Experimental Thermal and Fluid Science 79 (2016) 1–12

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Optimization of thermal and flow characteristics of R-404A vapor condensation inside corrugated tubes

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ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form 10 June 2016
Accepted 11 June 2016
Available online 14 June 2016

Keywords:
Condensation
Corrugated
R-404A
Optimization
Pareto

ABSTRACT

In the present study the condensation pressure drop and heat transfer coefficient of R-404A flowing through the corrugated tubes are experimentally investigated. The test section is a horizontal 1 m long double-pipe counter-flow heat exchanger where R-404A flows in the inner tube with internal diameters of 8.7 mm and coolant water flows through the annulus. The pressure drop and heat transfer coefficient are obtained for the plain tube and nine corrugated tubes, mass velocities ranging from 187 to 561 kg/m^2 s, vapor quality from 0.18 to 0.85 and average condensing temperature from 29.2 to 35.8 °C. Investigation shows that using the corrugated tube increases the heat transfer coefficient and pressure drop up to 59% and 115% above the plain tube values, respectively. New empirical correlations are developed to predict the heat transfer coefficient and pressure drop inside the corrugated tubes. Finally, artificial neural network and multi-objective genetic algorithm are used for finding optimal operational conditions during the condensation of R-404A refrigerant inside the corrugated tubes.

1. Introduction

In recent years, due to high cost of material and energy and limited energy sources, heat transfer enhancement methods have been developed for designing of more efficient heat exchangers [1–6]. Corrugated tubes are treated as one of the passive enhancement methods. These tubes increase the heat transfer coefficient with a reasonable increase of the pressure drop. Corrugated tubes are used in a wide variety of industrial applications such as condenser and evaporator of industrial refrigeration systems. Two-phase heat transfer and flow characteristics of refrigerants flowing through corrugated tubes were investigated by some researchers. Kareem et al. [7] presented a review of experimental and numerical investigations which were focused on the heat transfer enhancement inside corrugated tubes at the turbulent and laminar zone. Laohalertdecha and Wongwises [8,9] presented the heat transfer and flow characteristics during condensation and evaporation of R-134a flowing through corrugated tubes. The tests were conducted at the saturation temperatures of 40–50 °C, heat fluxes of 5–10 kW/m^2, mass fluxes of 200–700 kg/m^2 s, and equivalent Reynolds numbers of 30,000–120,000. They reported that the two-phase friction factor and Nusselt number for internal flow obtained from the corrugated tubes were higher than those obtained from the smooth tube under the same conditions. New correlations were developed for the prediction of condensing Nusselt number and two-phase friction factor inside the corrugated tubes. Aroonrat and Wongwises [10] experimentally investigated the thermal and flow characteristics of R-134a refrigerant during evaporation inside a vertical corrugated tube. The effects of heat flux, mass flux, and evaporation temperature on the heat transfer coefficient and friction factor were examined. They have reported that the corrugated tube increased the heat transfer coefficient and the two-phase friction factor approximately 0–10% and 70–140% higher than those obtained from the smooth tubes, respectively. Khoeini et al. [11] experimentally investigated the heat transfer coefficient during condensation of R-134a inside a corrugated tube with different inclinations ranging from −90° to +90°. The results showed that the highest average heat transfer coefficient was obtained for $\alpha = +30°$. Also, Targanski and Cieslinski [12] experimentally examined the evaporation of pure R407C and R407C/oil mixtures inside smooth, corrugated and micro-fin tubes. Experimental parameters included the average saturation temperature of 0 °C and the mass flux from 250 to 500 kg/m^2 s. During tests inlet vapor quality was set to 0 and outlet quality was set to 0.7.

In this Study R-404A is the refrigerant under consideration. It is a non-azeotropic refrigerant with ozone depletion potential (ODP) factor of zero, designed to use as a long-term replacement for low and medium temperature commercial and industrial refrigeration

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http://dx.doi.org/10.1016/j.expthermflusci.2016.06.012
0894-1777/

Nomenclature

ANN artificial neural network
C_p specific heat, kj/kgK
d inner diameter of tube, mm
e corrugation depth, mm
G mass velocity, kg/m^2 s
$\bar{h}$ average heat transfer coefficient, W/m^2 K
k thermal conductivity, W/m K
L length of test section, m
$\dot{m}$ mass flow rate, kg/s
MRE mean relative error, dimensionless
NSGA non-dominated sorting genetic algorithm
P pressure, Pa
p corrugation pitch, mm
Q heat transfer rate, W
T cooling water temperature, K
t refrigerant temperature, K
U uncertainty, dimensionless
x vapor quality, dimensionless

Greek symbols
α test section inclination angle, °
ΔP pressure drop, Pa
Δx change in vapor quality, dimensionless
ε void fraction, dimensionless
μ dynamic viscosity, Pa s
ρ density, kg/m^3

Dimensionless groups
$Fr_L = G^2/(1-x)gd_i\rho_L^2$ liquid Froude number
$\underline{Nu} = hd/k$ average Nusselt number
$Pr = \mu C_p/k$ Prandtl number
$Re = Gd/\mu$ Reynolds number
$Re_{Go} = Gd_i/\mu_G$ only vapor phase Reynolds number
$Re_L = Gd_i/(1-x)\mu_L$ liquid Reynolds number

Subscripts
as axial station
b bottom
c corrugated tube
fric friction
G vapor state
Go vapor only (all flow as vapor)
i inside wall of copper tube
in inside
le left
L liquid state
m mixture phases (liquid + vapor)
mom momentum
o outside wall of copper tube
out outside
p plain tube
r right
s saturation
sta static
t top
tot total
w water
wi inlet water
wo outlet water

applications. R-404A has become one of the most widely used refrigerants in transportable refrigerators, supermarket freezer cases, cold storage cells and ice machines. It was introduced as an alternative for ozone depletion refrigerants including CFCs (R-12 and R-502) and as an alternative for HCFCs (R-22). Literature review reveals that limited number of investigations have been done on R-404A vapor condensation. Salimpour and Yarmohammadi [13,14] experimentally examined the pressure drop and heat transfer coefficient of condensing R-404A inside twisted tape inserted tubes. They developed an empirical correlation to predict the pressure drop. Infante Ferreira et al. [15] experimentally investigated the condensing heat transfer coefficient and flow characteristics of R-404A inside smooth, micro-fin and cross-hatched horizontal tubes. They have also proposed modified correlations for the condensation heat transfer coefficient. Sapali and Patil [16] experimentally studied the condensing heat transfer coefficient of HFC-134a and R-404A inside smooth and micro-fin tubes for various condensing temperatures, with superheating and sub cooling. The results showed that the heat transfer coefficient for R-404A is lower than that of R-134a. New correlations for predicting heat transfer coefficient were proposed. Patil and Sapali [17] experimentally investigated the condensing pressure drop of HFC-134a and R-404A in smooth and micro-fin U-tubes for various average saturated condensing temperatures, ranging from 35 °C to 60 °C. The reported average frictional pressure drop of HFC-134a and R-404A for the micro-fin-tubes were 1–1.7 and 1–2.1 times larger than that in the smooth tube, respectively.

Using heat transfer enhancement methods increases both heat transfer coefficient and pressure drop. Then, in performance evaluation of the enhancement methods, it is necessary to consider both heat transfer enhancement and pressure loss simultaneously. Agrawal and Varma [18] proposed the rate of pumping power to enhanced heat transfer rate to be used as the evaluation criterion. Salimpour and Yarmohammadi [14] proposed the direct evaluation of energy effectiveness criterion proposed by Charun [19]. In order to evaluate the performance of heat transfer enhancement methods, heat transfer coefficient and pressure drop are considered as the main objective functions. Since mentioned objectives are conflicting, finding the best set of operational conditions, which results in optimum objective functions, is a multi-objective optimization problem. Therefore, there is no single optimal solution which is the best regarding all the objective functions. Instead, there is a set of optimal solutions, known as Pareto front or Pareto optimal solutions [20]. Several multi-objective evolutionary algorithms have been developed, including non-dominated sorting genetic algorithm, NSGA [20], and fast non-dominated sorting genetic algorithm, NSGA-II [21–26].

Artificial neural network is one of the developed techniques, which are utilized to predict the behavior of linear or non-linear input–output data without requiring the explicit mathematical representations [27–30].

Literature review reveals that the condensing pressure drop and heat transfer coefficient of R-404A vapor flowing through corrugated tubes are not reported in the previous studies. In the present study the condensing heat transfer coefficient and pressure drop of R-404A flowing through the plain and corrugated tubes are experimentally investigated. The effects of vapor quality, refrigerant mass velocity and tube geometry are discussed. The experimental data are validated with some available correlations. New empirical correlations are developed to predict the pressure