Available online at www.sciencedirect.com

SCIENCE DIRECT®

Applied Thermal Engineering 26 (2006) 1106–1114

APPLIED THERMAL ENGINEERING

www.elsevier.com/locate/apthermeng

Numerical and experimental investigations on the performance of coiled adiabatic capillary tubes

Zhou Guobing [a,*], Zhang Yufeng [b]

[a] *Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China*
[b] *School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China*

Received 3 August 2005; accepted 9 November 2005
Available online 20 December 2005

Abstract

The objective of this study is to investigate the performance of coiled adiabatic capillary tubes both numerically and experimentally by comparison with the straight capillaries. With the developed model including metastable both liquid and two-phase regions, three methods (M&N equation, M&N + Giri method and developed C–M&N method) are discussed to calculate friction factors for coiled capillary tubes. A one-pass-through experiment apparatus is set up for model verification. Mass flow rate through the capillary is measured with different tube geometries and under various operating conditions. Compared with the present experimental data and that in literature, the developed C–M&N method gives the best prediction with the average deviation of ±5%. The test results show that mass flow rate in a capillary tube increases with increase of coiled diameter (D), but changes little beyond $D = 300$ mm. And the mass flow rate with coiled diameter of 40 mm is approximately 10% less than that of straight capillary tube.

Keywords: Adiabatic capillary tube; Coiled tube; Friction factor; Two-phase flow; Metastable

1. Introduction

Capillary tubes are widely used as expansion devices in small refrigeration and air-conditioning units due to their simplicity, reliability and low cost. Recently, their uses have been extended to include larger units in size up to 35.2 kw [1]. Despite its simple configuration, the flow inside a capillary tube is very complex and its behavior has strong influence on the performance of the whole system. In the past decades, many studies have been made to understand its operating characteristics both experimentally and theoretically, most of which mainly focused on straight tubes [2–12]. However in practical applications, capillary tubes are generally coiled to save space. The effect of coiling was not well concerned with.

Kuehl and Goldschmidt [13] performed an experimental study to determine the effects of coiling on the characteristics of capillary tubes by measuring the distribution of pressure drops and concluded that the coiling tended to increase pressure drop by about 5%. They supposed that the possible reason for the coiled resistance increase could be the change of inner tube diameter during the coiling process. However, their comparison of internal volume for a coiled capillary with the original straight one showed no changes in the internal volume.

Wei et al. [14] quantitatively examined the performance difference between straight and coiled capillary tubes with R22 and R407c. Their test results indicated that the coiling effect increased with decrease of the coiling diameter. For tube diameter $d = 1.0$ mm and coiled diameter $D = 52$ mm, the mass flow rates of coiled tube are about 10–15% lower than those of straight tube. Beside the change of inner diameter, they suspected another possible reason for the reduction of mass flow rates is the secondary flow effect caused by the centrifugal force in coiled tubes.

* Corresponding author. Tel.: +86 10 62794194; fax: +86 10 62773461.
E-mail address: zhougb@mail.tsinghua.edu.cn (G. Zhou).

1359-4311/$ - see front matter
doi:10.1016/j.applthermaleng.2005.11.003

Nomenclature

A	capillary cross-sectional area (m^2)
D	coiled diameter (mm)
D'	reference length (mm)
d	tube inner diameter (mm)
f	friction factor
G	mass flux ($kg\ s^{-1}\ m^{-2}$)
h	specific enthalpy ($J\ kg^{-1}$)
K	entrance loss coefficient
k	Boltzmann constant (1.380662×10^{-23})
L	length (m)
m	mass flow rate ($kg\ s^{-1}$)
n	exponent constant in Eq. (18)
P	pressure (Pa)
Re	Reynolds number
T	temperature (°C)
v	specific volume ($m^3\ kg^{-1}$)
U	capillary cross-sectional perimeter (m)
V	velocity ($m\ s^{-1}$)
x	quality
y	mass ratio of total saturated phase to total phase

Greek letters

α	proportional coefficient in Eq. (18)
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
ε	tube wall roughness (mm)
σ	surface tension ($N\ m^{-1}$)
ω	coefficient in Eq. (19)
ψ	coefficient in Eq. (19)

Subscripts

c	coiled or critical (T_c)
cap	capillary
cn	condensation
e	evaporation
g	gas phase
in	inlet
l	liquid
lm	metastable liquid phase
ls	saturated liquid phase
m	average
out	outlet
s	straight
sat	saturated
sc,sub	subcooled
tm	metastable two phase
tp	two phase
vap	vaporization
w	wall

Kim et al. [15] experimentally compared the mass flow rates of coiled capillary tubes with different coiled diameters of 40, 120, and 200 mm with those of straight tubes. They reported the mass flow rate of the coiled capillary tube with coiled diameter of 40 mm is approximately 9% less than that of straight tube. They agreed to the point that the pressure drop of a coiled tube was increased due to the existence of a secondary flow generated by a centrifugal force as the case of common coiled pipes and thus the reduced mass flow rate.

To the author's knowledge, the only reported literature in simulation investigation on coiled capillary tubes is that Gorasia et al. [16] used Mori and Nakayama equation and Giri correlation in their model for calculating liquid and two-phase friction factors of coiled capillary respectively, and metastable regions are ignored. However, metastable phenomenon has been proved to exist by experiments of Mikol [2] and Li et al. [17]. In our previous work [18], a four-flow-region model including metastable both liquid and two-phase regions has been developed for straight capillary tubes. Therefore, the present work attempts to discuss the appropriate friction factor equations to be used in the four-flow-region model, which could relatively well predict the mass flow rates in coiled capillary tubes. Experiments are also conducted to investigate the coiling effect and verify the model precision.

2. Model description

As mentioned above, the coiling effect of a tube can be embodied in the calculation of friction factors. So, a straight tube model can also be applied to coiled capillary tubes by changing the corresponding friction factor equations. For convenience, the developed four-flow-region model [18] is briefly reviewed and then friction factors for coiled capillary tubes are discussed.

It is assumed that the capillary tube is constant inner diameter and roughness. Also, the flow inside it is considered to be one-dimensional, steady, adiabatic, no external work and the two-phase flow is homogeneous. The homogeneous assumption can be reasonable since visualization studies by Mikol [2] and Koizumi and Yokoyama [3] have confirmed that the two-phase flow was of a fog-like appearance or high-speed bubble-type flow in a glass capillary tube, and bubbles were observed to scatter uniformly and discretely in the liquid. Considering section 1 and section 2 shown in Fig. 1, the governing equations of mass, momentum and energy conservation can be written as follows:

$$G = V_1/v_1 = V_2/v_2 \tag{1}$$

$$G^2(v_2 - v_1) = p_1 - p_2 - f_m \frac{\Delta L}{d}\frac{G^2 v_m}{2} \tag{2}$$

$$h_1 + G^2 v_1^2/2 = h_2 + G^2 v_2^2/2 \tag{3}$$