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Experimental investigation on heat transfer and fluid friction correlations for circular tubes with coiled-wire inserts☆

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ABSTRACT

Heat transfer and pressure drop data for air flow and water flow in smooth tubes with coiled-wire inserts were measured. The wire diameter-to-tube inner diameter ratio (e/d) and coil pitch-to-tube inner diameter ratio (p/d) are in the ranges of 0.0725 to 0.134 and 1.304 to 2.319 respectively. It is found that the Nusselt number (Nu) increases with the e/d value, whereas it increases with a decrease of the p/d value. As air is the working fluid, the dependence of the heat transfer enhancement of the wire coil on the Reynolds number (Re) is minor; as water is the working fluid, the heat transfer enhancement considerably decreases with an increase of the Re value. Two heat transfer empirical equations, one for air and the other for water, are proposed. For both air and water, a common fluid friction empirical equation is established. To effectively and efficiently enhance the heat transfer, for air, the proposed e/d and p/d values of the wire coil are 0.101 and 2.319, respectively; for water, the proposed e/d and p/d values are 0.101 and 1.739, respectively.

1. Introduction

It is known that the convection heat transfer rate in a circular tube can be effectively increased by a coiled-wire insert [1–3]. For upgrading the performance of an existing vapor-compression type chiller under the condition without replacing its components, this heat transfer enhancement technique is especially useful. Inserting wire coils into the circular tubes in the evaporator and condenser of the chiller increases the overall heat transfer coefficients of the two components. At a fixed cooling load, this enables the evaporating temperature of the refrigerant to be raised and the condensation temperature to be lowered. Consequently the power consumption of the compressor is decreased.

In the past few decades, much work had been done on the heat transfer enhancement in circular tubes. Garcia et al. [4,5] presented heat transfer and fluid friction data for low Reynolds number flows ($Re < 2500$) in circular tubes with coiled-wire inserts. They also compared heat transfer performance of circular tubes inserted with wire coils to those of corrugated tubes and dimpled tubes. Saha [6] measured heat transfer and fluid friction data for an oil flow ($195 < Pr < 528$) in square and rectangular tubes with transverse ribs and coiled-wire insert. Kim et al. [7] showed flow pattern of a two-phase flow in a circular tube inserted with wire coils. Naphon [8] measured heat transfer and fluid friction data for flows in annuli inserted with wire coils. Won and Ligrani [9] analyzed heat transfer characteristics and flow structure in rectangular channels installed with two different turbulators. Promvonge [10] compared heat transfer performance of circular tubes with square cross sectional coiled-wire inserts to that with circular cross sectional coiled-wire inserts. Gunes et al. [11] investigated heat transfer enhancement of equilateral-triangle cross sectional coiled-wire inserts in a circular tube. Promvonge et al. [12] proposed a vortex ring device for enhancing heat transfer in circular tubes. Bali and Sarac [13] explored decaying of a swirling flow in a circular tube with vortex generators. Junkhan et al. [14] investigated the effect of three different turbulators on the convection heat transfer in circular tubes. Royal and Bergles [15] compared heat transfer performance of circular tubes with twisted-tape inserts to that with internal fins. Garcia et al. [16] measured heat transfer data for laminar, transition, and turbulent flows in circular tubes with coiled-wire inserts. Reddy and Rao [17] presented heat transfer and fluid friction data for an ethylene glycol-water solution with TiO_2 nanofluid additive flowing through a double pipe with/without coiled-wire insert. Saeedinia et al. [18] showed the combined effect of wire coil and nanofluid additive on the convection heat transfer in a circular tube. Sandhu et al. [19] investigated the effects of tube inclination angle and different insert devices on the heat transfer performance of a flat-plate solar collector. San and Huang [20] presented heat transfer and fluid friction data for air flow in circular tubes with internal transverse ribs. Huang and San [21] showed that boiling heat transfer characteristics of a circular tube with a fin-module insert is superior to that with internal helical threads.

Many heat transfer and fluid friction data for circular tubes with coiled-wire inserts can be found in the literature. A comparison of the experimental conditions arranged in these work is shown in Table 1. Overall, these experimental conditions are quite scattered. In addition, the forms of some correlation equations using for presenting the heat

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Nomenclature

A_s	inner surface area, m^2
c_p	specific heat, J/kg-K
d_i	inner diameter, mm
d_o	outer diameter, mm
e	wire diameter, mm
f	Darcy friction factor $[\Delta P/(L/D)(\rho U^2/2)]$
h	convection heat transfer coefficient, W/m^2-K
k	thermal conductivity of fluid, W/m-K
k_c	thermal conductivity of copper, W/m-K
L	effective heating length of test tube, m
$\dot{m}$	mass flowrate, kg/s
Nu	Nusselt number (hd/k)
p	pitch of wire coil, mm
ΔP	pressure drop, mm-H2O or Pa
Re	Reynolds number $(\rho Ud/\mu)$
r_1	heat transfer (Nu) enhancement index (Nu/Nu_o)
r_2	mechanical energy consumption index $[(Nu/f)/(Nu_o/f_o)]$
$T_{w,i}$	inner surface temperature, °C
$T_{w,o}$	outer surface temperature, °C
T_i	inlet temperature of working fluid, °C
T_e	outlet temperature of working fluid, °C
T_{s1}	inlet temperature of heating fluid, °C
T_{s2}	outlet temperature of heating fluid, °C
$T_{m,inner}$	average temperature of working fluid, °C
$T_{m,outer}$	average temperature of heating fluid, °C
U	average velocity, m/s
$\dot{V}$	volumetric flowrate, m^3/s

Greek symbols

μ	kinematic viscosity, kg/m-s
ρ	density, kg/m^3

Subscripts

o	tube without coiled-wire insert

transfer and fluid friction data are complex. This often causes inconvenience and uncertainty in an engineering design. Hence, to facilitate the applications of this heat transfer enhancement technique, establishing complete heat transfer and fluid friction data and presenting these data in simple correlation forms are important. In this work, heat transfer and fluid friction data for circular tubes with various coiled-wire inserts were measured. Nine wire coils with different wire diameters (e = 1, 1.4 and 1.8 mm) and coil pitches (p = 18, 24 and 32 mm) were selected as the inserts. The wire coils slightly differ in coil outer diameter. For obtaining a tight fit between the wire coils and the tubes, three smooth copper tubes with different inner diameters (d = 12.8, 13.4 and 13.8 mm) were individually used to match up with the wire coils. The effective heat transfer length of all the tubes is 1.07 m (Fig. 1).

2. Evaluation of Nusselt number and definitions of performance indexes

As a flow passes through a tube with isothermal wall, the average Nusselt number (Nu) between the flow and the wall can be evaluated using the following equation [22]

$$Nu = h_i d_i/k = \left(\frac{\dot{m}\, c_p}{\pi k L}\right) \ln\left(\frac{T_{w,i}-T_i}{T_{w,i}-T_e}\right). \tag{1}$$

The Darcy friction factor (f) can be evaluated as [22]

$$f = \Delta P/\left[(L/d_i)\left(\rho U^2/2\right)\right]. \tag{2}$$

Eqs. (1) and (2) were used to evaluate the Nu and f values for the tubes with/without coiled-wire inserts. In addition to the Nu and f value, two performance indexes (r_1 and r_2) were used to compare the heat transfer performance of the tubes with coiled-wire inserts to that of a tube without coiled-wire insert. The Nu enhancement index (r_1) is defined as the Nu value of a tube with a coiled-wire insert divided by that without the insert (Nu_o), while the mechanical energy consumption index (r_2) is defined as the Nu/f value of the tube with the insert divided by that without the insert (Nu_o/f_o).

3. Experimental setup and evaluation of tube wall temperature

3.1. Experimental setup

The main component in the experimental measuring system is a double-pipe device (Fig. 2a and b). The inner tube of the double pipe is the test tube, while the outer tube is a stainless steel tube with inner diameter of 22.3 mm and wall thickness of 1.8 mm. In the heat transfer measurement, four T-type thermocouples with wire diameter of 0.1 mm were used to measure the fluid temperatures at the inlet and outlet of the test tube and the annulus respectively. Two different approaches, one for air (Fig. 2a) and the other for water (Fig. 2b), were arranged to acquire the heat transfer data. As air is the working fluid in the test tube, hot water at 80 °C is the heating fluid in the

Table 1
A comparison of experimental conditions in previous work.

Investigators	Tube geometry	Re	Pr	Fluid
Ravigururajan and Bergles [1]	e/d = 0.024–0.047 p/d = 0.603–1.12	6000–25,000	0.7	Heating of air
Uttarwar and Raja Rao [2]	e/d = 0.0794, 0.135 p/d = 0.397–2.619	30–700	300–675	Heating of oil
Akhavan-Behabadi et al. [3]	e/d = 0.0768, 0.134 p/d = 0.461–2.65	10–1500	120–300	Heating of oil
Garcia et al. [4]	e/d = 0.076 p/d = 1.25–3.37	10–2500	200–700	Heating of propylene glycol
Naphon [8]	e/d = 0.112 p/d =0.357, 0.57	5000–25,000	~3	Cooling of water
Gunes et al. [11]	e/d = 0.0714, 0.0892 p/d = 1–3	3500–27,000	0.7	Heating of air
Garcia et al. [16]	e/d = 0.074–0.101 p/d = 1.17–2.68	80–90,000	2.8–150	Heating of propylene glycol-water solution
Reddy and Rao [17]	e/d = 0.246 p/d = 1, 2.5	4000–15,000	24.5–32.9	Heating of ethylene glycol-water solution with TiO2 additive
Saeedinia et al. [18]	e/d = 0.064–0.107 p/d = 1.79–2.5	10–120	–	Heating of oil with CuO additive