Applied Thermal Engineering 90 (2015) 879–894

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Experimental and numerical studies of choked flow through adiabatic and diabatic capillary tubes

Subodh D. Deodhar, Hardik B. Kothadia, K.N. Iyer, S.V. Prabhu *

Department of Mechanical Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai 400 076, India

HIGHLIGHTS

- Model is developed to design capillary tube in adiabatic and diabatic condition.
- Effect of coil curvature on pressure drop is studied experimentally.
- Correlation is developed to predict mass flow rate in helical capillary tubes.
- Flow visualization is carried out to check the type of two phase flow.
- Effect of choked flow on diabatic capillary tubes is studied experimentally.

ARTICLE INFO

Article history:
Received 15 April 2015
Accepted 25 July 2015
Available online 3 August 2015

Keywords:
Choked flow
Capillary tubes
Diabatic
Instability

ABSTRACT

Capillary tubes are extensively used in several cooling applications like refrigeration, electronic cooling etc. Local pressure variation in adiabatic straight capillary tube (mini channel) is studied experimentally and numerically with R134a as the working fluid. Experiments are performed on two straight capillary tubes. It is found that the diameter is the most sensitive design parameter of the capillary tube. Experiments are performed on five helically coiled capillary tubes to quantify the effect of pitch and curvature of helically coiled capillary tube on the pressure drop. Non dimensionalized factor to account coiling of capillary tube is derived to calculate mass flow rate in helically coiled capillary tubes. Flow visualization in adiabatic capillary tube confirms the bubbly nature of two phase flow. Numerical and experimental investigations in diabatic capillary tube suggest that the use of positive displacement pump and choking at the exit of the channel ensures flow stability.

1. Introduction

Flow in capillary tube finds wide applications in cooling and refrigeration. Adiabatic capillary tubes are used in refrigeration industry. Flow through the capillary tubes is two phase and generally choked at the exit. Automotive, aerospace and cryogenic industries use compact evaporators having diabatic capillary tubes (mini channels) to cope up with increased heat flux densities. Hence, choked flow through adiabatic and diabatic capillary tubes is explored for pressure drops and two phase flow instability.

1.1. Adiabatic flow through capillary tubes

Simulation of refrigerant flow through adiabatic capillary tubes is done by Wongwises and Pirompak [1], Bansal and Rupasinghe [2], Bittle and Pate [3] using homogeneous flow model. Bansal and Rupasinghe [2] (CAPIL) have used Churchill friction factor model for calculation of wall shear stress. Their procedure calculates friction factor (f_{tp}) as an average of friction factor values at each control volume over entire two-phase flow region. Viscosity model used for determination of two phase viscosity (μ_{tp}) is not mentioned. Model predicts the length of capillary tube for a given mass flow rate, condenser and evaporator pressure and inlet temperature of the refrigerant. On the contrary, model reported by Bittle and Pate [3] predicts mass flow rate of the refrigerant for a given length of tube, condenser and evaporator pressure and inlet temperature of the refrigerant. It uses entrance loss given by Collier and Thome [4] correlation and considers metastable under pressure as given by

* Corresponding author. Tel.: +91 22 25767515; fax: +91 22 25726875, +91 22 25723480.
E-mail address: svprabhu@me.iitb.ac.in (S.V. Prabhu).

http://dx.doi.org/10.1016/j.applthermaleng.2015.07.073
1359-4311/

Nomenclature

A	cross sectional area of capillary tube, m^2
D	coil diameter, m
d	diameter of the tube, m
dL	small incremental length, m
dP	pressure drop, Pa
e	surface roughness of the tube, μm
F	correction factor
f	friction factor
G	mass velocity, kg/m^2s
g	gravitational acceleration, m/s^2
h	specific enthalpy of fluid, kJ/kg
L	length of the tube, m
$\dot{m}$	mass flow rate of the refrigerant, kg/s
P	pressure, Pa
q	heat input, J
Re	Reynolds number
s	specific entropy of fluid, kJ/kg K
T	temperature, °C
ΔT	degree of subcooling, °C
V	velocity, m/s
v	specific volume, m^3/kg
x	dryness fraction
Greek letters	
Φ	two phase friction multiplier
μ	viscosity, Pa S
ρ	density, kg/m^3
σ	surface tension, N/m
τ	shear stress, N/m^2
Subscripts	
cal	calculated
ch	choked condition
ch,f	choked condition with liquid
ch,g	choked condition with vapor
$coil$	for coil
$cond$	condenser
$crit$	critical
eq	equivalent
$evap$	evaporator condition
$exit$	exit condition
exp	experimental
f	saturated liquid
fg	latent condition
g	saturated vapor
i	intermediate state, inlet
L	loss
lo	liquid phase only
$meta$	metastable
r	reference
s	straight tube
sat	saturation condition
s_{max}	maximum entropy
sp	single phase
sub	subcooling
tp	two phase
w	wall

Chen et al. [5]. Three models for calculating two-phase viscosity (McAdams, Duckler, Cicchitti) are tried. This model uses averaged values of velocity, two phase friction factor and specific volume over each control volume locally for calculations. Methodology followed by Wongwises and Pirompak [1] is used in this study with some modifications. Bansal and Wang [6] have developed a full range simulation diagram in order to understand choked flow phenomenon graphically. Their prediction of mass flow rate by numerical solution is found to be within ±7% of the experimental data for R22, R134a and R600a.

Kim et al. [7] have performed experiments on flow through adiabatic capillary tubes for R22 and its alternatives. Objective of their study is to present test results and develop a correlation for estimation of mass flow rate. They have used a cycle involving liquid pumping rather than the conventional vapor compression cycle of refrigeration. They have reported the effect of coiling on the mass flow rate of the refrigerant flowing through the helically coiled capillary tubes. However, pitch of the helical coils is not mentioned. Melo et al. [8] have performed experiments on flow through capillaries for CFC12, HFC 134a and HC 600a and developed a correlation for estimating mass flow rates. They have used a conventional vapor compression cycle for their experiments. Choi et al. [9] have developed a generalized correlation for predicting the mass flow rates through the straight capillary tubes using data for six refrigerants in open literature. It may be concluded that the information concerned to the effect of pitch and radius of curvature of helically coiled adiabatic capillary tubes on the mass flow rate and pressure drop is not much explored in the open literature.

Chingulpitak and Wongwises [10,11] developed model to design helically coiled capillary tubes for alternative mixture of refrigerants. Numerical results of their studied are compared with experimental data of Kim et al. [7] and Zhou and Zhang [12] for R-22. Their work concluded the effect of coil diameter on length of capillary tube and variation in pitch had no significant affect on capillary tubes. Chingulpitak and Wongwises [13] compare the results of helically coiled and straight capillary tubes and indicated the reduction in capillary tube length for different helical coil diameter compare to that of straight capillary tube length. Schenk and Oellrich [14] conducted experimental studies on adiabatic straight capillary tubes for refrigerant R600a. The published database of Melo et al. [8] is extended for the mass flow rate of 0.18–0.55 g/s. Shokouhmand and Zareh [15], Zareh et al. [16], and Javidmand and Zareh [17] simulated two phase refrigerant flow using drift flux model for adiabatic straight and helically coiled capillary tubes. The model is validated with experimental results for refrigerants R134a, R12 and R22. Mass flow through the helically coiled tube with 40 mm coil diameter is compared with straight capillary tube. Reduction in the length of helically coiled capillary tubes is analyzed for the same mass flow for different coil diameters. Yang and Zhang [18] developed a correlation for mass flow rate through adiabatic straight capillary tube and short tube orifices. Punia and Singh [19] conducted experimental work on adiabatic helically coiled capillary tube with liquefied petroleum gas (LPG) as a refrigerant. A correlation is developed for mass flow rate prediction.

1.2. Diabatic flow through capillary tubes

Saha et al. [20] have carried out experiments on uniformly heated boiling channel using Freon-113 to study the density wave oscillations (DWO). They have studied the effects of inlet subcooling, system pressure, inlet and exit restrictions, and inlet velocity on flow instability. Experiments on parallel mini channel heat sink with water are conducted by Xu et al. [21] to determine the onset of