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Experimental thermal and flow characteristics in a traverse corrugated tube fitted with regularly spaced modified wire coils

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ABSTRACT

The work presents experimental investigations on turbulent thermal and flow characteristics in a traverse corrugated tube (TCT) fitted with regularly spaced wire coils with gradually varying width (WCs-GVW). The experiments were performed in the TCT with WCs-GVW having constant heat flux conditions at Re = 6000 to 18000 by using air as working fluid. The goal motivated by this compound heat transfer enhancement technology was to induce transverse vortices by ribs and to generate swirl flows by WCs, aimed to impart flow separation and reattachment and flow mixing, and hence improvement in heat transfer. Three arrangements including the diverging arrangement of WCs (DWC), the converging arrangement of WCs (CWC) and the diverging and converging arrangement of WCs (DCWC) and five space ratios at S/D = 0.60, 1.55, 2.97, 5.34 and 10.09 were considered. Effects of those parameters on Nusselt number (Nu), friction factor (f), performance evaluation criterion (PEC), Bejan number (Be) and augmented entropy generation number (φ_s) were analyzed. The main findings are that the CWC arrangement possesses the lowest PEC and the Nu and f in the DWC arrangement increase with decreasing the space ratio. In contrast to the plain tube, the Nu in the TCT with WCs-GVW increases nearly 1.74 to 2.26 times while the f is in a range of about 4.18–10.68 times. The obtained results show that the maximum PEC of about 1.13 is achieved by the WCs-GVW with DWC arrangement at S/D = 10.09 and Re = 14102. However, all compound ones exhibit lower PEC values than the alone use of the TCT. In addition, it is found that the Be in the baseline of the plain tube is decreased via the employment of the alone TCT or co-use of the TCT and WCs-GVW, nevertheless, the total entropy production is dominated by the entropy production due to heat transfer under considered parameters. The φ_s in the plain tube is reduced to be less than unity by using the enhanced devices indicates the thermodynamic advantage of those TCT and TCT/WCs-GVW, and the lowest φ_s of about 0.5 is gained by utilizing the WCs-GVW with DWC arrangement at S/D = 0.60 and Re = 6517. At last, the empirical formulas of the investigated TCT and TCT/WCs-GVW in terms of Nu and f are proposed.

1. Introduction

Heat exchangers hold widely applications in many fields, such as power and thermal engineering, chemical engineering, nuclear power thermal utilization, solar energy thermal transfer and etc. Due to increasingly urgent energy crisis, the technologies focusing on improvement of heat transfer efficiency in heat exchangers are always hot issues nowadays from both environmental and economical viewpoints. The heat transfer enhancement technology to develop less expensive and more compact heat exchangers can be employed to realize this objective of saving energy. It can be classified in to active one and passive one, depending on whether extra power being needed for the enhancement process or not [1]. Since no extra power is required, the passive one can be implemented by mainly using rough surfaces [2], extended surfaces [3], additives [4,5], inserts [6,7] and etc. in heat transfer enhancement of tube/duct/channel flow. Among the family of the passive heat transfer enhancement technologies, one of the efficient way to achieve this goal is the wire coil (WC) which possesses merits of reducing equipment investment and decreasing volume size compared with its counterpart of the plain tube. It is achievable and advantageous

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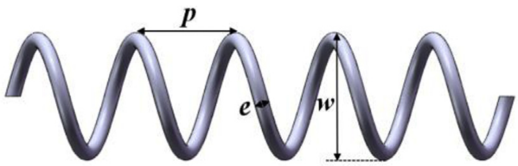

Fig. 1. Main geometric parameters for a typical wire coil.

in conducting heat transfer augment due to its low cost, easy fabrication and convenient maintenance, which attracts attentions in new heat exchanger design and old heat exchanger retrofit [1,8].

As illustrated in Fig. 1, dimensionless pitch p/d, dimensionless wire diameter e/d or pitch to wire diameter ratio p/e, width w, varied wire cross-section and changing pitch length are generally interesting factors in geometric parameter investigations for a typical WC.

In earlier years, experiments on thermal-hydraulic characteristics, vortex shedding frequency and pressure fluctuation amplitude in vortex, as well as the relationship between entropy generation and vortex characteristics in a inserted typical WCs tube were carried out by Yakut and Sahin [9] to evaluate the WC heat transfer enhancement technology under various criteria. Next, Naphon [10] investigated the influences of p/d and cold/hot water mass flow rates on heat transfer and frictional losses in a horizontal double pipe with typical WCs. A more comprehensive study involved with the analysis of Re, e/d, p/d and Pr on thermal-hydraulic performances in typical WCs was conducted by García et al. [11], using water and water-propylene glycol mixtures as working fluids. In their results, the transition of laminar flow to turbulent flow was found at $Re \approx 700$. In order to clarify the heat transfer enhancement and fluid flow mechanisms, García et al. [12] employed the hydrogen bubble visualization and PIV techniques to visualize the flow patterns in tubes inserted with typical WCs and observed that the flow structures were dominated by turbulence promotion, secondary flow promotion and hydraulic diameter reduction. Moreover, heat transfer performance and pressure drop in tubes with WCs under laminar and transitional flow were also experimentally examined by García et al. [13]. In their study, a smooth transition from laminar flow to turbulent flow was observed in the absence of the phenomenon of pressure drop fluctuations and flow instabilities that a plain tube behaved, and remarkably increased heat transfer could be obtained at $Re = 200$–1000.

In order to further improve heat transfer rate or enhance overall thermal performance at the constant pump power, there are much effort on investigating various types, arrangements and applications of WCs, which have been conducted in different tubes/ducts/channels under laminar/transitional/turbulent by utilizing water/air/oil/nanofluids as working fluids. In terms of that reported in WCs with varying types, a large amount of researchers engaged themselves in studies about this issue, including the works [14–20] aim to extend and cover WCs with more wide ranges of geometric parameters under different operating conditions and working fluids, the studies on WCs with periodically varying pitch ratios [21], the combined employment of wire coils with twisted tapes [22,23] or with a snail-type swirl generator [24], the simultaneous utilization of WCs with nanofluids [25–30], the co-use of WCs and transverse ribs [31,32], the use of WCs along with micro-fin tube [33] and the modified WCs with equilateral triangular cross section [34–37] or with square cross section [38,39]. As far as WCs arrangements were concerned, for instance, the effect of tandem wire coils at different lengths and free space ratios on heat transfer and frictional losses in a square channel [40], the numerical studies involved with the influence of varying outer diameters on convective heat transfer in a double WCs inserted tube [41] and the investigation of numbers and incline angles on thermo-hydraulic performance in a WCs inserted tube [42] were reported previously. Apart from the utilization in single convective heat transfer process in the above mentioned review, the WCs also hold wide applications in other fields, such as the evaporation [43,44] and condensation [45] heat transfer, the gas-liquid flow heat transfer [46], flow boiling heat transfer [47], the car radiator [48], the city gas stations [49], the oscillatory baffled reactors [50], the rectangular microchannel heat sink [51] and the flat-plate solar water collector [52,53].

As summed from the above review, it is proved that the WCs family has efficient heat transfer performance in various thermal applications. Despite many types or arrangements in WCs investigated by previous studies, no work has been performed to examine the turbulent heat transfer and flow characteristics in a traverse corrugated tube (TCT) fitted with regularly spaced WCs with gradually varying width (WCs-GVW). In this work, one aim in employing this compound heat transfer enhancement technology was to investigate the effects of WC arrangement directions and space ratios (or number) on the heat transfer and flow behaviors. The driven tubular air through the TCT with WCs-GVW at three arrangement directions (DWC, CWC and DCWC) and five space ratios ($S/D = 0.60$, 1.55, 2.97, 5.34 and 10.09) have been investigated at $Re = 6000$ to 18000 under constant heat flux conditions. The other goal of the present study was to reveal the tendencies of entropy production characteristics versus varying parameters. In addition, the thermal-hydraulic correlations in terms of Nu and f were developed.

2. Geometric parameters

Fig. 2 shows the photograph of a traverse corrugated tube (TCT), and the photographs and arrangements of wire coils with gradually varying width (WCs-GVW) are respectively presented in Figs. 3 and 4. A plain tube with material of 304 stainless steel was employed to verify the experiment rig and selected as a baseline. The length, inner diameter and wall thickness for the plain tube were about 1650 mm, 29 mm and 1.5 mm, respectively. A TCT, also machined by 304 stainless steel, with rib height ratio h/D of 0.034 and rib pitch ratio p'/D of 1.103, was fabricated to improve heat transfer. The WCs-GVW manufactured from circular cross-section carbon steel with gradually varying width were constructed to insert into the TCT to investigate tubular thermo-hydraulic performance. In the WCs-GVW, the pitch length p/e was varied from about 8.75 to 5.625 from one end to the other end. As presented in Fig. 4, the WC turbulators were placed into the TCT with three arrangements: 1) diverging arrangement of WCs (DWC), 2) converging arrangement of WCs (CWC) and 3) diverging and converging arrangement of WCs (DCWC). The coil length L and coil width $W1$ and $W2$ were respectively around 120 mm, 14 mm and 24 mm. In addition, for WCs-GVW with DWC, different number ranged from 12 to 4, i.e., five space ratios S/D of about 0.60, 1.55, 2.97, 5.34 and 10.09 were compared.

3. Experimental setup

Schematic diagram and photographs of the experimental facility are illustrated in Fig. 5. The experimental rig consists of a filter, a calming inlet section, a test section, a differential pressure transducer, a mixer, a vortex street flow meter, a ampere meter, a voltage meter, a voltage stabilizer, a voltage regulator, a blower and an instrument cabinet, an Agilent 34972A data logger and a computer. The tested tubes were heated by continually winding flexible electrical wires (Cr20Ni80,

Fig. 2. Photograph of the TCT.