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Numerical study on heat transfer and flow characteristics of a tube fitted with double spiral spring

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A B S T R A C T

Heat transfer and friction loss characteristics of a plain tube fitted with double spiral spring (DSS) are investigated by a three dimensional numerical simulation. The outer diameters of the DSS are 9 mm, 12 mm, 15 mm, and 18 mm, respectively. The simulation results indicate that the fluid in the tube inserted with DSS shows three-dimensional helical flow, and that the circumferential and the radial velocity of fluid near the tube wall are improved. At the same Reynolds number, the average radial and tangential velocities of the DSS tube are significantly higher than those of the plain tube. The Nusselt number increases and the friction factor decreases in tube with DSS insert as the Reynolds number increases. With the increase of the d_s/D of DSS, the friction factor becomes higher. The field synergy principle (FSP) and entransy dissipation extremum principle (EDEP) analysis provide a reliable criterion for exploring the mechanism of heat transfer enhancement. The field synergy number of the tube inserted with DSS is much higher than that of plain tube, which indicates effective improvement of flow and heat transfer by inserted DSS. Meanwhile, the value of performance evaluation criterion (PEC) could be up to 1.5.

1. Introduction

Shell-and-tube heat exchanger is indispensable equipment for heat transfer. It is extensively applied in numerous fields such as power generation, chemical industry, petrochemical industry, refrigeration, air-conditioning et al. [1-8]. In the heat exchanger, heat is transferred from the warm fluid to the cold fluid via the solid walls. An increase in the heat transfer coefficient often leads to a higher flow resistance, thereby reducing energy efficiency. The main challenges of heat exchanger design are to minimize the flow resistance as well as enhance the heat transfer performance.

The heat transfer enhancement in the tube side is usually prominent for the improvement of overall performance of heat exchangers. A variety of tube inserts have been applied for the tube side enhancement [9-12]. Recent research [13-15] on heat transfer enhancement in heat exchanger with tube inserts has been extensively reported. In the past years, the spiral spring inserts are widely used in heat exchangers to enhance the heat transfer. This could be attributed to the stable performance of the spiral spring. In addition, its manufacturing process is simple and low-cost and it is easy to install and disassemble.

Table 1 summarizes some previous studies in forced convection heat transfer in spiral spring insert heat exchangers. Although the structure of helical spring was proposed several decades ago, many researchers still employ this structure in their studies on heat transfer augmentation. The key geometrical properties of the spiral spring and the data are selectively reported. Naphon [16] experimentally studied the heat transfer characteristics and the pressure drop of a horizontal double tube with coil wire insert, the results indicated that the coil wire insert has significant effects on the enhancement of heat transfer especially in laminar flow region. Eren et al. [17] experimentally proposed a tube with inclined coil springs inserted. It was found that the incline angle has a major effect on heat transfer and friction loss while spring number has the minor effect. Gunes et al. [18] experimentally investigated the heat transfer and pressure drop in a coiled wire inserted tube. The result showed that the Nusselt number increases with the increase of Reynolds number and wire thickness and the decrease of pitch ratio. Jafari et al. [19] experimentally investigated the effects of four types of wire coil inserts on heat transfer enhancement and pressure drop by using artificial neural network analysis. It was found

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that the mean relative errors between the predicted result and experimental data are less than 1.79% for Nusselt numbers and less than 3.27% for friction factor. Promvonge [20] experimentally studied the heat transfer and turbulent flow friction characteristics of the tube fitted with coiled square wires. The experimental results revealed that the Nusselt number increases with the rise of Reynolds number and with the reduction of pitch for both circular and square wire coils.

Following the pervious researches, Gunes et al. [21] further experimentally studied the heat transfer and pressure drop in a tube with coiled wire inserts placed separately from the tube wall. The results showed that the Nusselt number and friction factor increase with decreasing pitch ratio and distance for coiled wire inserts. Xing et al. [22] investigated the heat transfer, flow resistance and rotating characteristics of the inserted spring rotors in circular tube. The results indicated that the heat transfer increases by 30% and the friction resistance increases fivefold compared to those of plain tubes. Wu [23] investigated the rotation and overall performance of heat exchanger tube with rotary spring inserted. The results showed that the increasing ratio of the total heat transfer coefficient is between 3.17% and 42.05% and the friction factor is a multiple of 1.52–4.46 compared with plain tube, respectively. It was found that the rotary spring has much lower friction factor compared with the stationary spring.

In addition, in the aspect of numerical simulation, Munoz-Esparza and Sanmiguel-Rojas [24] studied the laminar flow in pipes with wire coil inserts. It showed that the friction factor decreases with the increase of the non-dimensional *p/D*. Solano et al. [25] investigated the flow pattern and heat transfer enhancement in oscillatory baffled reactors with helical coil inserts. The results showed that the heat transfer for the helical baffled tube could be enhanced by a factor of four compared to the plain tube in the tested range of oscillation conditions.

As mentioned above, the thermal improvements are always coupled with an increased pressure drop. To optimize the overall thermal hydraulic performance of the tube fitted with spiral spring, a large amount of researchers have made improvements or modifications on the conventional spiral spring to achieve an anticipated heat transfer rate in an existing heat exchanger at an economic pumping power. However, to the best of the authors' knowledge, the heat transfer characteristics and pressure drop in the tube with double spiral spring (hereafter referred to as DSS) insert have rarely been reported. In the present study, the main focus is the numerical study on the heat transfer characteristics and pressure drop of the tube with DSS insert. The effects of various relevant parameters and outer diameter of DSS are also investigated. Additionally, the results obtained from the tube with DSS insert are compared to the plain tube and the tube with single spiral spring (hereafter referred to as SSS). In order to comprehensively evaluate the overall thermal hydrodynamic performance of different enhancement techniques, the performance evaluation criteria (hereafter referred to as PEC) are employed. In summary, the main objective of the present work is to explain the mechanism of heat transfer enhancement for tubes fitted with DSS inserts from the angle of field synergy principle (hereafter referred to as FSP) and entransy dissipation extremum principle (hereafter referred to as EDEP).

2. Numerical simulation

2.1. Physical model

The physical model of a plain tube with DSS is shown in Fig. 1. The calculation parameters are listed in Table 2.

Table 1
The summarized research results of spiral spring.

Authors	Working fluid	Condition	Configuration	Correlations
Naphon [16].	Water	$5000 \le Re \le 25{,}000$ $Pr > 3$	$p/D = 0.356–0.57$ $e/D = 0.112$	$Nu = 0.156\mathrm{Re}^{0.512}\mathrm{Pr}^{1/3}(p/d_s)^{0.253} f = 322.2(\ln Re)^{-1.849}(p/d_s)^{0.061}$
Eren et al. [17].	Water	$2500 \le Re \le 12{,}000$ $Pr = 0.7$	$d_s/D = 0.12–0.216$	$Nu = 0.023\mathrm{Re}^{0.83}\mathrm{Pr}^{0.4}\xi^{-1.64}(1+\tan\theta)^{0.93} f = 210.767\mathrm{Re}^{-1.4}\xi^{-3.26}(1+\tan\theta)^{1.82}$
Gunes et al. [18].	Air	$3500 \le Re \le 27{,}000$	$p/D = 1–3$ $e/D = 0.0714–0.0892$	$Nu = 0.598417\mathrm{Re}^{0.745064}(p/D)^{-0.268374}(a/D)^{0.813205}\mathrm{Pr}^{0.39}$ $f = 83.70924\mathrm{Re}^{-0.305268}(p/D)^{-0.388}(a/D)^{1.319018}$
Jafari et al. [19].	Air	$3500 \le Re \le 27{,}000$	$p/d_s = 0.156–0.354$ $e/d_s = 0.027–0.094$	$Nu = 1.2877\mathrm{Re}^{0.4515}\mathrm{Pr}^{0.6876}(p/d_s)^{-0.2565}(e/d_s)^{0.2865}$ $f = 3.2348\mathrm{Re}^{-0.3904}(p/d_s)^{-0.2565}(e/d_s)^{0.1674}$
Promvonge [20].	Air	$5000 \le Re \le 25{,}000$	$p/d_s = 15–47.5$	–
Gunes et al. [21].	Air	$4105 \le Re \le 26{,}420$	$p/d_s = 1–3$, $s = 1–2$	$Nu = 0.077156\mathrm{Re}^{0.716692}\mathrm{Pr}^{0.4}(p/D)^{-0.253417}(s/D)^{-0.124382}$ $f = 3.970492\mathrm{Re}^{-0.367485}(p/D)^{-0.31182}(s/D)^{-0.157719}$
Xing et al. [22].	Water	$10{,}000 \le Re \le 90{,}000$	$p/d_s = 3$, $e/d_s = 0.2$	
Wu [23].	Water	$10{,}000 \le Re \le 100{,}000$	$p/d_s = 1–1.5$ $d_s/D = 0.45–0.83$ $e/d_s = 0.035–0.06$	$Nu = 0.1015\mathrm{Re}^{0.7852}\mathrm{Pr}^{1/3}(e/D)^{0.2573}(p/D)^{-0.3311}(d_s/D)^{0.1656}(\mu/\mu_w)^{0.14}$ $f = 24.7511\mathrm{Re}^{-0.3764}(e/D)^{-0.514}(p/D)^{-0.7972}(ds/D)^{0.4508}$
Munoz-Esparza and Rojas [24].	Propyleneglycol	$50 \le Re \le 550$	$p/d_s = 1.5–4.5$ $e/d_s = 0.074$	–
Solano et al. [25].	Water	$10 \le Re \le 320$	$p/d_s = 1.5$ $e/d_s = 0.24$	–