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Experimental Thermal and Fluid Science 30 (2006) 675–686
Experimental Thermal and Fluid Science
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Effects of EHD on heat transfer enhancement and pressure drop during two-phase condensation of pure R-134a at high mass flux in a horizontal micro-fin tube

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Received 4 November 2005; received in revised form 19 January 2006; accepted 22 January 2006

Abstract

Effects of electrohydrodynamic (EHD) on the two-phase heat transfer enhancement and pressure drop of pure R-134a condensing inside a horizontal micro-fin tube are experimentally investigated. The test section is a 2.5 m long counter flow tube-in-tube heat exchanger with refrigerant flowing in the inner tube and cooling water flowing in the annulus. The inner tube is made from micro-fin horizontal copper tubing of 9.52 mm outer diameter. The electrode is made from cylindrical stainless steel of 1.47 mm diameter. Positive high voltage is supplied to the electrode wire, with the micro-fin tube grounded. In the presence of the electrode, a maximum heat transfer enhancement of 1.15 is obtained at a heat flux of 10 kW/m^2, mass flux of 200 kg/m^2 s and saturation temperature of 40 °C, while the application of an EHD voltage of 2.5 kV only slightly increases the pressure drop. New correlations of the experimental data based on the data gathered during this work for predicting the condensation heat transfer coefficients are proposed for practical application.

Keywords: Electrohydrodynamic; Condensation heat transfer; Heat transfer enhancement; Micro-fin tube

1. Introduction

Micro-fin tubes have been successfully implemented in the air-conditioning and refrigeration industries for effectively improving tube-side performance. This success is because of their ability to significantly improve the heat transfer coefficient with only a moderate increase of the friction penalty. A heat transfer enhancement technique utilizing electrohydrodynamic (EHD) can be achieved by utilizing the interaction between the electric field and fluid flow in a dielectric fluid medium. This interaction can result in the increase of fluid motion, which leads to a higher heat transfer coefficient.

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doi:10.1016/j.expthermflusci.2006.01.003

The physical basis of the electrically enhanced condensation and boiling are due to the EHD force, (f_e), generated by an electric field and is given by the following Eq. (1) [1]:

$$f_e = qE - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left\langle E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\rho\right\rangle \quad (1)$$

Eq. (1) can be further written in a more detailed form for non-polar fluids as follows in Eqs. (2) and (3):

$$f_e = f_1 + f_2 + f_3 + f_4 \quad (2)$$

$$f_e = qE - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{6}\varepsilon_o(\kappa-1)(\kappa-2)\nabla E^2 + \frac{1}{6}\varepsilon_o E^2\nabla\langle(\kappa-1)(\kappa-2)\rangle \quad (3)$$

The first term on the right of Eq. (3), known as the electrophoretic force, is the Coulomb force acting on the free

Nomenclature

A_{inside}	inside surface area of the test section (m^2)
A_c	cross-section area (m^2)
Bo	Bond number
c_p	specific heat at constant pressure (J/kg K)
D	hydraulic diameter (m)
D_f	maximum inside diameter of the test section (m)
D_o	outside diameter (m)
D_t	fin tip diameter (m)
E	electric field strength (V/m)
e_f	fin height (m)
f	unit force density (N/m^3)
f	friction factor
Fr	Froude number
G	mass flux (kg/m^2 s)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 K)
i	enthalpy (J/kg)
L	length of the test tube (m)
m	mass flow rate (kg/s)
N	number of fins
Nu	Nusselt number
p	pressure (Pa)
Pr	Prandtl number
Q	heat transfer rate (W)
q	electric charge density (C/m^3)
Re	Reynolds number
T	temperature (°C)
t	bottom thickness (m)
u	velocity (m/s)
x	quality
X	Martinelli parameter
z	distance (m)

Greek letters

β	spiral angle (degree)
γ	apex angle (degree)
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
ε	electric permittivity (F/m)
ε_0	electric permittivity of free space (8.854×10^{-12}) (F/m)
κ	relative permittivity $\left(\frac{\varepsilon}{\varepsilon_0}\right)$
σ	surface tension (N/m)
ϕ_l^2	two-phase multiplier

Subscripts

avg	average
e	with EHD
eq	equivalent
f	saturated liquid
F	friction
fg	difference in property between saturated liquid and vapor
Go	gas only
in	inlet
l	liquid
o	without EHD
out	outlet
ph	pre-heater
ref	refrigerant
sat	saturation
TS	test section
v	vapor
w	water
wall	wall

charges in a fluid. An electrophoretic force exists once a net charge is created in the fluid and it becomes dominant in applications where corona wind is utilized.

The second term (f_2) is a consequence of inhomogeneity or spatial change in the permittivity of the dielectric fluid due to non-uniform electric fields, temperature gradients, and phase differences.

The third term (f_3), the dielectophoretic force, represents the non-uniformity of the electric field. Condensate is pushed by this force into a higher electric field strength.

The forth term (f_4) is the electrostriction force which occurs whether or not an applied field is uniform. This force depends on the non-uniformity of electric permittivity. A similar principle applies when a charged needle electrode is brought close to a liquid surface.

Electro-convection is a phenomenon in which a previously quiescent fluid will start moving in a certain direction when a strong electric field is applied on the dielectric permittivity of the fluid, as shown in Fig. 1.

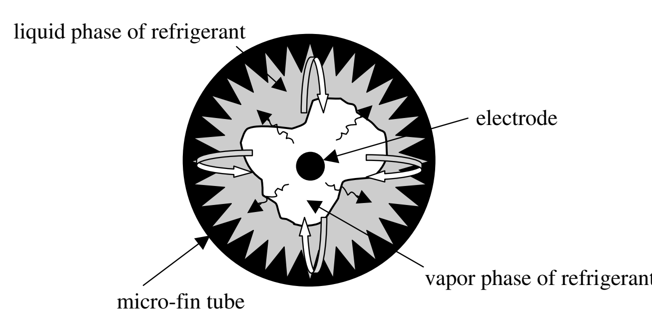

Fig. 1. Electro-convection phenomena [2].

Heat transfer enhancement using the EHD technique has been studied by a large number of researchers. However, heat transfer enhancement using the EHD technique during condensation has received little attention. Some of the EHD studies were conducted by [1–6], as shown in Table 1. All results found that heat transfer enhancement