J Ther Eng, Vol. 7, No. 7, pp. 1683–1693, November, 2021

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/jten.2021.0006

Research Article

# Numerical comparison study on heat transfer enhancement of different cross-section wire coils insert with varying pitches in a duct

**Taha Tuna GÖKSU[1,*], Fuat YILMAZ[2]**

[1]*Department of Mechanical Engineering, Adiyaman University, Adiyaman, Turkey*
[2]*Department of Mechanical Engineering, Gaziantep University, Gaziantep, Turkey*

## ARTICLE INFO

*Article history*
Received: 14 February 2020
Accepted: 07 April 2020

**Key words:**
Fluent; Thermo-hydraulic; Friction; PEC; Wire coil

## ABSTRACT

Heat transfer enhancement (HTE) efforts spent during the last half-century have become one of the most important working areas of researchers from both academia and industry. One of the most popular passive methods, with regard to the price-performance ratio, is to place wire coils in a pipe or duct. In this study, the heat and pressure drop characteristics of diamond, triangular, and circular cross-sectional wire coils (DWC, TWC, and CWC) in a square duct were investigated by using the FLUENT program. In addition to the cross-section examination, the thermo-hydraulic behavior of three different pitches (p = 54, 72, and 90 mm) for the specified geometries were also investigated. The Reynolds number was between 4387 and 18,415. The square duct was 1.25 m in length, and was 18 mm in diameter. The results showed that the Nusselt number of CWC, TWC, and DWC were higher than that of a smooth pipe within 38–88%, 37–93%, and 38–98% range, respectively. The friction of CWC, TWC, and DWC was observed to be higher than that of a plain tube within a range of 87–278%, 82–266%, and 107–366%, respectively. The TWC with 90 mm pitch showed the highest heat transfer performance evaluation criteria (PEC) with a performance coefficient of 1.3 at Reynolds number of 4504, whereas the DWC with 54 mm pitch was observed to show the lowest PEC. Thus, the as-obtained PEC, which is 30% higher than that of a plain tube, indicates the prominence and effectiveness of the numerical study in increasing the heat transfer.

**Cite this article as:** Göksu TT, Yilmaz F. Numerical comparison study on heat transfer enhancement of different cross-section wire coils insert with varying pitches in a duct. J Ther Eng 2021;7(7):1683–1693.

***Corresponding author.**
*E-mail address: tgoksu@adiyaman.edu.tr, taha_022@hotmail.com

*This paper was recommended for publication in revised form by Regional Editor Liu Yang*

Published by Yıldız Technical University Press, İstanbul, Turkey

## INTRODUCTION

Heat exchangers are widely used in industry to cool or heat a system. The performance of heat exchangers has been improved with different enhancement techniques. Here, one of the most popular and cost-effective technique is the passive technique. This method uses either a wire coil (WC) installation or twisted tape-type elements in the pipe. This method aims to increase performance evaluation criteria by affecting the thermal and flow areas by using a wire coil (WC) or twisted band or ring turbulators in a pipe. Placing external elements in a heat exchanger system is the most common method used in passive technique. WCs are one of the popular passive methods and its effectiveness in the circular tube has been well researched in the literature. In this context, many parameters of the installed WC are examined. Some of these parameters include the pitch ratio, the cross-section and geometry of the wire, and the use of different working fluids such as nanofluid types. To place external elements in the system is the most common method used in passive technique. In this context, many parameters of the placed WC should be examined. Some of these parameters can be listed as follows: pitch ratio, cross-section, and variation of geometry, and the use of different fluids such as nanofluid.

Garcia et al. [1] experimentally examined the effect of WC insertion on HTE within 80 to 90,000 Reynolds number range. Here, the WC's pitch ratio (p/D) was in the range of 1.17–2.68, and its helical pitch diameter (e) was 1 mm. The results of this study showed that, compared to that of a straight pipe, the WC's pressure drop increased about nine times, and its heat transfer was observed to increase four times. Garcia et al. [2] also experimentally studied the effect of WC's pitch ratio on HTE within 10 to 2500 Reynolds number range. According to the as-obtained results of this study, the heat transfer increased eight times compared to the straight pipe. Behabadi et al. [3] examined the effect of WC's pitch, within 12–69 mm range, on heat transfer. Here, WCs with 2 and 3 mm diameters were placed separately. In terms of heat transfer, when the WC with 65 mm pitch and 2 mm wire diameter selected for HTE, the lowest fanning friction factor was observed in comparison with the other inserts for the same order of enhancement. Garcia et al. [4] experimentally examined the heat transfer behavior of artificial roughness with corrugated and dimpled tubes, and WCs. Here, the artificial roughness was observed to show better pressure drop characteristics than the others.

Nanan et al. [5] examined the HTE effect of wire-rod bundles. The experiments were performed with three distinct pitch ratios (p/D = 1, 1.5, and 2), and three wire-rod numbers per bundle (4, 6, and 8). According to the results, the PEC increased with decreasing Reynolds number and pitch ratio. In addition, PEC showed an increase with the number of wire-rods per bunch.

San et al. [6] reported that the Nusselt number (Nu) is increased with the increasing WC diameter divided by pipe diameter (e/d), and is decreased with p/D. Promvonge [7] reported that HTE characteristics of square cross-sectional WC was 10–20% higher than that of circular cross-sectional one. Promvonge [8] also examined the HTE effect of both square and circular cross-sectional WC insert and different pitch ratios with a snail-type swirl generator. When the snail was used alone, the PEC of snail was smaller than that of square type wire coil with snail entry. The lowest PEC observed for the circular WC with snail entry.

Gunes et al. [9] examined the thermo-hydraulic behavior of a WC insert in a horizontal pipe. The pitch ratios used in this study were p/D = 1, 2, and 3. The results of this study showed that the maximum PEC was obtained as 36.5 % for a/D of 0.0892, and p/D of 1 at low Reynolds number. Eiamsa-ard et al. [10] experimentally examined the HTE effect of the combined insert devices. These devices consisted of twisted tape (TT) and constant/periodically varying wire coil. According to the as-obtained results, the highest PEC achieved at low Reynolds number with the combination of TT and DI coil.

Promvonge and Eiamsa-ard [11] experimentally examined the conical-nozzle turbulator insert on HTE in a circular pipe. These turbulators were (1) diverging nozzle settlement (D-nozzle turbulator) and (2) converging nozzle settlement (C-nozzle turbulator). The D-nozzle insert provided better HTE than that of C-nozzle insert. The heat transfer rate of nozzle turbulators generally shows better results than that of the plain tube within 236 to 344% range. Eiamsa-ard et al. [12] experimentally examined the insertion of tandem WC in a square duct. The results of this study showed that the PEC range was between 1.24 and 1.33. According to the as-obtained results, the full-length WC should have applied 1D and 2D instead of one to obtain a higher PEC, and the highest PEC had the value of 1.33.

Gunes et al. [13] experimentally examined the HTE characteristic of equilateral triangle cross-sectioned WC insert in the pipe. Here, WC was separated from the pipe wall and the distance between the tube wall and WC was set between 1 and 2 mm. In this experimental study, three-pitch ratios (1, 2, and 3) applied in the Reynolds number range of 4105 to 26,400. Here, the testing fluid was air. According to the as-obtained results, the highest PEC obtained was 1.5 for p/D of 1 and s of 1 mm.

Abdullah and Yılmaz [14] numerically investigated the HTE effect of isosceles triangle cross-sectional WC and TT insertion. Here, the highest PEC values of 1.26 and 1.50 were achieved, respectively. Hamid et al. [15] reported that using TiO2-SiO2 nanofluid has increased the heat transfer as high as 254.4%.

Hong et al. [16] experimentally examined the HTE of a WC with uniform pitch (WCs-UP) at p/D = 0.172 – 0.690 and WCs with gradually varying width (WCs-GVW) at w/d = 0.552 – 0.897 – 0.552. The Reynolds number was within 6000 to 20,000 range. Here, the highest PEC was obtained as 1.14 for p/D of 1.034. Tusar et al. [17] investigated numerically the HTE effect of helical screw tape insert. Results showed that both Nu and f increased 1.34–2.6 times, and 3.5–8 times, respectively, than that of the plain tube. Here, the maximum PEC was achieved as 3.79.

Keklikcioğlu and Ozceyhan [18] have experimentally examined the HTE of a WC insert in pipe with three pitch ratios of 1, 2, and 3. The results of this study showed that the highest PEC was obtained as 1.67 for p/D of 1. Garcia et al. [19] experimentally examined the HTE of a WC insert in a flat-plate solar water collector. This study's results showed that the collector efficiency was increased up to 14–31% in the range of mass flow rate. The turbulator-wire insert effect on HTE in a U-bend heat exchanger was experimentally examined by Andrzejczyk et al. [20]. Here, the wire insert increased the HTE up to 280%.

Chamoli et al. [21] numerically investigated a new type of anchor-shaped inserts on HTE. According to the as-obtained results, the PEC reached 1.72 at low Reynolds numbers. Sharifi et al. [22] numerically examined the HTE of helical wire inserts in a double pipe heat exchanger. The results showed that Nusselt number has increased up to 1.77 compared to the one without the insert.

Keklikcioglu et al. [23] numerically investigated the HTE effect of stepped nozzle inserted tube. Here, the highest PEC values of 1.1 were achieved. Göksu and Yılmaz [24] numerically investigated thermohydraulic characteristic of a combined design of twisted tape with equilateral triangular cross sectional wire coil insert in a pipe. The highest heat transfer performance was achieved around 1.23. Yılmaz et al. [25] studied the effects of wire coil inserts on the thermo-hydraulic performance of a parabolic trough solar collector. Results show that the wire coil inserts can improve the overall thermal efficiency and reduce the circumferential temperature gradient on the receiver tube of the collector.

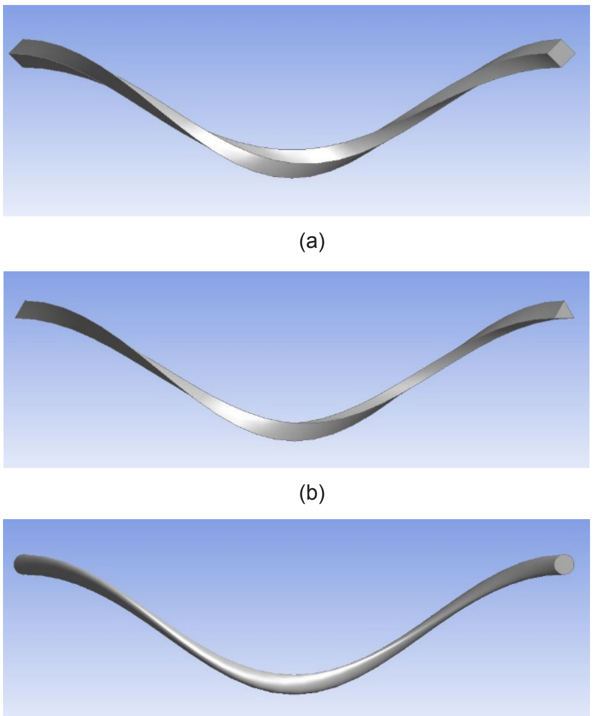
Numerous studies have been conducted on HTE with WC insert. As can be clearly seen from the literature, the effect of WC elements with different cross-sections and pitch ratios on heat transfer and pressure drop characteristics has not been numerically investigated yet. The aim of this study is to show the effect of both the cross-section and pitch on HTE. So far, three different geometries have not been studied in the same regime, which makes this study unique. Another important point of this study is to show the effect of a WC with a triangular cross-section on HTE in duct, which also has not been investigated in the literature, although its circular or square cross-sectional counterparts have. As it is also implied in the literature, the HTE is more efficient in the turbulent regime, so that this study has been carried out in a similar regime. The experimental study of Gunes et al. [13] is used to validate this study. Here, a WC element with a pitch value of 3 has been selected for validation. A similar Reynolds number range of 4000–20,000 was also used for the current study accordingly with the literature [1–25].

## GEOMETRY

The length of the square duct was 1.25 m and each side of the duct was 18 mm. Equilateral triangular cross-sectional wire coil (TWC), circular cross-sectional wire coil (CWC), and diamond type of wire coil (DWC) were inserted separately from the wall in a square duct. Each side of TWC was 2 mm, the diameter of CWC was 2 mm, and also each length of DWC was 2 mm. The distance between the duct wall and the wire coil wall was 2 mm. Figures 1a, b and c show geometry of DWC, TWC, CWC, wire coil inserted in a square duct, respectively. Three different pitches (54, 72, and 90 mm) were examined. Figure 2 shows the TWC inserted in the duct. All the drawings were drawn in ANSYS, the reason we did this is to ask that the same geometry not experience cross-sectional changes on the mesh.

### Boundary Condition

Air was used as a working fluid. The temperature of the inlet section was 25 $^{o}$C. Uniform heat flux was applied on the wall of the square duct. Reynolds number was between 4105 and 19,000 for validation and 4387 and 18,415 for



(a)

(b)

(c)

**Figure 1.** (a) Diamond cross-sectional wire coil. (b) Triangular cross-sectional wire coil. (c) Circular cross-sectional wire coil.

J Ther Eng, Vol. 7, No. 7, pp. 1683–1693, November, 2021

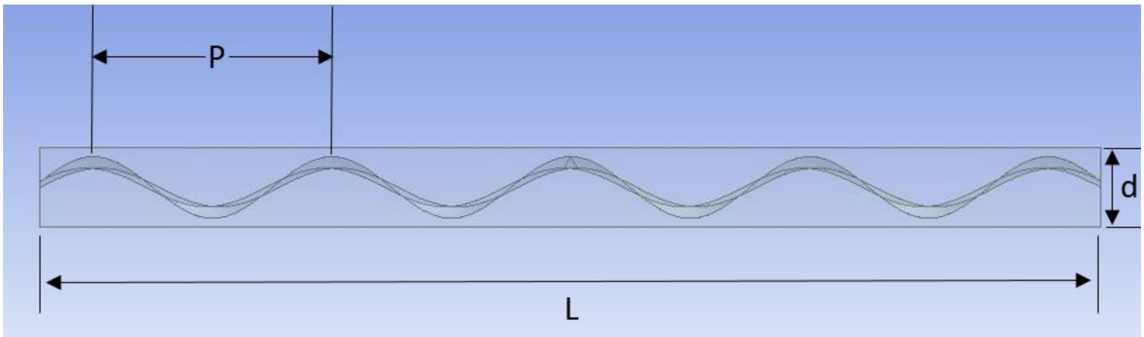



**Figure 2.** Wire coil inserted in a square duct.

DWC, TWC, and CWC type insert in the square duct, respectively.

### Numerical Solution

ANSYS FLUENT 17 was used to carry out the analysis. Pressure-based governing equations was used. RNG-k-ε turbulence solver was used. SIMPLE algorithm for pressure velocity coupling and RNG-k-ε turbulence were chosen within the Reynolds number range. The last step of the setup of fluent is the convergence criterion, $10^{-6}$ for energy, $10^{-4}$ momentum, continuity, k, and ε were selected, respectively.

### Mesh for Validation

Mesh was generated by using Ansys Meshing Module v17. Four different meshes were used for the mesh independency. The first mesh size was generated with 3535477 mesh elements. After this point, mesh elements were approximately raised up 2 times (8,937,123 mesh elements). The Nusselt number and friction deviations between 3,535,477 and 8,937,123 were equal to 1 and 5 percent, respectively. Therefore, the number of mesh elements was raised up to 13,184,499 mesh elements. The deviations between 8,937,123 and 13,184,499 were smaller than 1 percent. In this study, the element containing 8,937,123 mesh was selected for analysis. Mesh quality parameters are related with skewness and orthogonal quality. Maximum skewness and minimum orthogonal quality were obtained between 0.8–0.89, and 0.10 and 0.18, respectively. Mesh image of DWC shown in Figure 3. As clearly seen from Figure 3, the inflation thickness was quite low for getting better results.

### Mesh for Circular Cross-Sectional Wire Coil

Mesh independency is the necessary way of solution due to the deviation between results. Table 1 shows the study of mesh independency for CWC, TWC, and TWC, respectively. As clearly seen from Table 1, 8,341,116, 13,414,752, and 9,454,934 number of mesh elements were selected for 3, 4, and 5 pitch ratios in the group of CWC, respectively. 7,648,959, 7,570,517, and 6,051,072 number of mesh elements were selected for 3, 4, and 5 pitch ratios in the group of TWC, respectively. 11,596,186, 11,706,392, and 11,446,080 number of mesh elements were selected for 3, 4, and 5 pitch ratios in the group of DWC, respectively.

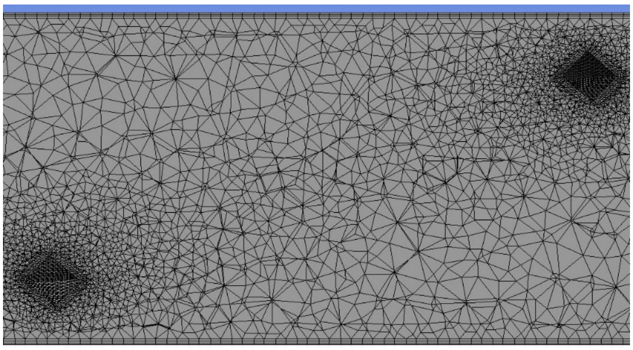


**Figure 3.** Cross-sectional mesh of DWC.

## DATA REDUCTION

In the current work, the working fluid of the experiment was air and runs were done under uniform heat flux condition. Reynolds number (Re), friction (f), and convective heat transfer coefficient (h), Nusselt number (Nu) were calculated by using equations 1, 2, 3, and 4, respectively.

$$\mathrm{Re} = \frac{\rho . U_{mean} . D_{hydraulic}}{\mu} \tag{1}$$

$$f = \frac{2.\Delta P.D}{\rho . U_{mean}{}^{2} L} \tag{2}$$

$$h = \frac{m.C_p (T_0 - T_i)}{A(T_w - T_b)} \tag{3}$$

$$Nu = \frac{h.D_{hydraulic}}{k} \tag{4}$$

**Table 1.** Mesh independency for CWC, TWC and DWC

| Mesh | Re | Nusselt Nu | Friction |
|---|---|---|---|
| **CWC for p/D=3** | | | |
| 2,498,663 | 4460.45 | 23.90083 | 0.1396 |
| 8,341,116 | 4473.04 | 23.10835 | 0.1461 |
| 10,343,793 | 4473.10 | 23.02076 | 0.1476 |
| **CWC for p/D=4** | | | |
| 4,996,657 | 4466.52 | 22.2501 | 0.11242 |
| 13,414,752 | 4469.69 | 22.0459 | 0.12018 |
| 16,736,296 | 4469.45 | 22.0576 | 0.12007 |
| **CWC for p/D=5** | | | |
| 6,965,002 | 9222.585 | 37.60862 | 0.06457 |
| 9,454,934 | 9222.957 | 37.61683 | 0.06552 |
| 14,264,885 | 9225.853 | 37.38856 | 0.06544 |
| **TWC for p/D=3** | | | |
| 4,854,852 | 4511.77 | 23.859 | 0.14149 |
| 7,648,959 | 4506.51 | 24.059 | 0.140441 |
| 11,362,117 | 4505.43 | 24.077 | 0.14001 |
| **TWC for p/D=4** | | | |
| 4,925,983 | 8235.12 | 35.297 | 0.07537 |
| 7,570,517 | 8240.4 | 34.911 | 0.07455 |
| 11,745,660 | 8240.66 | 34.927 | 0.07407 |
| **TWC for p/D=5** | | | |
| 3,982,837 | 9301.27 | 37.8863 | 0.0608 |
| 6,051,072 | 9304.53 | 37.523 | 0.06167 |
| 8,235,559 | 9307.61 | 37.4673 | 0.06195 |
| **DWC for p/D=3** | | | |
| 2,566,889 | 4390.246 | 23.8341 | 0.168 |
| 11,596,186 | 4394.125 | 23.8423 | 0.1819 |
| 20,265,672 | 4394.479 | 23.8821 | 0.1807 |
| **DWC for p/D=4** | | | |
| 7,806,020 | 8028.67 | 34.0447 | 0.08783 |
| 11,706,392 | 8029.02 | 34.1002 | 0.09058 |
| 15,802,815 | 8029.02 | 34.1668 | 0.09049 |
| **DWC for p/D=5** | | | |
| 7,674,685 | 9064.56 | 36.3237 | 0.0774 |
| 11,446,080 | 9063.91 | 36.3857 | 0.07662 |
| 14,046,612 | 9066.46 | 36.2415 | 0.07593 |

$$f = \frac{0.316}{Re^{0.25}} \tag{5}$$

Equation 5 and 2 were used for smooth pipe and wire coil inserted in pipe, respectively. Performance evaluation factor (PEC) [26] expresses the heat transfer enhancement efficiency. It was calculated by equation 6. $Nu_a$ and $Nu_0$ express the Nusselt number of wire coil insert and smooth pipe, respectively. $f_a$ and $f_0$ express the friction of the wire coil insert and smooth pipe, respectively.

$$PEC = \frac{Nu_a}{Nu_0}\left(\frac{f_a}{f_0}\right)^{1/3} \tag{6}$$

Nusselt number of smooth pipe was calculated by using Gnielinski equation (7). This equation can be written such as

$$Nu = \frac{\left(f/8\right)\left(Re-1000\right)Pr}{1+12.7\left(f/8\right)^{1/2}\left(Pr^{2/3}-1\right)} \qquad 3000 \le Re \le 5.10^{6} \tag{7}$$

## RESULTS AND DISCUSSION

### Numerical Results of Validation

In the current study, the effect of cross-section and pitch were examined with using ANSYS FLUENT. Reynolds number of the study was in the range of 4387–18415. The first step of the numerical study is validation. The reason for using validation is to compare the results of numerical with experimental. Gunes et al. [13] experimental study chosen because of the similar to the triangular wire coil. Figure 4 and 5 show the compared results of Nusselt number and friction versus Reynolds number, respectively. As a result of validation showed that the Nusselt number and friction deviation band was in the range of 2.43 to 9.56 %, 1.87 to 15.59 %, respectively. To reduce experimental errors, several assumptions adopted these assumptions comes from the Gunes et al. [13] were operated attached Teflon rings. This rings provides to fix the body of the wire coil inserted pipe.

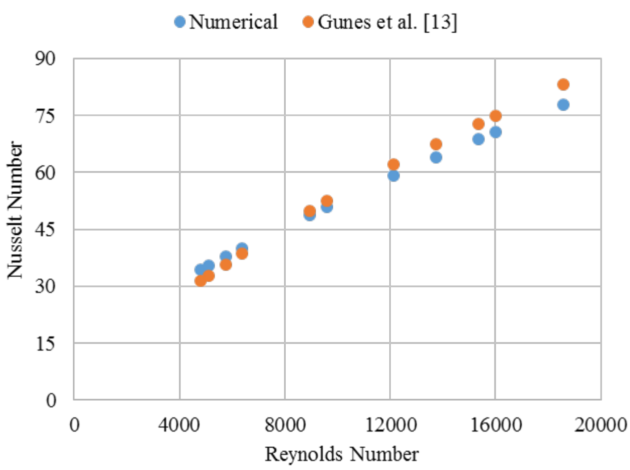



**Figure 4.** Nusselt number of numerical and Gunes et al. [13] versus Reynolds number.

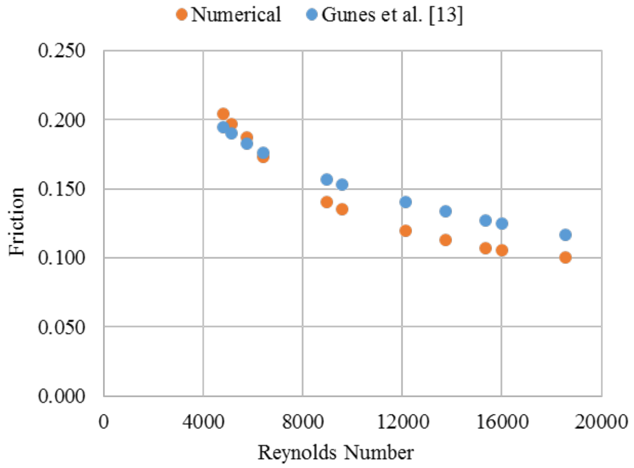



**Figure 5.** The friction results of numerical and Gunes et al. [13] versus Reynolds number.

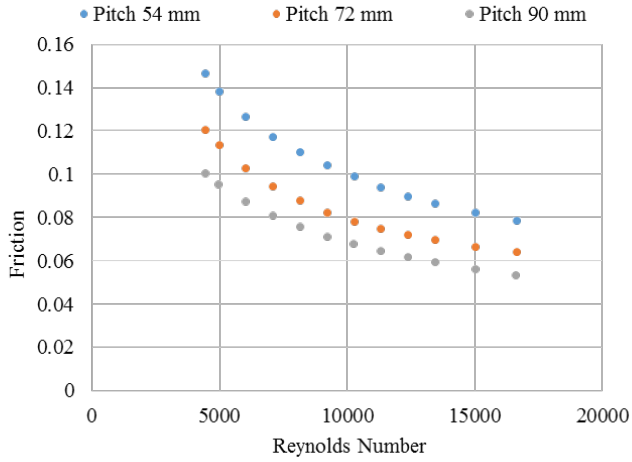



**Figure 7.** Results of friction versus Reynolds number for CWC insert.

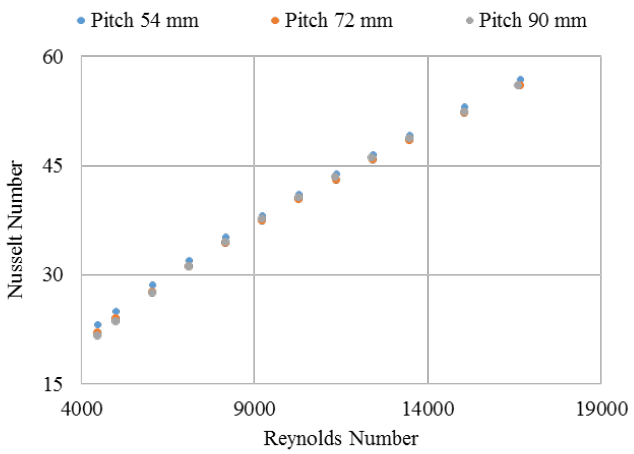



**Figure 6.** Results of Nusselt number versus Reynolds number for CWC insert.

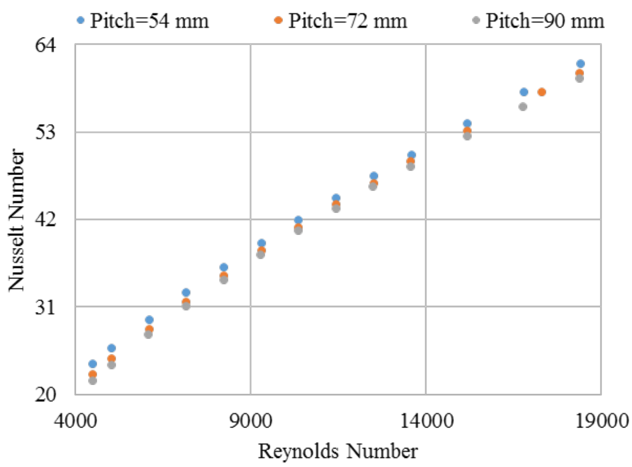



**Figure 8.** Results of Nusselt number versus Reynolds number for TWC insert.

**Numerical Results for TWC, CWC, and DWC Insert in the Square Duct**

In the first study, a Circular cross-sectional wire coil (CWC) was inserted in a square duct. The diameter of the CWC was 2 mm. Three types of pitches were implemented on wire coil geometry. These pitches were 54 mm, 72 mm, and 90 mm. Figures 6 and 7 show the Nusselt number and friction versus Reynolds number for different pitches.

Figure 6 shows the Nusselt number raised with decreasing pitch and increasing Reynolds number. At lower Reynolds number, the CWC's Nusselt number with a pitch of 54 mm was observed to be 3.92% and 5.42% higher than those of the 72 and 90 mm pitch, respectively. At higher Reynolds number, Nusselt number with 54 mm pitch was higher than 72 mm and 90 mm about 1.52 and 2.08 %, respectively.

Figure 7 illustrates the friction factor decreased with increasing pitch and Reynolds Number. At lower Reynolds number, the friction factor with 54 mm pitch was higher than 72 and 90 mm about 22.11 and 45.4 %, respectively. At higher Reynolds number, the friction with 54 mm pitch was higher than 72 and 90 mm about 21.3 and 47.9 %, respectively. In the second study, the triangular cross-sectional wire coil (TWC) was inserted in a square duct. Each side of TWC was 2 mm. Three pitches with 54, 72, and 90 mm were studied. Figures 8 and 9 show the Nusselt number and friction versus Reynolds number, respectively.

Figure 8 shows the Nusselt number raised with decreasing pitch and increasing Reynolds number. At lower Reynolds number, the TWC's Nusselt number with 54 mm pitch was higher than 72 mm and 90 mm about 5.1 and 8.25 %, respectively. At higher Reynolds number, the TWC's Nusselt number with 54 mm pitch was higher than 72 mm and 90 mm about 1.95 and 3.15 %, respectively.

Figure 9 demonstrated that the friction factor decreased with increasing pitch and Reynolds number. At lower

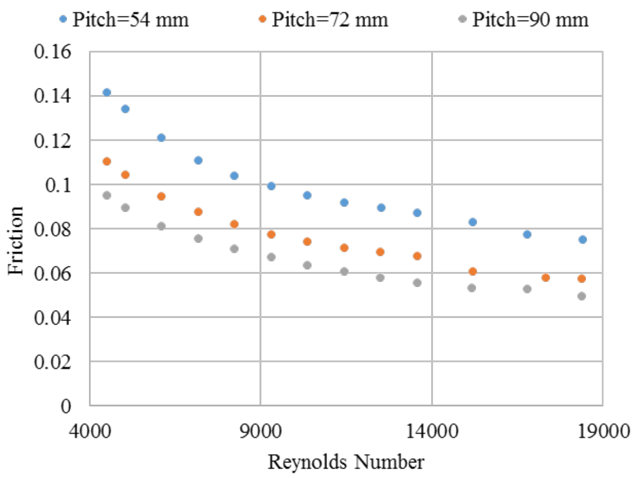



**Figure 9.** Results of friction versus Reynolds number for TWC insert.

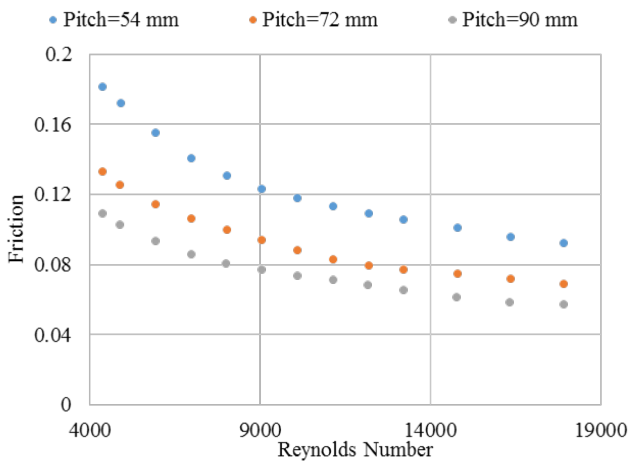



**Figure 11.** Results of friction versus Reynolds number for DWC insert.

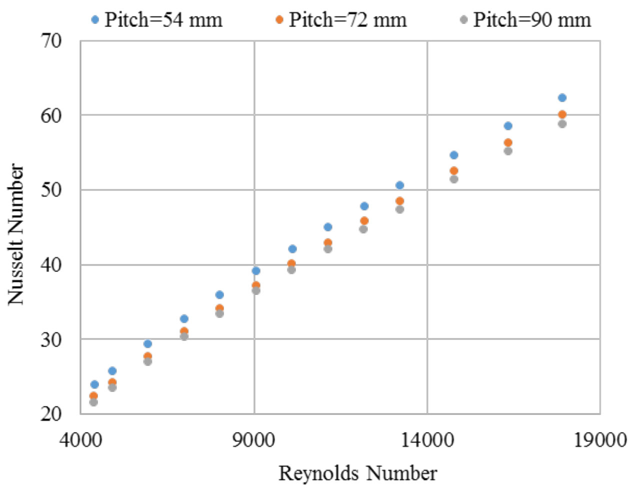



**Figure 10.** Results of Nusselt number versus Reynolds number for DWC insert.

Reynolds number, the TWC's friction with 54 mm pitch was higher than 72 mm and 90 mm about 27.9 and 48.23 %, respectively. At higher Reynolds number, friction factor with 54 mm pitch was higher than 72 mm and 90 mm approximately 33.8 and 51.85 %, respectively. Results showed that the Nusselt number and friction increased with decreasing pitch such as in literature [1–3, 5, 9].

In the third study, Diamond type Wire Coil (DWC) with 54, 72, and 90 mm pitches were inserted in a square duct. Each side of the DWC was 2 mm. Figures 10 and 11 show the Nusselt number and friction versus Reynolds number, respectively.

Figure 10 shows the Nusselt number increased with decreasing pitch and increasing Reynolds number. At lower Reynolds number, the DWC's Nusselt number with 54 mm pitch was higher than 72 mm and 90 mm about 5.47 and 9.76 %, respectively. At higher Reynolds Number, the DWC's Nusselt Number with 54 mm pitch was higher than 72 mm and 90 mm about 2.1 and 6.02 %, respectively.

As inferred from Figure 11 the friction factor decreased with increasing pitch and Reynolds number. At lower Reynolds number, the DWC's friction with 54 mm pitch was higher than 72 mm and 90 mm about 35.5 and 67.2 %, respectively. At higher Reynolds Number, the DWC's friction with 54 mm pitch was higher than 72 mm and 90 mm about 35.47 and 65.6 %, respectively. Results showed that the Nusselt number and friction increased with decreasing pitch such as in literature [1–3, 5, 9].

Figures 12 and 13 show the Nusselt number and friction versus Reynolds number of all studies, respectively.

Figure 12 shows the DWC's with 54 mm pitch showed the highest Nusselt number and the DWC for pitch 90 mm showed the lowest Nusselt number within Reynolds number range. In the 54 mm pitch study, the DWC's Nusselt number was higher than TWC and CWC and the Nusselt number of TWC was higher than CWC. The DWC's Nusselt number was higher than the smooth pipe around 47 to 98%. As clearly seen from Figure 13, the highest friction was observed on DWC with a 54 mm pitch and the lowest friction was observed TWC with 72 mm pitch. The Nusselt number of CWC, TWC, and DWC were higher than the smooth pipe in the range of 38–88%, 37–37%, and 38–98%, respectively. The friction factors of CWC, TWC, and DWC were higher than the smooth pipe in the range of 87–278%, 82–266%, and 107–366%, respectively.

Figure 14 shows the PEC versus Reynolds number of all studies. Results showed that the maximum 30.46 % heat transfer enhancement was achieved in the TWC group for the case of 90 mm. CWC and TWC for the case of 54, 72, and 90 mm pitch can be selected instead of smooth pipe to heat transfer performance within the Reynolds number range. In terms of heat transfer enhancement, the DWC can be used instead of a plain tube for the case of

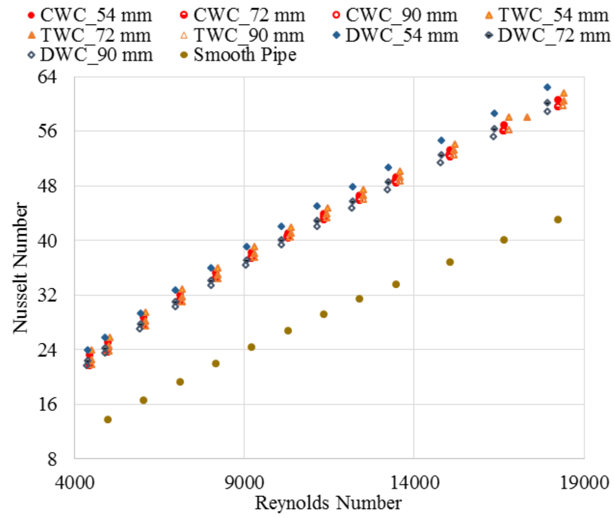



**Figure 12.** Results of Nusselt number versus Reynolds number for all study.

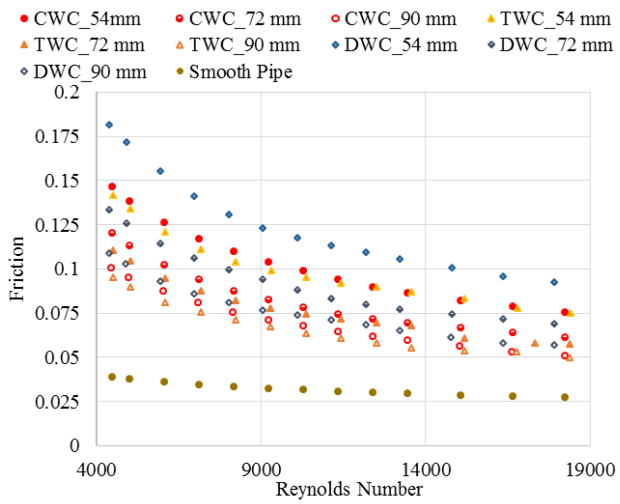



**Figure. 13.** Results of friction versus Reynolds number for all study.

72 and 90 mm. However, DWC for a 54 mm pitch cannot be selected instead of a smooth pipe for the case of high Reynolds number.

As inferred from Figures 12 and 13, the Nusselt number was within 21 to 63 range and the friction was within 0.049 to 0.18 range. The PEC range of the current study was between 1 and 1.30 as shown in Figure 14.

In the current study, run of examining the heat transfer characteristics of validation, mesh independency and CWC, TWC, and DWC insertions were 33, 27, and 117 runs in FLUENT, respectively. The total run of the presented study was 177. The maximum y+ value was obtained 1.1.

Table 2 shows the correlation of the whole numerical results of the presented study. As can be seen from the

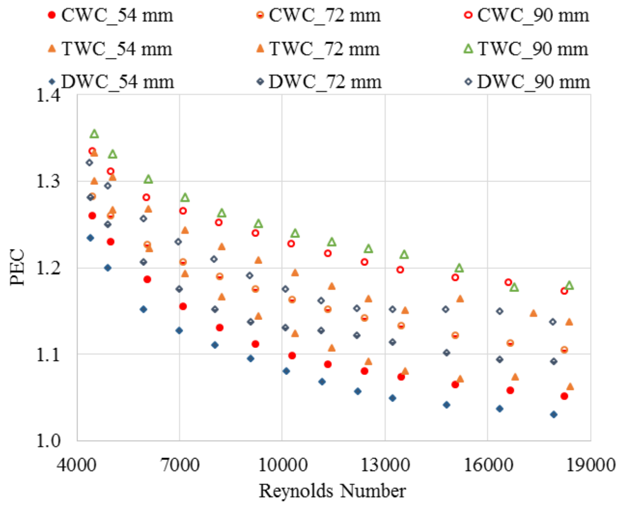



**Figure 14.** Results of PEC versus Reynolds number for all study.

**Table 2.** Reynolds versus Correlation Table

| Type | Nu | f |
|---|---|---|
| CWC 54 | 0.9978 | 0.9577 |
| TWC 54 | 0.998 | 0.944 |
| DWC 54 | 0.9983 | 0.94 |
| CWC 72 | 0.9973 | 0.9411 |
| TWC 72 | 0.9971 | 0.9541 |
| DWC 72 | 0.9985 | 0.9484 |
| CWC 90 | 0.996 | 0.9611 |
| TWC 90 | 0.9966 | 0.9481 |
| DWC 90 | 0.9982 | 0.9543 |

correlation, the results of the numerical study were quite accurate and clear. The considering especially the results of Nusselt number, the rate obtained was quite close to 1. Consequently, the result of the present study fitted and formulas were shown in equation 8 and 9. The predicted values shows in good agreement with the numerical values.

$$Nu = 0.075.Re^{0.693}.\left(P/D\right)^{-0.0789} \tag{8}$$

$$f = 21.941.Re^{-0.478}.\left(P/D\right)^{-0.852} \tag{9}$$

Table 3 express that comparing the results of the current study with literature. Table 3 shows the Reynolds number of the literature [1–25] was between 10 and 100,000. However, the most commonly used was within 4000–18,000 Reynolds number range and this range is proper for the using turbulent modelling (k-ε) in FLUENT. The joint regime of p/D and e/D of literature 3, 4, 5 and 0.111, respectively. These

**Table 3.** PEC comparing with Literature

| Literature | P/D | e/D | Re | PEC |
|---|---|---|---|---|
| **Current study** | 3, 4, 5 | 0.111 | 4387–18,415 | 0.97–1.30 |
| [1] | 1.17– 2.68 | 0.074– 0.101 | 80–90,000 | 1–3 |
| [2] | 1.25, 1.72, 3.37 | 0.076 | 10–2500 | – |
| [3] | – | – | 10–1500 | 1–2.3 |
| [4] | 0.906, 0.886, 1.173 | 0.114, 0.057, 0.074 | 100–100,000 | – |
| [5] | 1, 1.5, 2 | 0.0312 | 6000–20,000 | 0.75–1.02 |
| [6] | 1.304–2.319 | 0.0725–0.134 | – | – |
| [7] | 0.31, 0.42 | 0.0421, 0.0631 | 5000–25,000 | 1–1.3 |
| [8] | 0.31, 0.42 | 0.0421, 0.0631 | 5000–25,000 | 0.82–1.5 |
| [9] | 1, 2, 3 | 0.0714, 0.0892 | 3500–27,000 | 0.94–1.36 |
| [10] | 8, 6, 4 | 0,101 | 4600–20,000 | 0.9–1.25 |
| [11] | 2, 4, 7 | – | 8000–18,000 | – |
| [12] | – | – | 4000–25,000 | 0.9–1.33 |
| [13] | 1, 2, 3 | 0.107 | 4105–26,400 | 1–1.5 |
| [14] | 1, 2, 3 | 0.2, 0.4 | 4000–20,000 | 0.9–1.5 |
| [15] | 0.83–4.17 | 0.25 | 2300–12,000 | 1.19–2.1 |
| [16] | 0.172–1.034 | 0.1034 | 6000–20,000 | 0.64–1.14 |
| [17] | 1.92 | 0.0334 | 200–2300 | 2.4–3.79 |
| [18] | 1, 2, 3 | 0.0714, 0.0892 | 2851–27,732 | 0.9–1.67 |
| [20] | 1.1 | 0.24 | 800–9000 | – |
| [21] | 1, 1.5, 2, 2.5 | 0.00667–0.02 | 3000–18,000 | 1.1–1.72 |
| [22] | 0.9985– 2.649 | 0.0768, 0.1344 | 10–1200 | – |
| [23] | – | – | 6000–22,000 | 0.82–1.1 |
| [24] | 3.98 | – | 4650–21,780 | 1.13–1.23 |
| [25] | 1, 1.5, 2 | – | 15,000–1,160,000 | 0.4–1.4 |

values are chosen for the current study to compare results of numerical with literature. As clearly seen from Table 3, PEC was observed to be quite good compared to the literature [5, 7, 10, 16, 23, 24]. The reason why the PEC in the literature is greater than this study is that the p/D and e/D ratio of literature [8, 13–15, 17, 18, 21, 23, 24] is lower than the current study.

## CONCLUSION

The primary goal of the present study was to show the effect of wire coil geometry and pitch ratio on heat transfer enhancement. The cross-sectional geometry of the wire coil was circular, triangular, and diamond. The thermo-hydraulic behavior of CWC, TWC, and DWC with 54 mm, 72 mm, and 90 mm pitch ratios in square duct were examined with numerically. Reynolds number range of study was between 4387 and 18,415. The result showed that,

- The Nusselt number of CWC, TWC, and DWC were higher than the smooth pipe in the range of 38–88%, 37–93%, and 38–98%, respectively.
- The highest Nusselt number was obtained at DWC's with a 54 mm pitch and the lowest one was DWC for pitch 90 mm. In the 54 mm pitch study, the DWC's Nusselt number was higher than TWC and CWC and the Nusselt number of TWC was higher than CWC.
- Nusselt number increased with increasing Reynolds number and decreasing pitch ratios.
- The friction factors of CWC, TWC, and DWC were higher than the smooth pipe within 87–278%, 82–266%, and 107–366% range, respectively.
- The friction factor increased with decreasing Reynolds number and decreasing pitch ratio.
- The highest thermo-hydraulic performance of the study was observed especially at low Reynolds numbers.
- The 90 mm pitch showed the highest PEC (1.30) for the TWC group at Reynolds number 4504. The lowest PEC (0.97) was observed DWC with a 54 mm pitch. The maximum 30.46 % PEC was achieved in the TWC group for the case of 90 mm. The CWC and TWC for the case of 54, 72, and 90 mm pitch can be

selected instead of smooth pipe to heat transfer performance in the range of Reynolds number.

## NOMENCLATURE

| | |
|---|---|
| $A$ | area ($m^2$) |
| $C_p$ | fluid specific heat ($J.kg^{-1}.\ °C^{-1}$) |
| $CWC$ | circular wire coil |
| $d$ | diameter of pipe (m) |
| $D_h$ | hydraulic diameter (m) |
| $DWC$ | diamond wire coil |
| $f$ | friction factor |
| $h$ | heat transfer coefficient ($W.m^{-2}.K^{-1}$) |
| $HTE$ | heat transfer enhancement |
| $k$ | fluid thermal conductivity ($W.m^{-1}.K^{-1}$) |
| $L$ | length of pipe (m) |
| $l$ | length of wire coil (m) |
| $\dot{m}$ | mass flow rate |
| $Nu$ | Nusselt number |
| $p$ | pitch (m) |
| $PEC$ | heat transfer enhancement efficiency, performance evaluation factor |
| $p/D$ | pitch ratio |
| $\Delta p$ | pressure drop (Pa) |
| $TWC$ | triangular wire coil |
| $Re$ | Reynolds number |
| $Pr$ | Prandtl number |
| $T_o$ | outside temperature (K) |
| $TT$ | twisted tape |
| $U_{mean}$ | mean velocity (m/s) |
| $Y$ | twist ratio |
| $WC$ | wire coil |

**Greek Symbols**

| | |
|---|---|
| $\rho$ | density ($kg/m^3$) |
| $\mu$ | viscosity (kg/ms) |

**Subscript**

| | |
|---|---|
| $a$ | augmented |
| $b$ | bulk |
| $h$ | hydraulic diameter |
| $i$ | inlet |
| $o$ | smooth pipe |
| $w$ | wall |
| 0 | smooth pipe |

## AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

## DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

## CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## ETHICS

There are no ethical issues with the publication of this manuscript.

## REFERENCES

[1] García A, Vicente PG, Viedma A. Experimental study of heat transfer enhancement with wire coil inserts in laminar-transition-turbulent regimes at different Prandtl numbers. Int J Heat Mass Transf 2005;48:4640–4651. [CrossRef]

[2] García A, Solano JP, Vicente PG, Viedma A. Enhancement of laminar and transitional flow heat transfer in tubes by means of wire coil inserts. Int J Heat Mass Transf 2007;50:3176–3189. [CrossRef]

[3] Akhavan-Behabadi MA, Kumar R, Salimpour MR, Azimi R. Pressure drop and heat transfer augmentation due to coiled wire inserts during laminar flow of oil inside a horizontal tube. Int J Therm Sci 2010;49:373–379. [CrossRef]

[4] García A, Solano JP, Vicente PG, Viedma A. The influence of artificial roughness shape on heat transfer enhancement: Corrugated tubes, dimpled tubes and wire coils. Appl Therm Eng 2012;35:196–201. [CrossRef]

[5] Nanan K, Pimsarn M, Jedsadaratanachai W, Eiamsa-ard S. Heat transfer augmentation through the use of wire-rod bundles under constant wall heat flux condition. Int Commun Heat Mass Transf 2013;48:133–140. [CrossRef]

[6] San J-Y, Huang W-C, Chen C-A Experimental investigation on heat transfer and fluid friction correlations for circular tubes with coiled-wire inserts. Int J Heat Mass Transf 2015;65:8–14. [CrossRef]

[7] Promvonge P. Thermal performance in circular tube fitted with coiled square wires. Energy Convers Manag 2008;49:980–987. [CrossRef]

[8] Promvonge P. Thermal enhancement in a round tube with snail entry and coiled-wire inserts. Int Commun Heat Mass Transf 2008;35:623–629. [CrossRef]

[9] Gunes S, Ozceyhan V, Buyukalaca O. Heat transfer enhancement in a tube with equilateral triangle cross sectioned coiled wire inserts. Exp therm fluid sci 2010;34:684–691. [CrossRef]

[10] Eiamsa-ard S, Nivesrangsan P, Chokphoemphun S, Promvonge P. Influence of combined non-uniform wire coil and twisted tape inserts on thermal performance characteristics. Int Commun Heat Mass Transf 2010;37:850–856. [CrossRef]
[11] Promvonge P, Eiamsa-ard S. Heat transfer and turbulent flow friction in a circular tube fitted with conical-nozzle turbulators. Int Commun Heat Mass Transf 2007;34:72–82. [CrossRef]
[12] Smith E, Koolnapadol N, Promvonge P. Heat transfer behavior in a square duct with tandem wire coil element insert. Chin J Chem Eng 2012;20:863–869. [CrossRef]
[13] Gunes S, Ozceyhan V, Buyukalaca O. The experimental investigation of heat transfer and pressure drop in a tube with coiled wire inserts placed separately from the tube wall. Appl Therm Eng 2010;30:1719–1725. [CrossRef]
[14] Abdullah AL, Yilmaz F. Computational Analysis of Heat Transfer Enhancement in a Circular Tube Fitted with Different Inserts 2018;40:59–69.
[15] Abdul Hamid K, Azmi WH, Mamat R, Sharma KV. Heat transfer performance of TiO2–SiO2 nanofluids in a tube with wire coil inserts. Appl Therm Eng 2019;152:275–286. [CrossRef]
[16] Hong Y, Du J, Wang S, Huang S-M, Ye W-B. Heat transfer and fluid flow behaviors in a tube with modified wire coils. Int J Heat Mass Transf 2018;124:1347–1360. [CrossRef]
[17] Tusar M, Ahmed K, Bhuiya M, Bhowmik P, Rasul M, Ashwath N. CFD study of heat transfer enhancement and fluid flow characteristics of laminar flow through tube with helical screw tape insert. Energy Procedia 2019;160:699–706. [CrossRef]
[18] Keklikcioglu O, Ozceyhan V. Experimental investigation on heat transfer enhancement in a circular tube with equilateral triangle cross sectioned coiled-wire inserts. Appl Therm Eng 2018;131:686–695. [CrossRef]
[19] García A, Martin RH, Pérez-García J. Experimental study of heat transfer enhancement in a flat-plate solar water collector with wire-coil inserts. Appl Therm Eng 2013;61:461–468. [CrossRef]
[20] Andrzejczyk R, Muszynski T, Kozak P. Experimental investigation of heat transfer enhancement in straight and U-bend double-pipe heat exchanger with wire insert. Chem Eng Process 2019;136:177–190. [CrossRef]
[21] Chamoli S, Lu R, Xie J, Yu P. Numerical study on flow structure and heat transfer in a circular tube integrated with novel anchor shaped inserts. Appl Therm Eng 2018;135:304–324. [CrossRef]
[22] Sharifi K, Sabeti M, Rafiei M, Mohammadi AH, Shirazi L. Computational Fluid Dynamics (CFD) Technique to Study the Effects of Helical Wire Inserts on Heat Transfer and Pressure Drop in a Double Pipe Heat Exchanger. Appl Therm Eng 2018;128:898–910. [CrossRef]
[23] Keklikcioglu O, Dagdevir T, Ozceyhan V. A cfd based thermo-hydraulic performance analysis in a tube fitted with stepped conical nozzle turbulators. J Therm Eng 2016;2:913-920. [CrossRef]
[24] Göksu TT, Köşker M,Yılmaz F. Birleşik bir turbülatörün ısı transferi analizi. DÜMF Mühendislik Dergisi 2020;11:193-200. [CrossRef]
[25] Yılmaz İH, Mwesigye A, Göksu TT. Enhancing the overall thermal performance of a large aperture parabolic trough solar collector using wire coil inserts. Sustain Energy Technol Assess 2020;39:100696. [CrossRef]
[26] Webb RL. Performance evaluation criteria for use of enhanced heat transfer surfaces in heat exchanger design. Int J Heat Mass Transf 1981;24:715–726. [CrossRef]