. Their results showed that diameter affects the mass flux more significantly than the other parameters.

Chingulptak and Wongwises [15–17] also developed a homogenous two-phase flow model for refrigerant flow through helical capillary tube, where metastable liquid region was ignored. They found for the same length, mass flux through a coiled capillary tube with coil diameter of 40 mm is reduced by 9% compared to the straight tube.

A one-dimensional numerical simulation for R22, R12 and R-134a through straight adiabatic capillary tubes, using a drift flux model was reported by Liang and Wong [19]. They used the criteria pressure gradient criteria when dp/dz approaches to infinity in the exit of capillary tube.

In the past, there have been limited numerical or experimental works dedicated to choked flow phenomenon in capillary tubes [2,18]. Therefore, considering the scarcity of devoted literature on choked phenomenon in helically capillary tube, main objects of this work are choked phenomenon investigation and determination of the critical mass flow rate through coiled capillary tube under choked conditions. In most of the previous studies reviewed here, the flow in straight and coiled capillary tubes is simulated either by homogenous or by separated two-phase flow model for refrigerants R12 and R22. So, in the present work, a numerical model simulation is presented along with experimental investigation that predict the choked flow through coiled adiabatic capillary tube with various refrigerants, especially R134a under critical conditions.

To this end, a *drift flux flow* model using proper friction factor equations is numerically developed for helical capillary tube choked flow modeling and the generated simulation results are verified using present experimental data included herein as well as previously published relevant data.

2. Numerical modeling and resolution

Ignoring of the metastable flow passing through straight and coiled capillary tubes, it could be divided into single liquid phase and liquid–vapor flow regions [15–17 and 19]. Single-phase flow continues up to the point where flow pressure reaches the saturation pressure corresponding to its temperature [19]. Therefore, a model is first proposed for straight capillary tube and is then extended to coiled capillary tube, using proper friction factor correlation.

This proposed model is based on the following assumptions: fixed capillary tube geometry (inner diameter and relative roughness) through its length, oil-free refrigerant, adiabatic refrigerant flow, one-dimensional and steady state flow, and neglect of metastable flow. In drift flux flow model, the conservation of mass, momentum, and energy equations are applied by considering the two-phase region as a mixture of two liquid and vapor phases with different velocity [19]. Therefore, the formulation of the two-phase flow is constructed in terms of three equations for the mixture (continuity, momentum, and energy) and one drift velocity equation only for one of the vapor or liquid phases. In what follows, development of the governing equations for single phase and two-phase refrigerant flow are presented.

2.1. Single phase region in straight and coiled capillary tubes

The equation of conservation momentum for refrigerant flow in liquid phase going steady and one-dimensional flow is expressed in Eq. (1). Integration of the Eq. (1) along the length of capillary tube from inlet to the saturation point of the incompressible refrigerant fluid flow results in:

$$\frac{dp}{dz} = -\frac{f_D G^2}{2d\rho_f} \tag{1}$$

$$\frac{p_{in} - p_{sat}}{L_{sub}} = \frac{f_D G^2}{2d\rho_f} \tag{2}$$

where P_{sat} is defined as the saturated pressure corresponding to the refrigerant temperature at inlet. From Eq. (2) the sub-cooled liquid's length through capillary tube is obtained as: