Experimental Investigation of Simultaneous Heat Transfer and Pressure Drop Measurements for Plain and Micro-fin Tubes

by

Tam, Hou Kuan

Doctor of Philosophy in Electromechanical Engineering

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Faculty of Science and Technology

University of Macau

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Abstract

In this study, a detailed investigation on the effects of entrance flow, buoyancy, inlet configurations, and fin geometries on heat transfer and friction factors in the entrance and fully developed regions of horizontal plain and micro-fin tubes under laminar, transition, and turbulent regimes is presented. The Reynolds numbers for the ethylene glycol-water mixtures throughout the experiments ranged from 800 to 25,000.

The reliability of the experimental system was verified by plain tube heat transfer and friction factor experiments. Owing to the lack of information on entrance flow friction factors in the open literature, the effects of the inlet and heating on the entrance and fully developed flow friction factors are presented in this study. The results showed that the transition range was inlet-dependent and the effect of heating on friction factors was obvious in laminar and transitional regions. Furthermore, correlations predicting non-isothermal entrance and fully-developed friction factors in laminar and transitional regions for square-edged and re-entrant inlets were developed.

From micro-fin tube heat transfer and friction factor test results, the transition from laminar to turbulent flow was clearly established and the transition Reynolds number was shown to be inlet- and fin geometry-dependent. The influence of buoyancy and entrance flow on heat transfer was obvious in the laminar region and the obvious effect of heating on the friction factor in the lower transitional region was observed. Correlations to predict forced and mixed convection heat transfer in laminar, transitional, and turbulent regions were developed. Also, correlations for predicting isothermal and non-isothermal entrance and fully-developed friction factors in laminar and transitional regions were developed.

In this study, several soft computing methods were used to develop heat transfer correlations for plain and micro-fin tubes and determine optimal fin geometry for micro-fin tubes. The results showed that soft computing correlations are superior to correlations developed by the traditional least-squares method and that soft computing methods are applicable for the optimization problem of micro-fin tubes.

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Declaration

I declare that the thesis here submitted is original except for the source materials explicitly acknowledged and that this thesis as a whole, or any part of this thesis has not been previously submitted for the same degree or for a different degree.

I also acknowledge that I have read and understood the Rules on Handling Student Academic Dishonesty and the Regulations of the Student Discipline of the University of Macau.

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Nomenclature

English Letters

a	output vector
A	cross-sectional area of the test section (tube) [=$\pi D_i/4$], ft^2 or m^2
b	bias
b	bias matrix
c_p	specific heat of the test fluid evaluated at T_b, Btu/(lbm-ºF) or kJ/(kg-K)
C	parameter of Eq. (4.26)
C_f	fully-developed friction factor coefficient (Fanning friction factor) [=$\Delta P \cdot D_i /(2 \cdot L \cdot \rho \cdot V^2)$]**,** dimensionless
$C_{f,m}$	fully-developed friction factor coefficient (Fanning friction factor) for micro-fin tubes [=$\Delta P \cdot D_i /(2 \cdot L \cdot \rho \cdot V^2)$], dimensionless
$C_{f,p}$	Fully developed friction factor coefficient (Fanning friction factor) for plain tubes [=$\Delta P \cdot D_i/(2 \cdot L \cdot \rho \cdot V^2)$], dimensionless
D_i	inside (or fin-base) diameter of the test section (tube), ft or m
D_o	outside diameter of the test section (tube), ft or m
e	internal fin height, ft or m
F	Symbolic function
f	activation (or transfer) function
f_{app}	apparent Fanning friction factor [=$\Delta P_{0-x} D_i/(2\ x \cdot \rho \cdot V^2)$], dimensionless
fcn	function
Gr	local bulk Grashof number [=$g \cdot \beta \cdot \rho^2 \cdot D_i^3 (T_w - T_b) / \mu^2$], dimensionless
Gz	local Graetz number [=$Re \cdot Pr \cdot D_i /x$], dimensionless
g	acceleration of gravity, ft/s^2 or m/s^2

h	fully-developed peripheral heat transfer coefficient, Btu/(hr-ft^2-^{o}F) or W/(m^2·K)
h_b	local peripheral heat transfer coefficient at the bottom of the tube, Btu/(hr-ft^2-^{o}F) or W/(m^2·K)
h_t	local peripheral heat transfer coefficient at the top of the tube, Btu/(hr-ft^2-^{o}F) or W/(m^2·K)
j	Colburn-j factor [=St·Pr$^{0.67}$], dimensionless
j_m	Colburn-j factor [=St·Pr$^{0.67}$] for micro-fin tube, dimensionless
j_p	Colburn-j factor [=St·Pr$^{0.67}$] for plain tube, dimensionless
k	thermal conductivity of fluid, Btu/(hr-ft-^{o}F) or W/(m·K), evaluated at T_b.
k_{cu}	thermal conductivity of copper, Btu/(hr-ft-^{o}F) or W/(m·K)
L	length of the test section (tube), ft or m
L	length of the binary string
l_{csw}	modified characteristic length for swirling flows, ft or m
m	an exponent of viscosity correction factor, dimensionless
n	an exponent of viscosity correction factor, dimensionless
N	number of iterations
Nu	local average or fully-developed peripheral Nusselt number [=h·D_i/k], dimensionless
Nu_l	local average or fully developed peripheral laminar Nusselt number, dimensionless
Nu_t	local average or fully developed peripheral turbulent Nusselt number, dimensionless
Nu_{tr}	local average or fully developed peripheral transition Nusselt number, dimensionless

N_s	Number of starts (fins) per cross-sectional area, dimensionless
n_{sc}	Number of sharp corners
n	net input column vector
p	input vector
p	axial fin pitch [$=\pi \cdot D_i / (N_s \cdot \tan \alpha)$], ft or m
P_j	contribution of the j^{th} independent variable p_j
Pr	local bulk Prandtl number [$=c_p \cdot \mu_b / k$], dimensionless
Q_k	contribution of the k^{th} neuron output to the ANN model
Ra	local bulk Rayleigh number [$= Gr \cdot Pr$], dimensionless
Re	local bulk Reynolds number [$=\rho \cdot V \cdot D_i / \mu_b$], dimensionless
S	number of neurons
St	local average or fully-developed peripheral Stanton number [$=Nu/(Pr \cdot Re)$], dimensionless
T	temperature, ^oF or ^oC
T_b	local bulk temperature of the test fluid, ^oF or ^oC
T_{in}	Inlet temperature, ^oF or ^oC
T_{out}	Outlet temperature, ^oF or ^oC
T_w	local inside wall temperature, ^oF or ^oC
t	mean fin width (or fin thickness), ft or m
t	target vector
$\mathbf{u}^1$, $\mathbf{u}^2$, $\mathbf{u}^3$	coefficient matrices
$\mathbf{v}^1$, $\mathbf{v}^1$, $\mathbf{v}^3$	coefficient matrices
V	average fluid velocity in the test section, ft/s or m/s
w	weight matrix
x	local axial distance along the test section from the inlet, ft or m

x	input vector

Abbreviations

ANN	artificial neural networks
AOC	algorithms of changes
CG	conjugate gradient
GA	genetic algorithms
index	index of contribution
LM	Levenberg-Marquardt
MSE	mean squared error
QN	quasi-newton
RI	relative importance
SDA	steepest descent algorithms
SDA-VLR	steepest descent algorithm with variable learning rates
SR	symbolic regression
SVM	support vector machines
υ-SVR	υ-support vector regression

Greek Symbols

α	Spiral angle, degree
γ	kernel parameter of Eq. (4.30)
γ_{cu}	electrical resistivity of copper, ohm-in
ρ	density of the test fluid evaluated at T_b, lbm/ft^3 or kg/m^3
β	coefficient of thermal expansion of the test fluid evaluated at T_b, K^{-1}
β'	fin included angle of Figure 3.2, degree

ΔP	pressure difference, lbf/ft^2 or Pa
ΔP_{0-x}	pressure drop from the inlet to a specific location down the tube, lbf/ft^2 or Pa
μ	dynamic viscosity, lbf/(hr-ft) or Pa-s
μ_b	local bulk dynamic viscosity of the test fluid evaluated at T_b, lbf/(hr-ft) or Pa·s
μ_w	local bulk dynamic viscosity of the test fluid evaluated at T_w, lbf/(hr-ft) or Pa·s
ζ	dimensionless axial distance [$=(x/D_i)/Re$], dimensionless
η	efficiency index [$=(j / j_p) / (C_f / C_{f,p})$], dimensionless
$\mathbf{\Phi}$	vector

Superscripts

M	output layer
m	layer

Subscripts

b	bulk
cal	calculated (or predicted) value
cr	critical value at the onset of turbulence
exp	experimental value
force	forced convection
iso	isothermal condition
i	dummy parameter
j	j^{th} input variable

k	k^{th} hidden neuron
l	laminar region
m	micro-fin tube
max	maximum value
min	minimum value
mix	mixed convection
normal	normalized input variable
p	plain tube
Q	sample sets
R	number of inputs
red	reduced format
S	number of hidden neurons
t	turbulent region
tr	transition region
w	wall
heat	non-isothermal (or heating) condition

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