Chapter 10

A Review of Heat Transfer Enhancement Methods Using Coiled Wire and Twisted Tape Inserts

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Additional information is available at the end of the chapter

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Abstract

Heat transfer enhancement is categorized into passive and active methods. Active methods need external power to input the process; in contrast, passive methods do not require any additional energy to improve the thermohydraulic performance of the system. Passive methods are widely used in both experimental and numerical applications when investigating heat transfer enhancement and friction losses to save energy and costs. The many passive methods for increasing heat transfer rate include various components located in the fluid flow path, such as twisted tapes, coiled or tangled wires, and nozzle turbulators. The present paper represents a comprehensive review that focused on heat transfer enhancement methods with coiled wire and twisted tape inserts since the installation of inserts is easier and more economical. The thermodynamic performance of heat exchange components is also affected by the flow conditions such as laminar or turbulence. The present review comprises investigations on the enhancement of heat transfer using twisted tape and coiled wire inserts in laminar and turbulent flow region.

Keywords: heat transfer enhancement, coiled wire, twisted tape, heat transfer, friction factor

1. Introduction

As a result of the global energy crisis, which is one of the most crucial problems due to the large and continuous increase in the consumption and the increment shortage of energy resources as well as the high cost, many researchers have performed to increase the efficiency of thermal systems and reduction of the size and thus energy consumption rates.

Heat transfer enhancement is a process of increasing the heat transfer rate and thermohydraulic performance of a system using various methods. The methods of heat transfer enhancement are employed for developing the heat transfer without affecting the overall realization of the systems significantly, and it covers a wide range of areas where heat exchangers are used for such functions as air-conditioning, refrigeration, central heating systems, cooling automotive components, and many uses in the chemical industry.

Heat transfer enhancement methods exist on three general classifications which are passive, active, and compound techniques. Active methods require external power to input the process; in contrast, passive methods do not require any additional energy to improve the thermohydraulic performance of the system. Also, two or more passive and active techniques can be used together and that is called compound technique, which is employed to produce a higher augmentation than using one passive or active technique independently.

1.1. Passive techniques

In the passive techniques, any external power is not required; rather, geometry or surface of the flow channel is modified to increase the thermohydraulic performance of the systems. The inserts, ribs, and rough surfaces are utilized to promote fluid mixing and the turbulence in the flow, which results in an increment of the overall heat transfer rate. Passive techniques have also some advantages in relation to the other heat transfer enhancement techniques such as low cost, easy production, and installation.

1.2. Active techniques

Active techniques are more complex than the passive techniques in the expression of design and application because of the necessity of external energy to adjust the flow of fluid so as to obtain an improvement in thermal efficiency. Providing external energy in most applications is not easy; for this reason, the use of active techniques in scientific fields is limited.

1.3. Compound techniques

A compound technique consists of the combination of more than one heat transfer enhancement method (active and/or passive) to increase the thermohydraulic performance of heat exchangers. It can be employed simultaneously to generate an augmentation that promotes the performance of the system either of the techniques operating independently. Preliminary studies on compound passive augmentation technique of this kind are quite encouraging.

2. Simple definitions used to evaluate heat transfer enhancement

The basics of performance evaluation criteria (PEC) were determined for the fixed geometry criteria (FG), which was related with heat transfer and friction factor characteristics of various augmentation techniques in Ref. [1]. The PEC define the performance advantages of a heat exchanger having enhanced surfaces, relative to a reference exchanger, for example, one having smooth surfaces [1].

The fixed geometry criteria are used for many passive techniques which include various types of inner ribs or inserts in the tube. The investigations of heat transfer enhancement with passive techniques are generally conducted at the same pumping power in accordance with the fixed geometry criteria. Thus, comparison of results for the tube with inserts and without inserts can be carried out in ease. The Nusselt number can be written in below as to calculate the thermal performance of the system:

$$Nu = \frac{hD}{k} \tag{1}$$

And, the Reynolds number for fluid is

$$\mathrm{Re} = \frac{UD}{\nu} \tag{2}$$

The friction factor, f, is calculated as follows, for the fully developed isothermal flow:

$$f = \frac{\Delta P}{\frac{1}{2}\rho.U^2 \frac{L}{D}} \tag{3}$$

where U represents the mean fluid velocity in the tube.

The heat transfer rate and friction factor of the smooth tube and smooth tube fitted with inserts are evaluated under the same pumping power as below [2]:

$$\left(\dot{V}\,\Delta P\right)_s = \left(\dot{V}\,\Delta P\right)_a \tag{4}$$

$$\left(f\mathrm{Re}^3\right)_s = \left(f\mathrm{Re}^3\right)_a \tag{5}$$

$$\mathrm{Re}_s = \mathrm{Re}_a\left(f_a/f_s\right)^{1/3} \tag{6}$$

The overall enhancement ratio (OER) is the parameter that is usually used in heat transfer augmentation to determine the performance of different variations of heat exchangers. The parameter can be written as in Eq. (7) for the same pumping power based on the fixed geometry criteria [2]:

$$\eta = \frac{h_a}{h_s}\bigg|_{pp} = \frac{Nu_a}{Nu_s}\bigg|_{pp} = \left(\frac{Nu_a}{Nu_s}\right)\left(\frac{f_s}{f_a}\right)^{1/3} \tag{7}$$

3. Heat transfer enhancement with twisted tape and coiled wire inserts

Many researchers have performed the reviewing on passive or active heat transfer enhancement methods [3–10]. This paper focuses on the reviewing of the recent investigations about the heat transfer enhancement with coiled and twisted tape inserts which are widely used as a passive technique in tubular flow. The coiled wire inserts intensify the disturbance of viscous sublayer and promote redevelopment of the thermal and hydrodynamic boundary layers in the tube flow effectively [11]. Also, twisted tape inserts are used commonly on heat transfer process. Due to the simple design and easy installation, twisted tape inserts are widely preferred to generate swirl flow and increase the turbulence rate in the flow. Additionally, they are used extensively over decades in scientific research as well as industrial applications.

3.1. Twisted tape inserts

Twisted tape inserts are one of the most used enhancement methods of heat transfer. Twisted tape inserts increase both convective heat transfer and fluid friction in the flow region. They induce the turbulence and promote the swirl flow. Moreover, geometric configurations of twisted tape inserts can disturb the boundary layer; with this way, better heat transfer rate can be obtained. However, increment of the fluid friction can negatively affect the overall enhancement ratio for a heat exchanger tube. The performance of a heat exchanger with twisted tape inserts depends on pitch and twist ratios. In recent investigations, a lot of researchers have conducted both experimental and numerical studies to determine the optimal configuration in accordance with the ratios of pitch and twist.

Man et al. [12] carried out an experimental investigation on heat transfer and friction characteristics of dual-pipe heat exchanger for single-phase forced convective flow with alternate clockwise and counterclockwise twisted tape (ACCT tape) and typically twisted tape (TT tape) for the Reynolds number ranging from 3000 to 9000. They reported that the maximum values of performance evaluation criteria (PEC) with the full-length ACCT tape insert reached 1.42 in experimental flowing conditions. Suri et al. [13] experimentally investigated the augmentation in heat transfer and friction in a flow through heat exchanger tube with multiple square perforated twisted tape inserts. The experiments were conducted with the Reynolds number between 5000 and 27,000, perforation width ratio a/W_T from 0.083 to 0.333, and twist ratio $T_L = W_T$ from 2.0 to 3.5. The maximum enhancement is observed at a/W_T of 0.250 and $T_L = W_T$ of 2.5. Sundar et al. [14] investigated the effectiveness of solar flat-plate collectors with and without twisted tapes in Al_2O_3/water nanofluid flow region. The experimental results indicated that the heat transfer rate enhanced 49.75% with the twist ratio of 5 at the Reynolds number 13,000. The maximum friction penalty of 1.25 times was observed for 0.3% nanofluid with twist ratio of 5 with the comparison of water in a smooth tube. Saysroy and Eiamsa-ard [15] conducted a numerical study to determine the thermohydraulic performance of a multichannel twisted tape inserts in laminar and turbulent flow regions. The numerical results showed that for the laminar flow, the maximum thermal performance factor of 7.28 was obtained by using the tube with the multichannel twisted tape with $N = 2$ and $y/w = 2.5$ at the Reynolds number of 2000. Heat transfer and pressure drop of CuO/water nanofluid with twisted tape inserts were explored by Wongcharee and Eiamsa-ard [16]. The results demonstrated that using CuO nanofluid with twisted alternate axis (TA) obtain a higher Nusselt number and thermal performance, and the twisted tape in alternate axis was about 89% more effective than typical twisted tape. Various types of twisted tape such as hollow, double, perforated, and dimpled configurations based on the physical properties, e.g., hollow widths and hole diameters, were investigated in many studies [17–21]. Li et al. [22] carried out a

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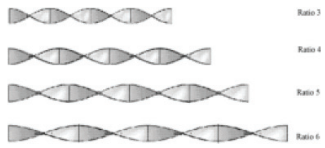
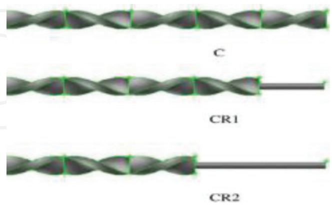
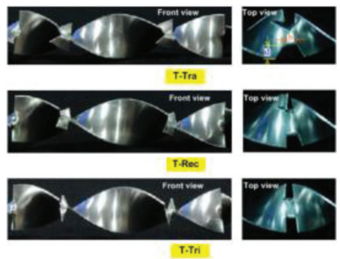
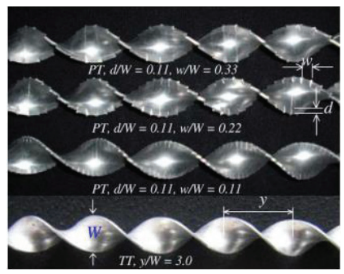
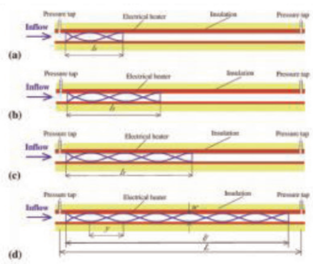
numerical study on her transfer enhancement in a tube with centrally hollow narrow twisted tape under laminar flow conditions. They reported that the tube with cross hollow twisted tape inserts has the best overall heat transfer performance for different hollow widths of the tape. Eiamsa-ard et al. [23] investigated the effect of helically twisted tapes on the thermal performance. Three different twist and helical pitch ratios were used under the turbulent flow region (**Tables 1–3**).

The results were compared to conventional helical tape, and it was reported that the helically twisted tape showed higher thermal performance than the conventional helical tape. Piriyarungrod et al. [40] studied the effects of inserted tapered twisted tapes, their taper angle and twist ratio on heat transfer rate, pressure drop, and thermal performance factor characteristics. They reported that thermal performance factor tended to increase with increasing taper angle and decreasing tape twist ratio. Promvonge et al. [41] investigated turbulent convective heat transfer characteristics in a helical-ribbed tube fitted with twin twisted tapes. The results obtained from the ribbed tube and the twin twisted tape insert were compared with those from the smooth tube and the ribbed tube acting alone. Prasad and Gupta [42] studied to enhance the rate of heat transfer of Al_2O_3 nanofluid in a U-tube heat exchanger with twisted tape insert for the Reynolds number ranging from 3000 to 30,000. The Nusselt number of the entire pipes for 0.03% concentrations of nanofluid with twisted tape inserts was enhanced by 31.28% compared to water. Pal and Saha [43] presented an experimental study to investigate the friction factor and Nusselt number in a circular duct having spiral rib roughness and fitted with twisted tapes with oblique teeth. The experiments were conducted for laminar flow region using viscous oil. The thermohydraulic performance was also evaluated, and the twisted tapes with oblique teeth in combination with integral spiral rib roughness performed significantly better than the individual enhancement technique. Eiamsa-ard and Kiatkittipong [44] investigated the enhancement of thermal performance in a heat exchanger with multiple twisted tapes. TiO_2/water nanofluid was used in experiment as working fluid. They reported that the tube inserted with multiple twisted tapes showed superior thermal performance factor when compared with the plain tube or the tube inserted with a single twisted tape.

3.2. Coiled wire inserts

Transverse or helical ribs, for example, coiled wire inserts, are an attractive method to create the surface roughness [45]. The coiled wire inserts intensify the disturbance of laminar boundary layer and promote redevelopment of the thermal and hydrodynamic boundary layers in the tube flow effectively [11]. Moreover, helically coiled wire can be used to generate secondary flow which helps to enhance the heat transfer rate with the increment of vorticity in the tubular flow. They have also some advantages in relation to the other passive methods such as easy manufacturing and installation; lower manufacturing cost; better fluid mixing and disturbance of laminar boundary layer; possibility to use different fluid types, e.g., nanofluid, water, viscous oil, and air; and possibility to install with various passive techniques together.

The enhancement of heat transfer rate by using coiled wire inserts has been widely studied both experimentally and numerically by many researchers. Garcia et al. [46] analyzed the thermohydraulic performance of three types of passive heat transfer enhancement based on

Authors	Fluid	Type	Flow region	OER	Sample of twisted tape inserts
Jaisankar et al. [24]	Water	Helically twisted tape	3000 ≤ Re ≤ 23,000 turbulence	1.2	
Jaisankar et al. [25]	Water	Full-length left-right twisted and fitted with rod	700 ≤ Re ≤ 1600 laminar	1.1–1.9	
Wongcharee and Eiamsa-ard [26]	Water	Twisted tapes with wing shape including triangle, rectangle, and trapezoid	5500 ≤ Re ≤ 20,200 turbulence	1.42	
Eiamsa-ard et al. [27]	Water	Peripherally cut twisted tape	1000 ≤ Re ≤ 20,000 laminar-turbulence	1.29–4.88	
Eiamsa-ard et al. [28]	Air	Full- and short-length twisted tape	4000 ≤ Re ≤ 20,000 turbulence	0.95–1.04	
Bas and Ozceyhan [29]	Air	Twisted tape	5132 ≤ Re ≤ 24,989 turbulence	1.2–1.74	

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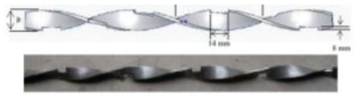
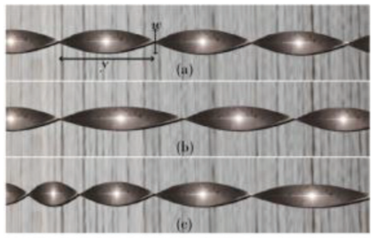
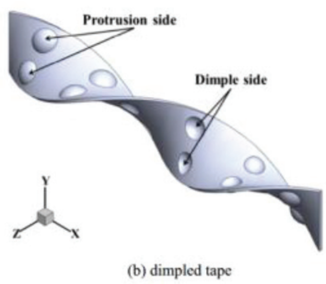
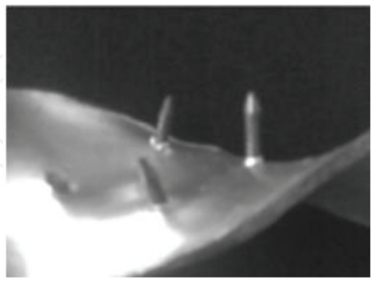
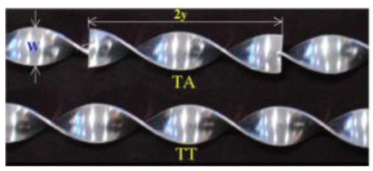
Authors	Fluid	Type	Flow region	OER	Sample of twisted tape inserts
Salam et al. [30]	Water	Rectangular cut	10,000 ≤ Re ≤ 19,000 turbulence		
Sarada et al. [31]	Air	Twisted tape	6000 ≤ Re ≤ 13,500 turbulence	1.36–1.48	
Maddah et al. [32]	Al_20_3/ water nanofluid	Modified twisted tape	5000 ≤ Re ≤ 21,000 turbulence	1.03–1.6	
Zheng et al. [20]	Al_20_3/ water nanofluid	Dimpled twisted tape	1000 ≤ Re ≤ 10,000 Laminar-turbulence	1.25	
Murugesan et al. [33]	Water	Twisted tape with wire nails	2000 ≤ Re ≤ 12,000 Laminar-turbulence	1.05–1.75	
Wongcharee and Eiamsa-ard [16]	CuO/ water nanofluid	Twisted tape with alternate axis	830 ≤ Re ≤ 1990 turbulence	5.53	

Authors	Fluid	Type	Flow region	OER	Sample of twisted tape inserts
Nanan et al. [34]	Air	Twisted tape	$6000 \le Re \le 20{,}000$ turbulence	1.28	

Table 1. Various examples of twisted tape inserts for heat transfer enhancement.

Authors	Fluid	Flow region	Nusselt number	Friction factor
Jaisankar et al. [24]	Water	$3000 \le Re \le 23{,}000$ Turbulence	$Nu = 0.000115\, Re^{1.169}\, Pr^{2.424}\, Y^{-0.511}$	$f = 271.1\, Re^{-0.947}\, Y^{-0.584}$
Ibrahim [35]	Water	$570 \le Re \le 1310$ Laminar	$Nu = 6.11\, Re^{0.199}\, (1 + x)^{-0.064}\, Y^{-0.318}$	$f = 54.41\, Re^{-0.87}\, (1 + x)^{-0.045}\, Y^{-0.146}$
Sivashanmugam and Suresh [36]	Water	Laminar	$Nu = 0.017\, Re^{0.996}\, Pr\, Y^{-0.5437}$	$f = 10.7564\, Re^{-0.387}\, Y^{-1.054}$
He et al. [17]	Air	$5600 \le Re \le 18{,}000$ Turbulence	$Nu = 0.3415\, Re^{0.5911}\, Pr^{0.32}$ $(0.9058c^3 + 0.5439c^2 – 1.345c + 1.271)$	$f = 9.348$ $Re^{-0.3959}(5.53c^3 + 2.578c^2 – 7.307c + 3.499)$
Paisarn Naphon [37]	Water	$7000 \le Re \le 23{,}000$ Turbulence	$Nu = 0.648\, Re^{0.36}\, (1 + D/H)^{2.475}\, Pr^{1/3}$	$f = 3.517\, Re^{-0.414}\, (1 + D/H)^{1.045}$
Tamna et al. [18]	Air	$5300 \le Re \le 24{,}000$ Turbulence	$Nu = 0.1687\, Re^{0.701}\, Pr^{0.4}\, B_R^{0.172}$	$f = 5.494\, Re^{-0.263}\, B_R^{0.729}$
Eiamsa-ard et al. [27]	Water	$1000 \le Re \le 20{,}000$ Turbulence	$Nu = 0.244\, Re^{0.625}\, Pr^{0.4}\, (d/W)^{0.168}(w/W)^{-0.112}$	$f = 39.46\, Re^{-0.591}\, (d/W)^{0.195}(w/W)^{-0.201}$
Eiamsa-ard et al. [38]	Water	$2000 \le Re \le 12{,}000$ Turbulence	$Nu = 0.01014\, Re^{0.929} Pr^{1/3}\, (1 + S)^{-0.266}$	$f = 4.143\, Re^{-0.398}\, (1 + S)^{-0.376}$
Seemawute and Eiamsa-ard [39]	Water	$5000 \le Re \le 20{,}000$ Turbulence	$Nu = 0.076\, Re^{0.718}\, Pr^{0.4}$	$f = 6.42\, Re^{-0.428}$
Jaisankar et al. [25]	Water	Laminar	*Phase 1* $Nu = 0.00395$ $Re^{1.067} Pr^{0.757} Y^{0.033}(1 + S/D)^{-0.0304}$ *Phase 2* $Nu = 0.00363$ $Re^{1.433} Pr^{0.266} Y^{0.154}(1 + S/D)^{-0.024}$	*Phase 1* $f = 1.30\, Re^{-0.310}\, Y^{-0.124}(1 + S/D)^{-0.063}$ *Phase 2* $f = 3.527\, Re^{-0.436}\, Y^{-0.145}(1 + S/D)^{-0.066}$

Table 2. Correlations for the Nusselt number and friction factor for twisted tape inserts.

artificial roughness. According to the results, the use of coiled wire at a lower Reynolds number was more advantageous than corrugated and dimpled tubes. Ozceyhan [47] numerically analyzed conjugate heat transfer and thermal stress in a tube with coiled wire inserts.

Gunes et al. [58] investigated the effects of coiled wire on heat transfer enhancement and pressure drop in a tube. It was found that the best overall enhancement efficiency was achieved for the configuration with P/D = 1. In another study Gunes et al. [59] reported on the

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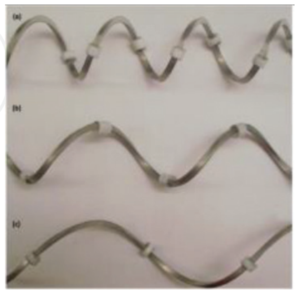
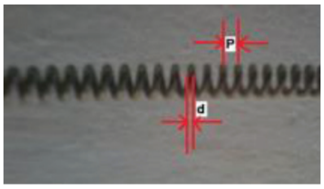
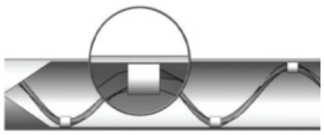
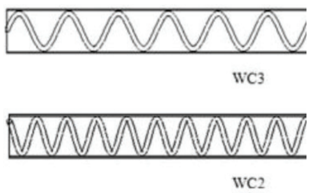
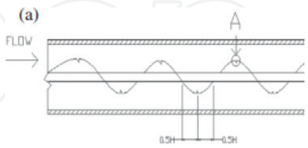
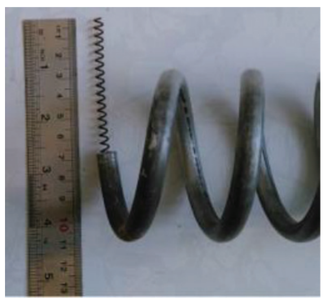
characteristics of heat transfer and pressure drop in a tube with coiled wire inserts separated from the tube wall by two different distances. The results showed that the Nusselt number and pressure drop increase with decreasing distance between the coiled wire and the tube wall.

Authors	**Fluid**	**Type**	**Flow region**	**OER**	**Sample of twisted tape inserts**
Keklikcioglu and Ozceyhan [48]	Air	Triangle cross-sectional coiled wire	$2851 \le Re \le 27{,}732$ turbulence	1.67	
Reddy and Rao [49]	Ethylene glycol water-based TiO_2	Helically coiled wire	$4000 \le Re \le 15{,}000$ Turbulence	1.06–1.38	
Keklikcioglu and Ozceyhan [50]	Air	Triangle cross-sectional coiled wire	$3429 \le Re \le 26{,}663$ Turbulence	1.82	
Chandrasekar et al. [51]	Al_20_3/water nanofluid	Coiled wire	$600 \le Re \le 2275$ laminar	—	
Roy and Saha [52]	Servotherm medium oil	Coiled wire	Laminar	—	
Panahi and Zamzamian [53]	Water and air	Coiled wire	$4000 \le Re \le 18{,}000$ turbulence	1.26–1.52	

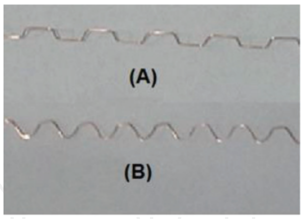
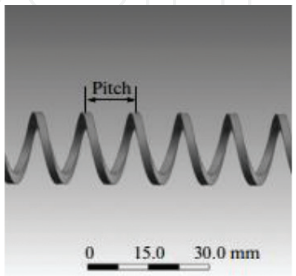
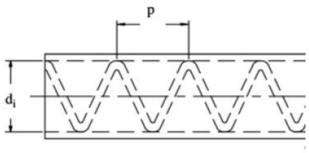
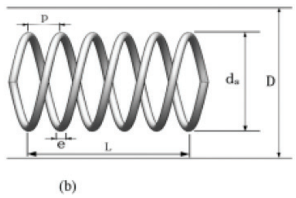
Authors	Fluid	Type	Flow region	OER	Sample of twisted tape inserts
Goudarzi and Jamali [54]	Al_2O_3-EG nanofluid	Coiled wire	18,500 ≤ Re ≤ 22,700 turbulence		
Goodarzi et al. [55]	Water	Square cross-sectional coiled wire	5800 ≤ Re ≤ 18,500 turbulence	0.93–0.97	
Sharifi et al. [56]	Engine oil	Helically coiled wire	100 ≤ Re ≤ 1200 Laminar	1.77	
Zhang et al. [57]	Air	Double spiral coiled wire	6000 ≤ Re ≤ 31,000 Turbulence	1.5	

Table 3. Various examples of coiled inserts for heat transfer enhancement.

Promvonge [60] presented the experimental results for the heat transfer and flow friction characteristics in a circular tube in which coiled wire with a square cross section was inserted. The thermal performance of helically twisted tapes was experimentally investigated by Eiamsa-ard et al. [61]. They reported that the heat transfer rate and the friction factor increase as the twist ratio and helical pitch ratio increase. In another study, Eiamsa-ard et al. [62] studied the thermal performance of a tube fitted with both twisted tape and a coiled wire. Heat transfer and friction factor analyses of coiled wire inserted tube using various types of nanofluid as working fluid were performed by many researchers [63–73]. Promvonge [74] conducted another investigation of thermohydraulic performance in a tube with coiled wire insert and a snail entry. The heat transfer and the friction factor characteristics of the laminar flow of oil in square and rectangular ducts with transverse ribs and coiled wire were studied by Saha [75]. Feng et al. [76] carried out a numerical study of the laminar liquid flow and coupled heat transfer performance in rectangular microchannel heat sink (MCHS) equipped with coiled wire inserts. In the study the effects of the length and arrangement of coiled wire inserts on heat transfer enhancement were analyzed. Chougulea et al. [77] investigated heat transfer and friction factor characteristics of MWCNT/water nanofluid flowing through a uniformly heated horizontal tube with and without coiled wire. Solano et al. [78] carried out a numerical study of the flow pattern and heat transfer enhancement in oscillatory-baffled reactors with helical coil inserts. The heat transfer enhancement rate was discussed, considering the compound effect of oscillatory motion and helical coil inserts in the paper. Garcia et al. [79] investigated the thermal performance in a round tube with a coiled wire insert for laminar and transitional flow fields, while Arici and Asan [80] studied enhancement of heat transfer for turbulent flows in a tube with coiled wire inserts. Zohir et al. [81] studied the effect of pulsation on the heat transfer rate in a pipe with coiled wire inserts. Apart from the pulsation, the thermohydraulic performances of the process were solely studied for a coiled wire insert with different pitch values. Vahidifar and Kahrom [82] studied the characteristics of the heat transfer and the pressure drop of a heat exchanger with an inserted coiled wire and rings. San et al. [83] measured the heat transfer and pressure drop data for air flow and water flow in a tube fitted with a coiled wire.

4. Conclusions

The present review comprises both recent and important investigations on the enhancement of heat transfer using twisted tape and coiled wire inserts in laminar and turbulent flow region. Most of the studies for both twisted tape and coiled wire inserts emphasize the increased heat transfer rate and fluid friction or pressure drop. The main objective to design a heat exchanger is to enhance the heat transfer without causing more pressure drop. For this purpose many articles have been evaluated in terms of overall enhancement ratio (OER) in this review study. In conclusion, the following statements can be generalized as a result of this review study:

- Both twisted tape and coiled wire inserts can be used together with nanofluid flow to eliminate the pressure drop penalty on OER.
- Most of the researchers oriented to find better configuration of internal ribs to determine the minimum pressure drop and the maximum heat transfer.
- Twisted tape inserts generally show better performance in laminar flow region.
- Twisted tape inserts cause high-pressure drop penalty in turbulent region so they are not good at enhancing thermohydraulic performance.
- Coiled wire shows better performance to create swirl flow inside the tube.
- Coiled wire inserts have the ability to destruct the laminar boundary layer.
- When the pressure drop penalty in considered, coiled wire inserts show better performance than twisted tape inserts.
- The configuration and physical properties of inserts are the most important parameters to enhance the overall thermohydraulic performance of a heat exchanger.

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Appendices and nomenclature

D inner diameter of the tube (m)

f friction factor

h convective heat transfer coefficient (W/m^2 K)

k thermal conductivity (W/m K)

L length of the test tube (m)

Nu Nusselt number (hD/k)

ΔP pressure drop (N/m^2)

Re Reynolds number (UD/v)

T steady-state temperature (K)

U mean fluid velocity (m/s)

$\dot{V}$ volumetric flow rate (m^3/s)

Greek letters

ρ fluid density (kg/m^3)

U overall enhancement efficiency

υ kinematic viscosity (m^2/s)

Subscripts

a augmented tube

$pp.$ pumping power

s smooth tube

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