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PERFORMANCE EVALUATION OF WIRE COIL INSERTS IN TURBULENT TUBE FLOW – CRITICAL REVIEW

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Abstract

There are different kinds of inserts employed in the heat exchanger tubes such as helical/twisted tapes, coil wires, ribs/fins/baffles, and winglets. This paper presents performance evaluation of some wire coil inserts, using a simple evaluation criterion to assess the possible energy benefit. Wire coil inserts, classical and modified, with different geometrical parameters in the ranges: $e/D = 0.06 - 0.12$, $p/e = 1.8 - 33.0$, *with working fluids as air or water in the range* $\mathrm{Re} = (0.4 - 1.2)\times 10^5$ *have been taken into consideration.*

Keywords: performance evaluation; wire coil inserts; turbulent flow.

INTRODUCTION

The heat transfer enhancement technology has been developed for many years by many researchers using both active and passive techniques. The active techniques increase the heat transfer rate in a heat exchanger with additional external power sources such as electrostatic fields, impinging jets, mechanical aids, surface/fluid vibration, and injection/suction fluid. The passive techniques are those that do not require additional external sources and include rough/extended surfaces, displaced enhancement devices, additives for liquids or gases, swirl generators (twisted tape, helical screw tape, snail entrance, axial/radial guide vane, propeller), and turbulators (wire coil, conical ring, etc.).

The heat transfer rate can be improved by introducing a disturbance in the fluid flow, but in the process, pumping power may increase significantly and ultimately the pumping cost can become high. Therefore, to achieve a desired heat transfer rate in an existing heat exchanger at an economic pumping power, several different techniques have been proposed in recent years.

Wire coils are a type of inserted elements which present some advantages compared to other enhancement techniques, such as artificial roughness by mechanical deformation. They may be installed in an existing smooth tube heat exchanger. Their installation is easy and their cost is very low.

The flow pattern is responsible for heat transfer enhancement and knowledge of it is very useful to optimize the geometry of enhancement techniques. Two basic types of flow can occur inside a ribbed tube enhanced with intermediate helix angles [1]. The first is the rotational flow mainly caused by the helix angle of the ribs. The extent to which this is carried from the near-wall region into the core depends on the existing flow conditions. The other type of flow commonly encountered in ribbed tubes is crossover flow. The momentum in the axial direction is much larger than the angular momentum caused by the ribs. One of the characteristics of this flow is the reattachment of the fluid to the surface between the ribs. An important design factor that controls this reattachment length is the ratio of rib pitch to height, p/e.

In an enhanced tube the type of flow depends, to a large extent, on the height e, helix angle β, and pitch of disruption p, Reynolds number *Re*, and to a lesser extent, on the profile shape.

The insertion of a device such as a wire coil inside a smooth tube produces an increase in the heat transfer due to one or more of the following phenomena [2]:

(i) Turbulence promotion: Wires attached to the wall cause separation in the flow that increases its turbulent level. They act also as roughness element mixing up the flow in the viscous sublayer.

(ii) Secondary flow promotion. Many inserted devices induce secondary flows which can favor thermal exchange. Helical wire coils produce a helicoidal flow at the periphery superimposed on the main axial flow. Due to the flow velocity increase and to the appearance of the centrifugal forces, convection increases.

(iii) Hydraulic diameter reduction. Any inserted element in the smooth tube will reduce the cross-sectional area increasing the average flow velocity. The wetted perimeter also increases and the hydraulic diameter decreases.

Many studies have been conducted to determine the effect of wire coil inserts on the heat transfer and friction factor [3-13]. Sethumadhavan and Raja Rao [1] studied the influence of the pitch, helix angle and wire diameter on the heat transfer and friction factor and used the a similarity law approach to interpret and correlate the results. Prasad and Shen [4] studied the effect of the wire coils on the heat transfer enhancement based on exergy analysis. Wang and Sunden [5] reported a comparison of the performance characteristics between twisted tape and wire coil inserts in

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both laminar and turbulent flow regimes. García et al. [6] reported the effect of helical wire coils fitted inside a round tube on the thermohydraulic behaviors in laminar, transition and turbulent flow using water and water-propylene glycol mixtures as a working fluid. García et al. [7] presented the flow mechanism in tubes with wire coils using hydrogen bubble visualization. Promvonge [8] reported the effects of wires with square cross section forming a coil as a turbulator on the heat transfer and turbulent flow friction behavior. Promvonge [9] also studied the influence of the insertion of wire coils in connection with a snail-type swirl generator mounted at the tube entrance on heat transfer and friction factor characteristics. The results revealed that the use of snail entry with coiled square wire provided higher heat transfer rate compared to the wire coil alone. Promvonge [10] examined the heat transfer and friction factor behaviors in a tube using wire coils with the twisted tape inserts. The results indicated that the presence of wire coil with twisted tape together leads to a double increase in heat transfer rate compared to the use of wire coil or twisted tape alone. Eiamsa-ard et al. [11] investigated the turbulent convective heat transfer in a tube fitted with two different wire coil inserts: (1) with typical/uniform coil pitch ratio and (2) with periodically varying three-coil pitch ratio. The experimental results showed that DI-coil (decreasing/ increasing three-coil pitch ratio arrangement performed better compared to the uniform-pitch ratio arrangement. San Jung et al. [12] studied experimentally air and water turbulent flow in smooth tubes with coiled-wire inserts to obtain heat transfer an pressure drop data and proposed the geometrical characteristics of the wire for efficiently enhanced heat transfer for air and water, respectively. Chang et al. [13] investigated experimentally thermal performance of the tubular flow enhanced by the grooved or/and ribbed square wire coils. Two sets of Nusselt number and friction factor correlations for turbulent flow are generated to assist to relevant applications.

The objective of this paper is to present a short review wherein the benefit of implementation of different kind of wire coil inserts is analyzed and evaluated using a simple criterion for preliminary assessment of their effectiveness.

EXPERIMENTAL RESULTS

Since the wire coil inserts are of practical interest, the data for heat transfer coefficient and friction factor are required to assess the benefit of their implementation in practice. Fig. 1 shows a smooth tube with wire soil insert. As aforementioned, the geometrical characteristics of the wire-coils are wire diameter or height of turbulator e, helix angle β, and wire pitch or pitch of disruption p. The geometrical parameters of the tubes under consideration in this study are presented in Tables 1-5, with the ratios e/D_i, p/e, p/D_i, and $\beta_* = \beta/90$, where D_i is the smooth tube inside diameter.

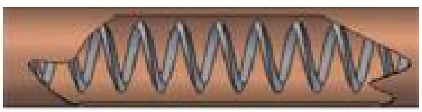

Fig. 1. Smooth tube with wire coil insert

The benefit that can be obtained from any heat transfer enhancement techniques depends on the variation of the ratios Nu/Nu_s and f/f_s with Reynolds number (subscript "s" denotes smooth pipe). Obviously, these ratios can be presented in the forms

$$f/f_s = f\left(\mathrm{Re}, e/D_i, p/e, \beta_*\right) \quad (1)$$

$$Nu/Nu_s = f\left(\mathrm{Re}, e/D_i, p/e, \beta_*\right) \; . \quad (2)$$

Some authors use the ratio p/D_i instead of p/e in Eqs. (1) and (2). Tables 1 and 2 present the geometrical parameters of the wire coil inserts studied in [3, 4]. From

Table 1 Geomertical parameters of wire coils [3]

No	D_i	p	e	p/e	e/D_i	β
	mm	*mm*	*mm*	-	-	-
1	25	66	2	33.00	0.08	0.555
2	25	38	2	19.00	0.08	0.713
3	25	22	2	11.00	0.08	0.826
4	25	10	2	5.00	0.08	0.919
5	25	66	3	22.00	0.12	0.555
6	25	38	3	12.67	0.12	0.713
7	25	22	3	7.33	0.12	0.826
8	25	10	3	3.33	0.12	0.919

Table 2 Geomertical parameters of wire coils [4]

No	D_i	p	e	p/e	e/D_i	β
	mm	*mm*	*mm*	-	-	-
611	14	8.47	0.813	10.42	0.058	0.879
612	14	5.08	0.813	6.25	0.058	0.927
613	14	3.63	0.813	4.46	0.058	0.948
614	14	2.82	0.813	3.47	0.058	0.959
621	14	8.47	1.016	8.34	0.073	0.879
622	14	5.08	1.016	5.00	0.073	0.927
623	14	3.63	1.016	3.56	0.073	0.948
624	14	2.82	1.016	2.78	0.073	0.959
631	14	8.47	1.575	5.38	0.113	0.879
632	14	5.08	1.575	3.23	0.113	0.927
633	14	3.63	1.575	2.30	0.113	0.948
634	14	2.82	1.575	1.79	0.113	0.959

these publications the forms of Eqs. (1) and (2) have been obtained through the experimental results depicted in the figures in [3, 4] as follows:

$$E_f \equiv f_R / f_S = c_f \,\mathrm{Re}^m \, , \quad (3)$$

$$E_h \equiv Nu_R / Nu_S = c_h \,\mathrm{Re}^n \, . \quad (4)$$

The values of c_f, c_h, m and n can be found in [13].

Table 3 Geomertical parameters of wire coils [6]

No	D_i	p	e	p/e	e/D_i	p/D_i
	mm	*mm*	*mm*	-	-	-
W01	18.00	21.12	1.34	15.76	0.074	1.17
W02	18.00	48.32	1.45	33.32	0.081	2.68
W03	18.00	30.66	1.40	21.90	0.077	1.70
W04	18.00	46.22	1.68	27.51	0.093	2.57
W05	18.00	33.57	1.79	18.75	0.099	1.86
W06	18.00	25.31	1.82	13.91	0.101	1.41

The geometrical parameters of the tube studied in [6] are presented in Table 3. The experimental correlations

$$f / f_s = 118.35(p/e)^{-1.16}\,\mathrm{Re}^{0.033}, \qquad (5)$$

$$Nu = 0.132(p/D_i)^{-0.372}\,\mathrm{Re}^{0.72}\,\mathrm{Pr}^{0.37}, \qquad (6)$$

and

$$Nu_s = 0.0147(\mathrm{Re}-1000)^{0.86}\,\mathrm{Pr}^{0.39}, \qquad (7)$$

have been used to calculate the ratios Nu/Nu_s and f/f_s at $\mathrm{Pr} = 7.0$ and $\mathrm{Re} = (3-30.0)\times 10^3$.

Table 4 contains the parameters of the tube studied in [10] where two different wire coils are introduced: with typical/uniform coil pitch ratios: CR1, CR2 and CR3, and two periodically varying three-coil pitch ratios: D and DI.

Table 4. Geomertical parameters of wire coils [10]

No	D_i	p	e	p/D_i	e/D_i
	mm	*mm*	*mm*	-	-
CR1	47.5	192	4.8	4	0.101
CR2	47.4	288	4.8	6	0.101
CR3	47.5	384	4.8	8	0.101
D	47.5		4.8	8:6:4:8:6:4	0.101
DI	47.5		4.8	8:6:4:4:6:8	0.101

The experimental data are fitted by the following empirical equations in the range $\mathrm{Re} = (4.5-20.0)\times 10^3$.

- Correlations for typical/uniform coil pitch ratio (CR):

$$Nu = 0.0545\,\mathrm{Re}^{0.767}\,\mathrm{Pr}^{0.4}\,CR^{\,0.02}, \qquad (8)$$

$$f = 6.47\,\mathrm{Re}^{-0.243}\,CR^{\,-0.375}. \qquad (9)$$

- Correlations for periodically varying coil pitch ratios, D-coil:

$$Nu = 0.042\,\mathrm{Re}^{0.81}\,\mathrm{Pr}^{0.4}, \qquad (10)$$

$$f = 3.67\,\mathrm{Re}^{-0.223}. \qquad (11)$$

- Correlations for periodically varying coil pitch ratios, DI - coil:

$$Nu = 0.06\,\mathrm{Re}^{0.77}\,\mathrm{Pr}^{0.4}, \qquad (12)$$

$$f = 4.22\,\mathrm{Re}^{-0.24}. \qquad (13)$$

The next experimental results that have been assessed in this study are those of San Jung-Yang at al. [11]. The geometrical parameters of the wire coils used in this study are presented in Table 5.

Heat transfer and pressure drop data for air and water flow were measured and correlated as follows:

- heat transfer data for air

$$Nu = 0.00585\,\mathrm{Re}^{0.51+6.16(e/D_i)-23.15(e/D_i)^2}\times$$

$$\left[(e/D_i)^2 - 0.0042\right]^{-0.24}(p/D_i)^{-0.22}. \qquad (14)$$

for $\mathrm{Re} = 3700-17200$.

Table 5. Geomertical parameters of wire coils [11]

No	D_i	p	e	p/e	e/D_i
	mm	*mm*	*mm*	-	-
11	12.8	18	1	18.00	0.078
12	12.8	24	1	24.00	0.078
13	12.8	32	1	32.00	0.078
14	12.8	18	1.4	12.86	0.109
15	12.8	24	1.4	17.14	0.109
16	12.8	32	1.4	22.86	0.109
17	12.8	18	1.8	10.00	0.141
18	12.8	24	1.8	13.33	0.141
19	12.8	32	1.8	17.78	0.141

- heat transfer data for water

$$Nu = 2.55\,\mathrm{Re}^{0.57}(e/D_i)^{-0.17(p/D_i)+0.65}(p/D_i)^{-1.13} \qquad (15)$$

for $\mathrm{Re} = 5510-15080$.

- correlation for fluid friction data

$$f = 36.16\,\mathrm{Re}^{-0.36}(e/D_i)\left[\ln(p/D_i)\right]^{-0.52} \qquad (16)$$

in the range $\mathrm{Re} = 4000-19200$.

The last study investigated in this research is that of Chang et al. [12]. Thermal performances of the tubular flows enhanced by grooved or/and ribbed square wire coils with five pitch ratios p/D_i as 0.5, 1.0, 1.5, 2.0, 2.5 in the range $\mathrm{Re} = 10^4 - 4\times 10^4$ are experimentally examined, and correlations for Nusselt number and friction factor are obtained in the form

$$Nu/\mathrm{Pr}^{1/3} = A\times \mathrm{Re}^B, \qquad (17)$$

$$f = C_0 + C_1\times \exp(-C_2\,\mathrm{Re}), \qquad (18)$$

where the coefficients A, B, C_0, C_1 and C_2 are functions of p/D_i and varied with the type of wire coil insert. The numerical values of these coefficients can be found in [12], Tables 2 and 5.

PERFORMANCE EVALUATION AND DISCUSSION

Many performance evaluation criteria (PEC) have been developed for evaluating the performance of heat exchangers. They may be categorized as criteria based on the first law of thermodynamics [14], and criteria based on the second law of thermodynamics [15]. The performance evaluation of heat transfer enhancement in studies [3, 6, 10 - 12] was performed on the base of first law analysis, whereas this one in [4] – on the base of second law analysis.

A widely used method to evaluate the benefit of an enhanced heat transfer surface is to compare the performance of the enhanced surface with that of the corresponding plain (smooth) surface. The benefit depends on the goal to be achieved and the constraints imposed of the comparison. In general, the performance evaluation includes three considerations: the performance objective, operation conditions and constraints. The potential objectives could be: increased heat transfer rate, reduced pumping power, or reduced size of the heat exchanger. Possible constraints are: fixed mass flow rate, heat flow, pumping power, size of the heat exchanger, etc. The major operational variables include the heat transfer rate, fluid pumping power or pressure drop, flow rate, and fluid velocity. A PEC is established by selecting one of the operational variables for the performance objective subject to design constraints on the remaining variables.

The most common PEC, used by many researchers for easy evaluation of the practical application of heat transfer enhancement, are those proposed by Bergles et al. [16]. When the PEC are directed to evaluate the improvement of existing exchanger, then the basic geometry is fixed, and relationships are obtained related to the increase of heat flow or decrease in pumping power. If the objective is more heat flow to be transferred, this criterion is known as R_3 [16]

$$R_3 = \left(\frac{h}{h_s}\right)_{D,L,N,P,T_{in},\Delta T} = \frac{\dot{Q}}{\dot{Q}_s}. \qquad (19)$$

In this case, the process constraints are: fixed pumping power P, inlet fluid temperature T_{in}, and driving temperature difference ΔT. The constraint of equal pumping power requires different Reynolds numbers for the working fluid in reference and augmented channels, $\mathrm{Re} < \mathrm{Re}_s$, and

$$f(\mathrm{Re})\mathrm{Re}^3 = f_s(\mathrm{Re}_s)\mathrm{Re}_s^3. \qquad (20)$$

Consequently, the corresponding heat transfer coefficients in Eq. (19) should be calculated at these Reynolds numbers and Eq. (19) yields

$$R_3 = \frac{Nu(\mathrm{Re})}{Nu_s(\mathrm{Re}_s)} = \frac{\dot{Q}}{\dot{Q}_s}. \qquad (21)$$

It must be emphasized that the criterion R_3 has been developed with the assumptions of negligible external thermal resistance, $R_{ext} = 0$, and equal temperature difference ΔT in the comparative heat exchangers. In general, however, the ΔT will decrease due to the increased rate of heat transfer [16].

Sano and Usui [18] suggested evaluation of the heat transfer promoters by fluid dissipation energy, developing a criterion based on the correlation of the heat transfer coefficient as a function of the energy dissipation per unit mass of fluid (ε). For turbulent flow, this criterion takes the form [18]

$$i_E = \frac{Nu/Nu_s}{(f/f_s)^{0.291}} = f(\mathrm{Re}). \qquad (22)$$

It is important to note that the criterion i_E is identical to R_3 criterion of Bergles et al. [16], but is more convenient to use since the Nusselt numbers Nu, Nu_s, and friction factors f, f_s are defined at one and the same Reynolds number Re. It should also be emphasized that the two heat exchangers must work in turbulent regime, $\mathrm{Re} > 3\times10^3$, and $\mathrm{Re}_s > \mathrm{Re}$.

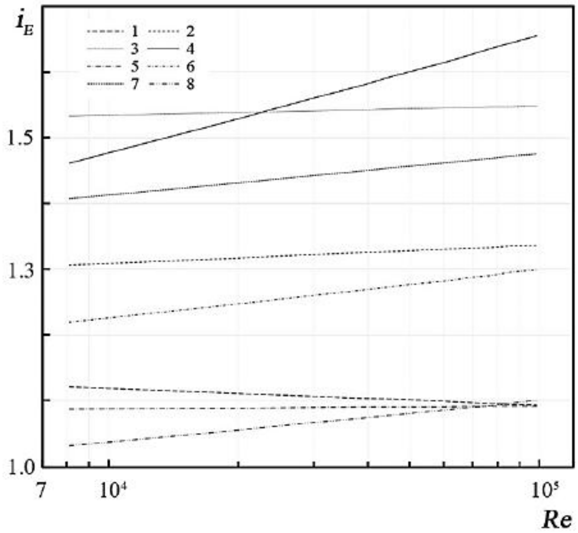

Fig. 1. The variation of i_E with Reynolds number . Experimental results of Sethumadhavan and Rao [3]

Fig.1 presents the variation of the criterion i_E with the Reynolds number in the augmented channel for the experimental results of Sethumadhavan and Rao [3]. As seen, all tubes 1-8 performed with $i_E > 1$ and the variation with the Reynolds number, excluding tube 4, is small. However, the benefit of some of them is very small, tubes 1, 5, 8. The greatest profit can be obtained by using the tubes 3 and 4 despite the fact that tube 4 behaves something strange. The comparison with the results published in [3] using the criterion R_3 and those in this study showed that the benefit assessed by criterion i_E is smaller than this one calculated through the criterion R_3. The performance ratio in [3] was not only evaluated as the ratio h/h_s but also as

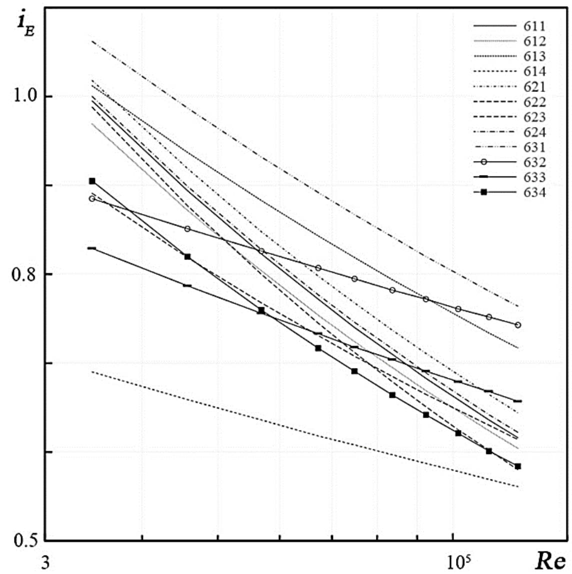

Fig.2. The variation of i_E with Reynolds number. Experimental results of Prasad and Shen [4].

U/U_s (ratio of the overall heat transfer coefficients) in view of the fact that *r* (the ratio of combined outside film and metal wall resistance to the inside film resistance) is not zero, but ranged from 0.3 to 2.5 for the overall range of Reynolds number studied. In this case the results for R_3 are smaller. As a result, it can be concluded that tube 3 is the most efficient from the all eight tube studied with performance ratio $i_E = 1.53 - 1.55$.

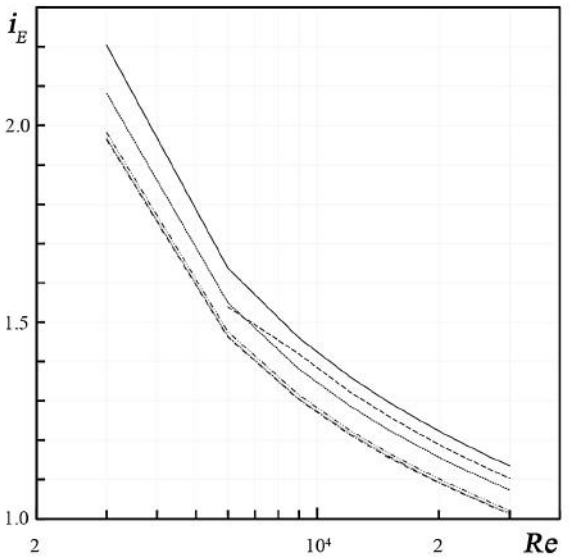

Fig.3. The variation of i_E with Reynolds number. Experimental results of García et al. [6].

Fig. 2 shows the variation of the criterion i_E with the Reynolds number for the experimental results of Prasad and Shen [4]. As seen, the evaluation of thermal performance of all tubes studied is negative, $i_E < 1$. That means that these combinations of geometrical parameters of the wire coils are not appropriate for heat transfer enhancement and should be declined.

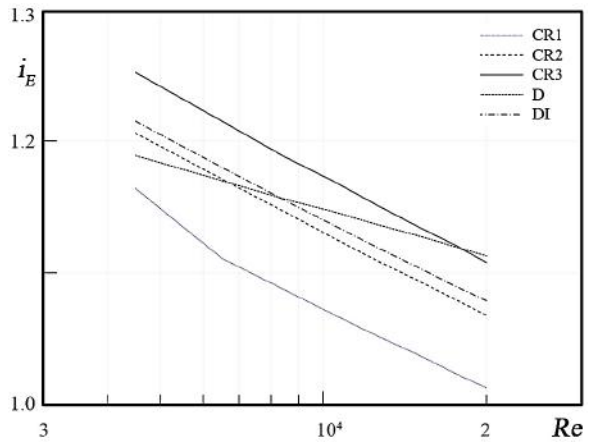

Fig.4. The variation of i_E with Reynolds number. Experimental results of Eiamsa-ard S. et al. [10].

Fig. 3 shows the variation of the performance parameter i_E for six wire coil inserts at $\mathrm{Pr} = 7$ (water) for the experimental results obtained by García et al. [6]. As seen, for all tubes tested $i_E > 1$, but the performance of tube W01 is the best, $2.20 > i_E > 1.14$. At $\mathrm{Re} > 3 \times 10^4$, the analysis allows to state that these wire coils are not advantageous. Even though the best tube W01 shows performance parameter $i_E < 1.10$. This fact significantly differs from Sethumadhavan and Rao [3] results which depend on wire geometry but not on Reynolds number.

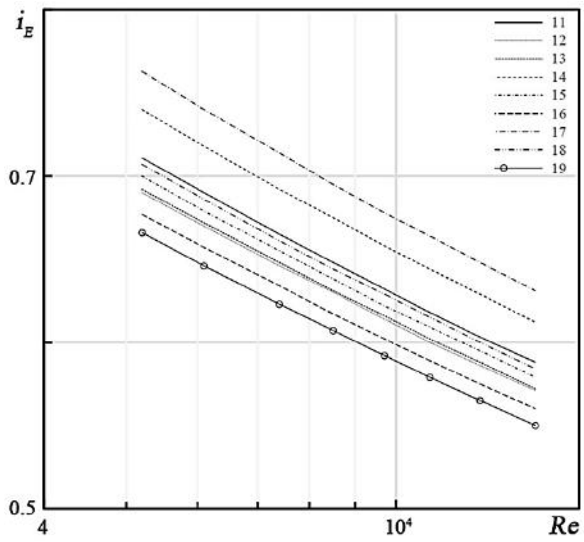

Fig.5. The variation of i_E with Reynolds number. Experimental results of San Jung-Yang et al. [11], Pr=6.2.

Fig. 4 presents the variation of i_E with Re, calculated by means of the experimental results of Eiamsa-ard et al. [10]. As seen, the DI-coil (decreasing/ increasing three-coil pitch ratio arrangement) performed better compared to the other tubes studied (highest values of i_E). However, the values of i_E are strongly dependent on Reynolds numbers and quickly decrease with the increase of Re in the range of study. At the end of the region, $\mathrm{Re} = 2 \times 10^4$, the benefit is only 10%.

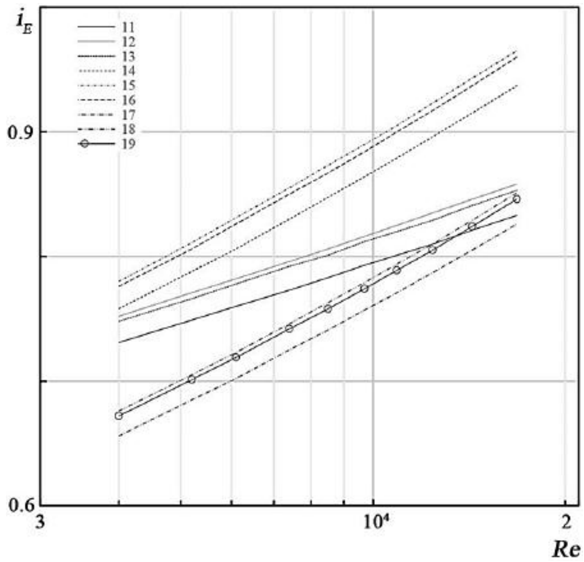

Fig.6. The variation of i_E with Reynolds number. Experimental results of San Jung-Yang et al. [11], Pr=0.7.

The variation of i_E with Re, using the experimental results of San Jung-Yang et al. [11] for water ($\mathrm{Pr} = 6.2$) and air ($\mathrm{Pr} = 0.7$) is presented in Figs. 5 and 6. It is interesting to note that for water the values of i_E gradually decrease when the Reynolds increase, and on the contrary for air they gradually increase. Nevertheless, the benefit remains negative, $i_E < 1$. In this respect, the combinations of these geometrical parameters of wire-coil inserts cannot be recommended for practical implementation.

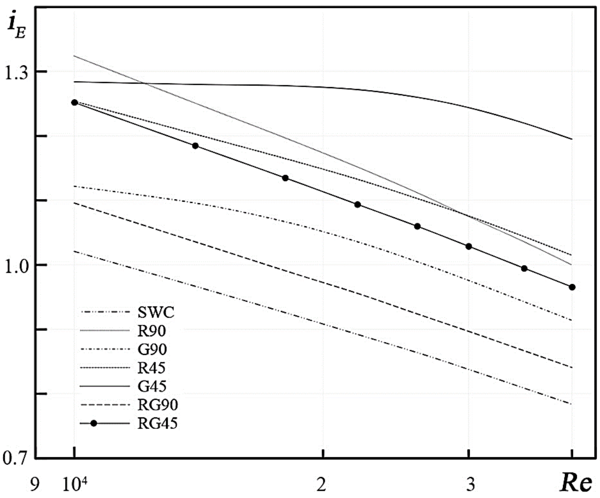

Fig.7. The variation of i_E with Reynolds number. Experimental results of Chang et al. [12], $p/D_i = 0.5$.

The evaluation of the experimental results of Chang et al. [12] through the performance parameter i_E is shown in Figs. 7-11. As seen from the figures, tube G45 shows the highest value of i_E for relative pitches $p/D_i =$ 0.5, 1.0, 1.5, 2.0. Only for $p/D_i = 2.5$ and $\mathrm{Re} < 3\times10^4$, tube R90 performs better than G45. It should be noted that the values of i_E for tube G45 decrease slowly with the increase of

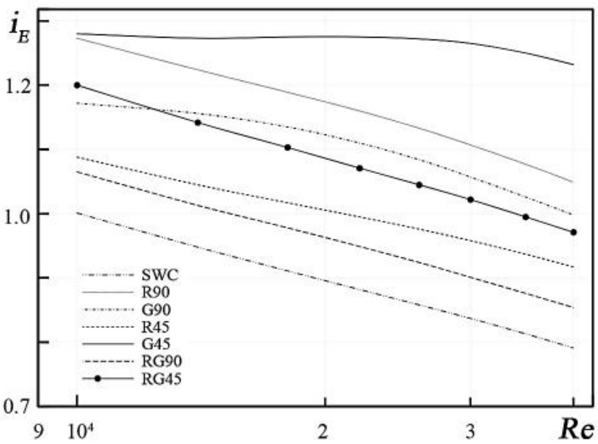

Fig.8. The variation of i_E with Reynolds number. Experimental results of Chang et al. [12], $p/D_i = 1.0$.

Reynolds number, $1.28 > \mathrm{Re} > 1.20$. For relative pitch $p/D_i = 2.5$ and $\mathrm{Re} > 3\times10^4$, the performance parameter for all tubes is $i_E < 1$ and these heat transfer enhancement techniques must be declined for any further consideration.

An examination of the articles [3, 4, 6, 11, 12] reveals that many different performance evaluation criteria have been used by the authors, some of them quite ambiguous. For instance, the criterion R_3, Eq. (21), has been applied in a right way only in [3, 6]. The comparison between the values of R_3 and i_E obtained by the experimental results of García et al. [6] showed practically no difference.

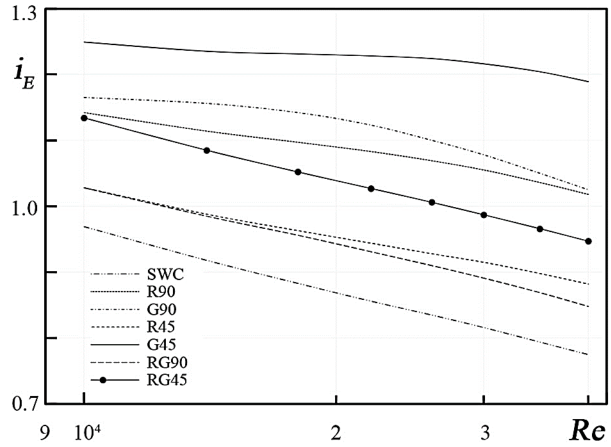

Fig.9. The variation of i_E with Reynolds number. Experimental results of Chang et al. [12], $p/D_i = 1.5$.

Prasad and Shen [4] used criterion derived from the second law of thermodynamics (exergy analysis) that do not permit easy comparison with the benefit from the other studies, evaluated by criterion derived by the first law of thermodynamic.

Eiamsa-ard et al. [10] used the criterion R_3 in the form

$$\eta = \left.\frac{h}{h_s}\right|_{pp} = \left.\frac{Nu}{Nu_s}\right|_{pp} = \left(\frac{Nu}{Nu_s}\right)\left(\frac{f}{f_s}\right)^{-1/3} . \quad (23)$$

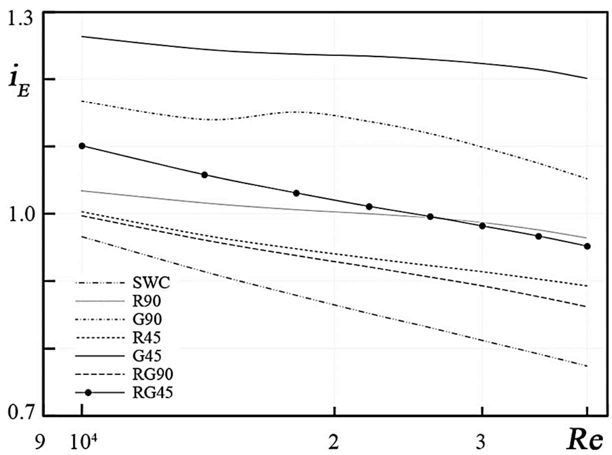

Fig.10. The variation of i_E with Reynolds number. Experimental results of Chang et al. [12], $p/D_i = 2.0$.

The definition of η is ambiguous and not sufficiently correct. Using the criterion, Eq. (23), Eiamsa-ard et al. [10] declared a maximum thermal performance factor for using CR3 about 1.14-1.02 in the range $4\times10^3 < \mathrm{Re} < 2\times10^4$. If the criterion i_E is used its value is 1.25-1.11 in the range of Reynolds number studied.

San Jung-Yang et al. [11] used two performance indexes r_1 and r_2, where $r_1 = Nu/Nu_s$ whereas r_2 is

$$r_2 = \frac{Nu/Nu_s}{f/f_s}. \quad (24)$$

According to these criteria they recommended wire coils with geometrical parameters as follows: if water was the working fluid, the $e/D_i = 0.101$ and $p/D_i = 1.739$ (tube 15); if air was the working fluid, the $e/D_i = 0.101$ and $p/D_i = 2.319$ (tube 16). A look on Figs. 5 and 6 reveals that in the both cases the best performance parameter i_E can be obtained by the use of tube 15. As aforementioned, however, $i_E < 1$, and no any benefit can be brought about by implementation of these wire coil inserts.

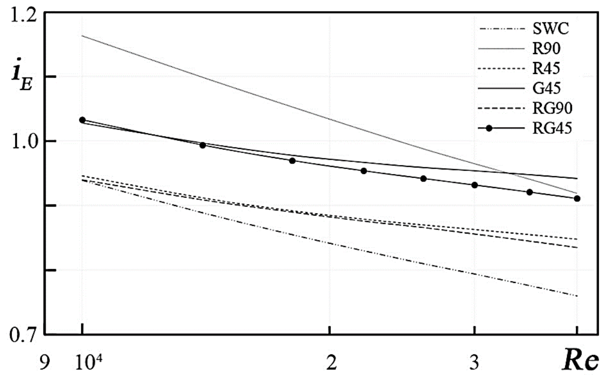

Fig.11. The variation of i_E with Reynolds number. Experimental results of Chang et al. [12], $p/D_i = 2.5$.

Chang et al. [12] evaluated the possible benefit that can be obtained implementing these kinds of wire-coil inserts, through the thermal performance factor (*TPF*). They also used the criterion R_3 in the form, Eq. (23),

$$TPF = \left(\frac{Nu}{Nu_s}\right)\left(\frac{f}{f_s}\right)^{-1/3} = f(\mathrm{Re}). \quad (25)$$

The difference between Eqs. (23) and (25) is that the Nusselt number and friction factor in Eq. (25) are calculated at one and the same Reynolds number. If Eq. (25) is compared with Eq. (22), it is obviously that different evaluation for the benefit will be obtained.

CONCLUSIONS

Performance evaluation of some wire coil inserts, using the experimental results [3, 4, 6, 10-12] has been fulfilled by means a simple evaluation criterion i_E to assess the possible energy benefit, according to the geometrical parameters of the wire coils and Reynolds number of the working fluid. Wire coils with geometrical parameters in the range $e/D = 0.06 - 0.12$, $p/e = 1.8 - 33.0$, and fluid flow in the range $\mathrm{Re} = (0.4 - 1.2)\times10^5$ have been taken into consideration. The working fluid in the studies was air and water. The results can be summarized as follows:

(i) All wire coil inserts studied by Prasad and Shen [4] and San Jung-Yang et al. [11] have shown negative benefit, $i_E < 1$, and should be discarded.

(ii) At some extent, the benefit obtained from the other studies is positive, $i_E > 1$. With the exception of the results of [3], the common tendency of the others [6, 10, 12] is that the benefit decreases quickly when the Reynolds number increases, Figs. 3, 4. The tubes with the greatest benefit are as follows: 3 and 4 [3], $i_E = 1.45 - 1.65$; W01 [6] $i_E = 2.20 - 1.15$; CR3 [10], $i_E = 1.25 - 1.11$; and G45 [12] with $i_E = 1.28 - 1.20$.

The geometrical parameters of the tubes with the greatest performance parameter are as follows: (classical wire coil inserts) tubes 3 and 4 [3] with parameters - $e/D_i = 0.08$, $p/e = 11$ and $e/D_i = 0.08$, $p/e = 5$; W01 [6] - $e/D_i = 0.074$, $p/e = 15.76$; (modified wire coil inserts): CR3 [10] - $e/D_i = 0.101$, $p/D_i = 8$; G45 [12] - $e/D_i = 0.094$ and $p/D_i = 0.5$.

(iii) It should be emphasized that the criterion i_E can be used only as a preliminary design guidance to the selection of any heat transfer enhancement technique. Similarly to the criterion R_3 it suffers from the same defects, particularly the assumption of equal ΔT. The benefit obtained by using i_E is too optimistic and non-real, since the real benefit is much lower, and in many cases, might be negative instead of positive as expected.

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