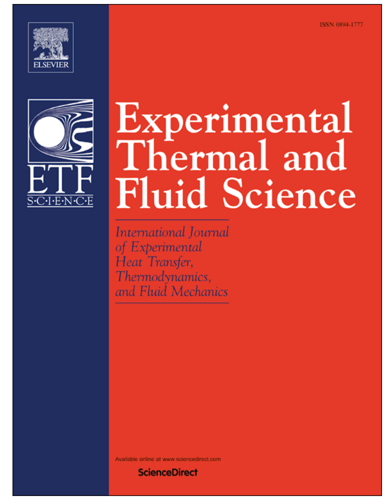
Accepted Manuscript



Experimental Correlations on Critical Reynolds Numbers and Friction Factor in Tubes with Wire-coil Inserts in Laminar, Transitional and Low Turbulent Flow Regimes

J. Pérez-García, A. García, R. Herrero-Martín, J.P. Solano

PII: S0894-1777(17)30299-6
DOI: https://doi.org/10.1016/j.expthermflusci.2017.10.003
Reference: ETF 9227

To appear in: *Experimental Thermal and Fluid Science*

Received Date: 28 July 2017
Revised Date: 14 September 2017
Accepted Date: 3 October 2017

Please cite this article as: J. Pérez-García, A. García, R. Herrero-Martín, J.P. Solano, Experimental Correlations on Critical Reynolds Numbers and Friction Factor in Tubes with Wire-coil Inserts in Laminar, Transitional and Low Turbulent Flow Regimes, *Experimental Thermal and Fluid Science* (2017), doi: https://doi.org/10.1016/j.expthermflusci.2017.10.003

Experimental Correlations on Critical Reynolds Numbers and Friction Factor in Tubes with Wire-coil Inserts in Laminar, Transitional and Low Turbulent Flow Regimes

J. Pérez-García*, A. García, R. Herrero-Martín, J.P. Solano

Departamento Ingeniería Térmica y de Fluidos
Universidad Politécnica de Cartagena
Campus Muralla del Mar
30202 Cartagena (Spain)

* Corresponding author: pepe.perez@upct.es

Abstract

This paper analyses 23 circular helicoidal wire-coils with different geometric characteristics ranging from: dimensionless pitch p/d=[0.25-3.37], dimensionless thickness e/d=[0.071-0.286] and a Reynolds number interval from 50 to 8000. This interval widely includes the Reynolds number range in which rigid wire-coil inserts present better performance as passive enhancement technique for tubular heat exchanger applications Re=[200-2000]. Based on their hydraulic performance, the wire-coil inserts are categorized according to a new dimensionless parameter: the *Transition Shape Parameter* (TSP). A new set of correlations are obtained to predict the Fanning friction factor coefficient as a function of Reynolds number and geometrical characteristics of the insert within the three flow regimes: laminar, transitional and low turbulent. Additional correlations are proposed to estimate the critical Reynolds number at the beginning and ending of the transition region, which allows to select the most adequate friction factor correlation as a function of the operational Reynolds number for a heat exchanger design application. Finally, a comparative between the proposed and the published correlations in the open literature for laminar and turbulent regimes is presented. This brings to light the need and interest of having the suitable and reliable set of correlations presented in this paper to compute the friction coefficient covering all the wire-coil applicability range as an enhancement technique.

Keywords: Wire-coil-inserts, friction factor correlations, critical Reynolds numbers, transition flow, laminar flow, low turbulent flow

Nomenclature

c_p	[J/kgK]	Specific heat
d	[m]	Internal tube diameter
d_h	[m]	Hydraulic diameter
e	[m]	Wire-coil diameter
f	--	Fanning friction factor
f_D	--	Darcy-Weissbach friction factor.
G	[kg/s]	Mass flow rate
k	[W/mK]	Thermal conductivity
l_e	[m]	Entrance pipe length in test pressure
l_p	[m]	Distance between pressure tapes in pressure tests
p	[m]	Wire-coil pitch
Δp	[Pa]	Pressure drop
t	[º C]	Static temperature
t_m	[º C]	Mean static fluid temperature in pressure tests

Special Characters

β	[K^{-1}]	Coefficient of thermal expansion
ρ	[kg/m^3]	Fluid density
μ	[Pa.s]	Fluid dynamic viscosity

Parameters

Re	Reynolds number
Pr	Prandtl number
TSP	Transition Shape Parameter

Subscripts

CL	Critical conditions (ending laminar flow regime)
CT	Critical conditions (beginning low turbulent flow regime)
H	High TSP
I	Intermediate TSP
in	Inlet static fluid temperature in test pressure
L	Low TSP
m	Mean static fluid temperature in test pressure
out	Outlet static fluid temperature in test pressure
s	Smooth
T	Turbulent fluid flow regime
Tr	Transition fluid flow regime

1. Introduction

Heat exchangers are widely used in the process industry. The shell and tube configuration is the most commonly employed due to its robustness, wide operational working fluids, pressure and volumetric flow ranges, mechanical reliability and availability. For this configuration, there exists many well-established and reliable design procedures and computational codes. The vast majority of these exchangers have smooth tubes; nevertheless, the use of enhancement techniques allows to build more compact and efficient designs.

Webb and Kim [1] claim that the most economically viable enhancement techniques are roughness surfaces and insert devices. Amongst roughness surfaces, the corrugated and dimpled tubes stand out due to its structural simplicity and low cost characteristics. These integral roughness tubes are widely used in turbulent flow and they are thoroughly used in single-phase and two-phase flows. Regarding conventional insert devices, they are grouped into five types: twisted tapes, extended surfaces, wire-coils, meshes and wall separated insert devices. The most studied insert device is twisted-tapes. Many design correlations are available for laminar, transitional and turbulent flow regimes that ease the practical implementation of twisted-tapes as enhancement technique.

Liu and Sakr [2] and Sheikholeslami et al. [3] carried out literature reviews of the different enhancement techniques used in heat exchangers. They enumerate the advantages and disadvantages of them and specify the feasible engineering applications. Regarding the applicability of wire-coils, the insert device studied in this work, they are currently employed in low Reynolds number applications such as: solar water heating, oil cooling devices, or pre-heaters and fire boilers [2], whereas in [3] are also mentioned: chemical process plants, refrigeration systems and air conditioning, food and dairy processes and heat recovery processes.

2. Literature review

Webb and Kim [1] established that the determining factor to employ an enhanced heat exchanger is the cost (including manufacturing and installation costs). They criticized the search of greater and greater complex geometric designs, without taken into account manufacturing difficulties and the corresponding repercussion on equipment cost. From this perspective, and considering that wire-coil use is less spread (mainly in laminar flow regime), an in-depth study, about this conventional insert device, has a special interest, due to their three inherent interesting advantages. First, wire-coils have lower pressure drop than other inserts that produce a more severe flow obstruction under similar flow conditions. Second, regarding artificial roughness techniques manufactured by cold external deformation, wire-coils do not modify the mechanical properties of the smooth tube, a key factor within petrochemical plants. Third, wire-coils can be inserted within smooth tube heat exchangers “in operation” conditions and can be easily removed in case of soiling or fouling, which make them very competitive in terms of ease of manufacturing and implementation and maintenance costs.

In this section, the most important experimental works in wire-coil inserts are summarized. These studies address the wire-coil thermal-hydraulic behaviour as an enhancement technique for heat exchanger applications, and, some of them provide correlations to obtain friction factor in laminar and/or turbulent flow regimes. For the transition region, friction factor correlations are not available in the open literature. Furthermore, a brief summary of combined inserts, non-conventional complex techniques, or nanofluid studies are reported, and the corresponding available correlations for friction factor calculation are summarized.

2.1 Studies on conventional wire-coils under laminar and transition regimes

The first notable work was carried out by Uttarwar and Rao in 1985 [4]. The authors obtained the friction factor coefficient in tubes fitted with wire-coil inserts using Servotherm Oil as the working fluid for the Reynolds number range [30-700]. They reported very low pressure drop augmentations with regard to the smooth tube, between 5-8%. Nevertheless, their tests were carried out under non-developed fluid flow conditions, fact that may jeopardize the reliability of the results.

Obot et al. [5] employed other authors results in tubes with transversal ribs, to study the friction factor in the transition region. They established the lack of available data within this flow region. They confirmed that enhancement surfaces create an early transition. Oliver and Shoji [6] compared different insert devices: meshes, twisted-tapes and wire-coils using sodium carboxymethylcellulose in water, as the working fluid for Reynolds numbers [200-2000]. They obtained similar pressure drop values than reported in [4], but they neither provide data correlations. They concluded that for Re<200 the best insert was the mesh specimen, and for Re≥200, the wire-coils increase heat transfer coefficient similarly to twisted tapes, but with a lower increase in pressure losses.

Chen and Zhang [7], Inaba et al. [8], and Nazmeev et al. [9], carried out experimental studies for wire-coils with different geometric characteristics, using different working fluids, covering the laminar, transition and low turbulent flow regime. They proposed the first friction factor correlations. It should be outlined that the correlation proposed in [8] is only valid in the turbulent flow region. Reference [9] provides the only available correlation in the open literature to define the critical Reynolds number for laminar-turbulent transition.

Tauscher and Mayinger [10] showed the effectiveness of roughness elements in the transition region, as later confirmed by Bergles [11]. Wang and Sunden [12], and Dewan et al. [13] compared different enhancement techniques and obtained pressure drop augmentations of only 8% using wire-coils inserts for Re=2000. Correlations were not provided.

Garcia et al. [14, 15] studied wire-coil behaviour in laminar, transition and low turbulent regimes providing specific correlations attending to each wire-coil geometry in laminar flow and a generalized correlation for turbulent flow and the set of wire-coils studied. They concluded that for Re<200, flow remains almost unaltered, accelerating the transition to turbulence at critical Reynolds numbers down to 700. Wire-coils were reported as the best performance inserts in the transition region, which was significantly modified regards to smooth tube. Based on wire-coil geometry, different trends were observed, covering a wide region from Re [300, 3000]. Wire coil inserts exhibit significant advantages over other enhancement techniques offering a predictable transition region.

Akhavan-Behabadi [16], and Roy and Saha [17] gave correlations for friction factor. The proposed correlation in [16] is valid for wire-coils of 2 mm thickness and only depends on Reynolds numbers from [20-500]. In [17] a generalized correlation is presented as a function of the wire-coil helix angle and the dimensionless thickness, valid for Re [15-1000], despite testing only three wire-coils.

In summary, the available correlations to predict friction factor in laminar regime are scarce and were obtained by testing a limited number of wire-coils (see

Table **1**). In some cases, the validity ranges (Reynolds numbers) of the correlations are not specified, and in others, the correlations are only valid for the singular wire-coil geometries tested in their study. Furthermore, sufficient information utterly verified is not provided to adequately determine the critical Reynolds numbers at the beginning and ending of the transition region. In this work, a novel set of correlations for friction factor under laminar regime was obtained and compared with the correlations available in open literature. The proposed correlations will be applicable to a significant wider geometrical range than previous works. Moreover, a correlation for the critical Reynolds number where laminar flow region ends was provided.

Authors	N_{wire}	Re	p/d	e/d	d (mm)	Working fluid (Pr)	Correlation proposed/Comments
Chen and Zhang (1993) [7]	8	273 – 2456	0.33 – 1.3	0.056 – 0.133	10	Turbine oil (194 – 464)	$f = 95.049 Re^{-0.129} Pr^{-0.23} (p/d)^{0.848} (p/e)^{-1.428}$ Non-isothermal
Nazmeev et al. (1994) [9]	7	40 – 2000	0.71 – 4.3	0.071 – 0.17	14	Transformer oil	$Re^* = 415 (p/d)^{0.73} \exp(-7.8 \cdot (e/d))$ $f_D = 64/Re \cdot \exp\left[-(p/d)^{0.5}\right] \exp\left[5.5 (e/d)^{0.4}\right]$ for Re<Re* $f_D = 530/Re^{0.36} (e/d)^{1.4} \exp\left[-(p/d)^{0.65}\right]$ for Re>Re*
García et al.. (2007) [15]	6	$40 – 8.10^4$	1.25 – 3.37	0.076	18	Water and Water - Propylene Glycol mixtures 50% (3.9 – 8.2)	Friction coefficient correlation only for specific wire coils e/d=0.076 $f = 14.5/Re^{0.93}$ valid for wire W01 p/d=1.25 [Re<400] $f = 14.8/Re^{0.95}$ valid for wire W02 p/d=1.72 [Re<450] $f = 13.3/Re^{0.97}$ valid for wire W03 p/d=3.37 [Re<700]
Akhavan-Behabadi (2010) [16]	7	10 – 1500	0.46 – 2.65	0.08 - 0.13	26	Engine oil (120 – 300)	$f = 16.8/Re^{0.96}$ valid for an specific wire of e=2mm [20≤Re<500]
Roy and Saha (2015) [17]	3	15 – 1000	0.77 – 1.54	0.0526, 0.0625, 0.07692	13, 16 and 19	Servotherm oil	$f \cdot Re = 3.55827 Re^{0.32281} (\sin\alpha)^{0.25811} (e)^{0.33739}$ with "e" in (mm)

Table 1. Available correlations in laminar flow regime for tubes fitted with wire-coils

2.2 Studies on conventional wire-coils under turbulent flow

The earliest remarkable works on turbulent flow were developed by Kumar and Judd [18], and Klaczak [19]. Both studies employed water as the working fluid for Reynolds numbers ranging from [$7 \cdot 10^3$ - $1 \cdot 10^5$] and [$1.7 \cdot 10^3$ - $2 \cdot 10^4$], respectively. The results obtained by Kumar and Judd showed an increase on pressure drop of 15 times regarding smooth tube. Afterwards, Chiou [20] carried out an extensive experimental work testing a wide number of wire-coils under turbulent flow regime. Nevertheless, in these three works friction factor correlations were not given.

The first friction factor correlation for turbulent flow in pipes with wire-coil inserts was developed by Sethumadhavan and Rao [21]. These authors tested wire-coils with different geometries for the Reynolds number range [$4 \cdot 10^3$ - $1 \cdot 10^5$]. They reported relatively low pressure drop increments, around 3-fold relative to a smooth tube. They correlated the experimental results using friction similitude laws, which are only valid for integral roughness techniques, but not for wire-coil inserts.

Zhang et al. [22] tested a wide number of wire-coils. Their work is considered as one of the most rigorous and reliable on this topic. They studied circular and rectangular wire-coils and did not report significant differences among them. The pressure drop increment obtained was between 4 and 9-fold relative to a smooth tube. They employed air as the working fluid and covered a Reynolds number interval [$6 \cdot 10^3$ - $1 \cdot 10^5$], obtaining a set of correlations for both wire-coil types as a function of dimensionless pitch and Reynolds number.

Rabas [23] analysed a broad experimental pressure drop data set in wires from previous authors, and evaluated the convenience of employing the discrete-element method to predict wire-coil friction factor. However, he finally advised against using this method. In a later paper, Ravigururajan and Rabas [24] presented heat transfer and friction factor data for different enhanced tubes (extruded tubes, ribs or disruptions with transverse and intermediate helix angles, spirally indented tubes, and tubes fitted with coil inserts) in turbulent flow regime. The authors only reported the data corresponding to a p/d=9.5 and e/d=0.038 wire-coil but concluded that in terms of performance wire-coil inserts were very similar to discrete extruded disruption tubes.

Inaba et al. [7] and García et al. [14], as mentioned in subsection 2.1, tested a wide set of wire-coils, using water as the working fluid and for Reynolds number ranging from [200 - 6000] and water and propylene-glycol mixtures as the working fluid [80 – $9 \cdot 10^4$], respectively. Both studies covered laminar, transitional and low turbulent regimes. The proposed correlations depended on Reynolds number, (p/e) [7], (p/d) [14] and (e/d) and were only valid for turbulent regime.

Naphon [25] studied heat transfer and friction factor in a concentric tube. The inside tube was fitted with a wire-coil separated from the wall. The author defined a non-isothermal friction factor correlation for the inside enhanced tube flow valid for Reynolds numbers from 5000 to $2.5 \cdot 10^4$.

Authors	N_{wire}	Re	p/d	e/d	d (mm)	Working fluid (Pr)	Correlation proposed/Comments
Sethumadhavan and Rao (1983) [21]	8	$4000 – 1.10^5$	0.4 – 2.64	0.08 – 0.12	25.0	Water/glycerol (5.2-32)	$f = \frac{2}{\left(R(h^+) - 2.5\log_{10}(2e/D_h) - 3.75\right)^2}$ with $R(h^+) = 7(\tan\alpha)^{-0.18}(h^+)^{0.13}$ h^+ roughness Reynolds number
Zhang et al. (1991) [26]	32 (12 Circ. cross-section)	$6000 – 1.10^5$	0.35 – 4.6	0.035 - 0.18	56.3	Air (0.7)	Wire coil with circular cross-section [0.037≤e/d<0.1] [0.35≤p/d<2.5] $f_D = 62.36(\log Re)^{-2.779}(e/d)^{0.816}(p/d)^{-0.689}$ $[6000 \le Re < 1.5\cdot 10^4]$ $f_D = 5.153(\log Re)^{-1.079}(e/d)^{0.796}(p/d)^{-0.707}$ $[1.5\cdot 10^4 \le Re \le 1\cdot 10^5]$
Inaba et al. (1994) [7]	19	400 – 6000	0.25 – 6.5	0.1 - 0.1875	16 and 20	Water (3.9 - 8.2)	$f_D = 11.5\, Re_D^{-0.39}(p/e)^{-0.87}$ $[400 \le Re < 6\cdot 10^3]$
Ravigururajan and Bergles (1996) [34]	Data-base	$5000 – 2.5.10^5$	0.1 – 7	0.01 – 0.2	Database		$f/f_p = \left[1 + \left\{29.1 Re^{R_1}(p/d)^{R_2}(e/d)^{R_3}(\alpha/90)^{R_4}(1 + 2.94/n)\sin\beta\right\}^a\right]^b$ f_p, R_1, R_2, R_3, R_4, a and b requires additional correlations. For circular wire-coils n=∞ and β=90°C
García et al. (2005) [14]	6	$80 – 9.10^4$	1.17 - 2.68	0.07 - 0.10	18	Water and Water - Propylene Glycol mixtures (2.8 - 150)	$f = 5.76\, Re^{-0.217}(p/d)^{-1.21}(e/d)^{0.95}$ $[2000 \le Re < 3\cdot 10^4]$ $f = 9.35\, Re^{-0.217}(p/e)^{-1.16}$
Jafari Nasr et al. (2010) [26]	4	$]]00 – 5.10^4$	0.156 – 0.354	0.027 – 0.094	16	Water	$f = 3.2348\, Re^{-0.3904}(p/d_h)^{-0.3039}(e/d_h)^{0.1674}$
San et al. (2015) [27]	9	3967 - 19245	1.3 – 2.32	0.0725 – 0.134	12.8, 13.4, 13.8	Air and water	$f_D = 36.16\, Re^{-0.36}(e/d)[\ln(p/d_h)]^{-0.52}$
Sharafeldeen et al. (2016) [28]	9	$1.4.10^4 – 4.3.10^4$	1 – 5	0.04 – 0.13	45	Air (0.7)	$f = 0.3251\, Re^{-0.101}(e/d)^{0.196}(p/d)^{-0.211}$

Table 2. Available correlations in turbulent flow regime for tubes fitted with wire-coils

Jafari Nasr et al. [26] applied artificial neural networks (ANNs) to characterize the thermo-hydraulic behaviour of helical wire-coil inserts inside tubes. They obtained heat transfer and pressure drop experimental data for four different wire-coil inserts. These data were employed to validate the prediction model. Finally, applying this methodology, they derived a correlation for friction factor, and concluded that the use of these techniques provided better results than employing the non-linear conventional correlations.

San et al. [27] obtained heat transfer and pressure drop data in smooth tubes with wire-coil inserts using air and water as the working fluids. The authors proposed a single correlation for friction factor for water and air flows. They concluded that friction factor was proportional to e/d and increased with decreasing Reynolds numbers or p/d. More recently, Sharafeldeen et al. [28] carried out a pressure drop experimental study in turbulent flow. They also proposed a friction factor correlation in terms of Reynolds number and inserts geometry.

In summary, the number of available turbulent flow correlations in the open literature is higher than the corresponding to laminar flow. Besides, they are more reliable. Nevertheless, in the wire-coil optimal performance region (transition and low turbulent region, $Re \leq 4000$) [29], the information is scarce. To the best authors knowledge, there are not available correlations in the transition region. Thus, the ones proposed in the present work will be of special interest, since this is the region in which wire-coils show an optimal thermohydraulic performance. Likewise, there are not reliable correlations to determine critical Reynolds number at the end of transition (the beginning of low turbulent region). The new set of proposed correlations in low turbulent flow will be compared with the correlations published by the aforementioned authors summarized in Table 2.

2.3 Studies on combined devices and/or non-conventional working fluids

In this subsection, the most significant works that define friction factor correlations using separated-wall wire-coils as a part of a combined insert, in non-circular tubes or using nanofluids as working fluid are listed.

In laminar flow regime, Saha et al. [30] studied different insert types in square and triangular tubes. They proposed friction factor correlations for circular and non-circular tubes, but the number of wire-coil specimens tested was very limited. Regarding nanofluid and non-Newtonian fluid studies, the works of Chandrasekar et al. [31] using Al_2O_3/water al 0.1% and Saeedinia et al. [32] employing oil and the nanofluid CuO/Oil with different concentrations are noteworthy. In addition, Martínez et al. [33] compared the friction factor coefficient in tubes with wire-coil inserts, using different types of non-Newtonian fluids (high and medium viscosity CMC solutions in water) and pure propylene-glycol.

In turbulent flow regime, Ravigururajan and Bergles [34] obtained global correlations for the friction factor, using air as working fluid, valid for triangular wire-coils separated from the tube wall. Promvonge [35] studied the effect of square cross section wires acting as a turbulator using also air as working fluid. He tested two wire-coils with different pitches and compared their friction coefficient data with the conventional correlation valid for smooth tube. However, no correlations were proposed. The author concluded that the best operating regime for the coiled square wire turbulator was found at lower Reynolds number.

Gunes et al. [36, 37] tested three triangular and circular wire-coils separated from the wall at two different distances. They concluded that for decreasing pitches and increasing wall distance, friction factor and heat transfer increase. They obtained correlations as a function of dimensionless pitch and dimensionless wall distance (dividing by tube diameter). Eiamsa-ard et al. [38] studied a tube fitted with combined devices (non-uniform wire-coil and twisted tape inserts) in turbulent regime. They proposed friction coefficient correlations for the combined devices studied. Eiamsa-ard et al. [39] also studied the effect of inserting a tandem of wire-coil elements, but in this case, they did not present any correlations.

Saha [40] studied experimentally turbulent flow of air through rectangular and square ducts with internal transverse rib turbulators on the two opposite duct surfaces and with wire-coil inserts. He proposed correlations for friction factor based on duct aspect ratio, coil helix angle and wire diameter of the coil, rib height and rib spacing, Reynolds number and Prandtl number. The author concluded that the transverse ribs in combination with wire-coil inserts performed much better than either ribs or wire-coil inserts acting alone, and recommended the rib-coil combination for enhancing turbulent flow heat transfer.

Chang et al. [41] studied the influence of grooved or/and ribbed square wire-coils with five pitch ratios. The authors proposed a general correlation with specific coefficients for each grooved and/or ribbed square wire-coils studied. They concluded that the friction factor increased when using smooth-coil tube, “due to flow interactions between the tube-core vortices and the bursting or/and separated flows induced by the 90º or 45º grooves/ribs along the wire-coils”.

Keklikcioglu and Ozceyhan [42] tested a circular tube with wire coil inserts separated 1 and 2 mm from the inner tube wall. The wire inserts had an equilateral triangular cross-section (constant side length). They concluded that these triangular wire-coils were effective destroying the laminar sublayer and proposed a friction factor correlation as a function of pitch and dimensionless wall distance (dividing by tube diameter). Naik et al. [43] studied the effect of using CuO/Water nanofluid under turbulent conditions for twisted tape and wire-coil inserts fitted in tubes. They carried out a complete and interesting work, reporting correlations from other authors employing nanofluids in twisted-tape and wire-coil fitted tubes and proposed a single correlation for all type of inserts as a function of nanofluid concentration and dimensionless pitch. Besides, the wire-coil inserts increased friction factor in 1.19 times compared to water flowing in a tube at Re=20000 . According to the authors, wire-coils were considered to be more effective than twisted tape inserts under same particle loading and flow rate.

In conclusion, there are many studies on combined devices and/or using nanofluids as working fluids, using non-circular section conducts and other modified geometries.

Table **3** presents a summary including the friction factor correlations. However, it is important to stress the opinion of Webb and Kim [1] against the search of increasing complex designs without accounting for manufacturing difficulties and the corresponding repercussion on equipment cost.

In light of this literature review many works address wire-coil inserts as an enhancement technique. However, in laminar, transition and low turbulent flow regions, where wire-coils present their best performance, the studies are very limited and a high friction factor data dispersion is encountered. This implies that there are not reliable and validated correlations for friction factor computation, which can be partially conditioning the use of wire-coils as an enhancement technique in heat exchangers. On the other hand, the most recent works present very complex combined devices, using nanofluid as a common working fluid and ignoring manufacturing practical difficulties and the corresponding costs.

Authors	**N_{wire}**	Re	p/d	e/d	d (mm)	Working fluid (Pr)	Correlation proposed/Comments
Laminar and transition							
Saha (2010) [30]	4	20 – 1000	0.44 – 1.47	0.0441, 0.0735	13, 17.3 and 19.5	Oil (195 < Pr < 525)	Square (AR=1) and rectangular ribbed duct (AR=0.5 and 0.333) with wire coil insert $f_{cir} = 1.896\,Re^{-0.258}(e/d_h)^{0.0532}(\tan\alpha)^{0.187}$ $f_{non-cir} = f_{cir}(0.283 + 1/AR)^{0.126}$
Chandrasekar et al. (2010) [31]	2	<2300	2 – 3	0.11	4.5	Nanofluid Al_2-O_3-Water $\varphi = 0.1\%$	Nanofluid $f = 530.8\,Re^{-0.909}(p/d)^{-1.388}(1+\varphi)^{-51226}$
Saeedinia et al. (2012) [32]	4	10 – 120	1.78 – 2.5	0.064 – 0.107	14	Nanofluid CuO/Oil φ = [0 - 0.3] %	Nanofluid $f = 198.7\,Re^{-0.708}(p/d)^{-0.943}(e/d)^{0.362}(\mu_s/\mu_m)^{0.58}$ $f = 198.7\,Re^{-0.708}Pr^{-0.23}(p/d)^{-0.943}(e/d)^{0.362}(\mu_s/\mu_m)^{0.58}$
Turbulent							
Ravigururajan and Bergles (1996) [34]	5	$5000 – 2.5.10^4$	0.6 - 1.2	0.02 - 0.05	68.0	Air (0.7)	Separated wire coil with triangular cross-section $f = 3.970492\,Re^{0.367485}(p/d)^{0.31182}(s/d)^{0.157719}$
Gunes et al. (2010) [36][37]	9	Triangular $3500 – 2.7.10^4$ Circular $4100 – 2.6.10^4$	1, 2, 3	0.0714, 0.0892. 0.1	56	Air (0.7)	Separated wire coil with triangular and circular cross-section $f = 83.70924\,Re^{-0.305268}(p/d)^{-0.388}(e/d)^{1.319018}$ $f = 3.970492\,Re^{-0.367485}(p/d)^{-0.31182}(e/d)^{-0.157719}$
Eiamsa-ard et al. (2010) [38]	3	$4600 – 2.10^4$	4 – 8	4.8	47.5	Air (0.7)	Correlations for combined device between twisted-tape and non-uniform varying pitch ratio wire coil $f = 12.313\,Re^{-0.232}Y^{-0.302}$ Decreasing pitch coil and Twisted Tape (TT) $f = 133.366\,Re^{-0.277}Y^{-0.449}$ Decreasing/increasing pitch coil and TT Where Y=tape twist length (180º rotation),m/width of tape,m
Saha (2010) [40]	12	$1.4.10^4 – 7.10^4$	0.22 – 1.47	0.077 – 0.01	51, 68 and 40.8	Air (0.7)	Square (AR=1) and rectangular ribbed duct (AR=0.5 and 0.25) with wire coil insert. Correlations for only wire coil $f_{cir} = 0.1384\,Re^{-0.273}(e/d_h)^{0.0782}(\tan\alpha)^{0.253}$ $f_{non-cir} = f_{cir}(0.271 + 1/AR)^{0.139}$
Chang et al. (2015) [41]	7	$1.10^4 – 4.10^4$	0.5 – 2.5			Air	Grooved or/and ribbed square wire coils $f = C_0 + C_1 e^{-C_2 Re}$ with C_0, C_1, $C_2 = E + K \cdot exp^{-M(p/d)}$ Values for E, K and M are provided for each grooved and/or ribbed square wire coils
Keklikcioglu and Ozceyhan (2016) [42]	6	3429 - 26663	1, 2, 3	0.107	56	Air	Separated 1, 2 mm wire coil with equilateral triangular cross-section $f = 6.423\,Re^{-0.301}(p/d)^{-0.587}(s/d)^{-0.106}$
Naik et al. (2014) [43]	2 2	$4000 – 2.10^4$	h/d= 5, 10 p/d= 1.97, 2.95	0.1428	14	Nanofluid CuO/Distilled water. Conc. φ [0 - 0.3] %	Correlation valid for twisted and wire coil inserts $f = 0.3345\,Re^{-0.25}(1+\varphi)^{0.19}(1+h/d)^{0.0.038}(1+p/d)^{0.1}$

Table 3. Available correlations on combined devices and/or non-conventional working fluids

This work is aimed at studying the friction factor coefficient in tubes fitted with wire-coils, a simple and low-cost specimen, avoiding complex devices that complicate final implementation stage. Water was used as the working fluid and a wide and representative set of wire-coils was analysed for a dimensionless pitch range of p/d= [0.25-3.37] and dimensionless thickness range of e/d=[0.071-0.286], for Reynolds number from 50 to 8000, covering laminar, transition and low turbulent regimes. A new dimensionless parameter, "Transition Shape Parameter" (TSP), will be defined to categorize the hydraulic behaviour of these insert devices. The TSP is able to distinguish the different patterns on transition to turbulence region, and allow to group the wire-coils to obtain the most suitable correlations according to their geometric characteristics.

3. Wire-coil geometrical characteristics and experimental set-up

Table 4 summarizes the geometrical characteristics of the 23 wire-coils studied. The A, B, C and D wire-coil types are tested in the present work. They are characterized by a constant nondimensional thickness and a variable nondimensional pitch for each group. All of them present an internal tube-side diameter of 7 mm. The wire-coil types E and F were tested by García et al. [14], and they all present a variable nondimensional thickness and nondimensional pitch, and a constant internal diameter of 18 mm.

	d (mm)	p (mm)	e (mm)	p/d	e/d	p/e		d (mm)	p (mm)	e (mm)	p/d	e/d	p/e
W1A	7.00	1.75	0.50	0.250	0.071	3.500	**W1E**	18.00	21.12	1.34	1.173	0.074	15.761
W2A	7.00	3.50	0.50	0.500	0.071	7.000	**W2E**	18.00	48.32	1.45	2.684	0.081	33.324
W3A	7.00	7.00	0.50	1.000	0.071	14.000	**W3E**	18.00	30.66	1.40	1.703	0.078	21.900
W4A	7.00	10.50	0.50	1.500	0.071	21.000	**W4E**	18.00	46.22	1.68	2.568	0.093	27.512
W5A	7.00	14.00	0.50	2.000	0.071	28.000	**W5E**	18.00	33.57	1.79	1.865	0.099	18.754
W1B	7.00	1.75	0.70	0.250	0.100	2.500	**W6E**	18.00	25.31	1.84	1.406	0.102	13.755
W2B	7.00	3.50	0.70	0.500	0.100	5.000	**W1F**	18.00	22.50	1.37	1.250	0.076	16.400
W3B	7.00	10.50	0.70	1.500	0.100	15.000	**W2F**	18.00	30.96	1.37	1.720	0.076	22.632
W4B	7.00	14.00	0.70	2.000	0.100	20.000	**W3F**	18.00	60.66	1.37	3.370	0.076	44.300
W1C	7.00	1.75	1.40	0.250	0.200	1.250							
W2C	7.00	7.00	1.40	1.000	0.200	5.000							
W3C	7.00	7.50	1.40	1.071	0.200	5.357							
W1D	7.00	7.00	2.00	1.000	0.286	3.500							
W2D	7.00	8.50	2.00	1.214	0.286	4.250							

Table 4. Geometrical characteristics of the wire coils studied

The main characteristic of the experimental set-up is its capability to stablish under steady, isothermal and reproducible conditions, a continuous Reynolds numbers range from 50 to 8000. This range covers laminar, transition and low turbulent regimes in detail, and allows to identify the different flow patterns reliably.

The experimental set-up for friction tests consists of two circuits connected through a heat exchanger (2) from Cipriani Scambiatori, model 2C2 (Fig.1). The main circuit (left) is used to carry out the pressure drop tests in the tube fitted with the corresponding wire-coils under isothermal conditions. The secondary circuit (right) is used for regulating the tank temperature to a desirable value. The cooling machine (1) model HRS050-W is manufactured by SMC.

The working fluid is distilled water (Type II) which is driven by a variable speed centrifugal pump model TPE by Grundfos (3) to the test section. The corresponding mass flow rate is regulated by an electro-valve AVM105SF132 by Sauter (4) and measured with a Coriolis Micro-Motion® F-series F025S mass flow-meter (5). Pressure drop is acquired using differential pressure sensors (7) of different ranges to cover the full range from 50 to 500 mbar. Two differential pressure transducers of different full scales are duly employed to assure the accuracy of the experiments. Inlet and outlet tube temperatures are measured by RTD Pt-100 class B 1/10 DIN sensors (6) and (8) to obtain fluid properties. Inlet fluid temperatures range from 10 ºC to 50 ºC were tested.

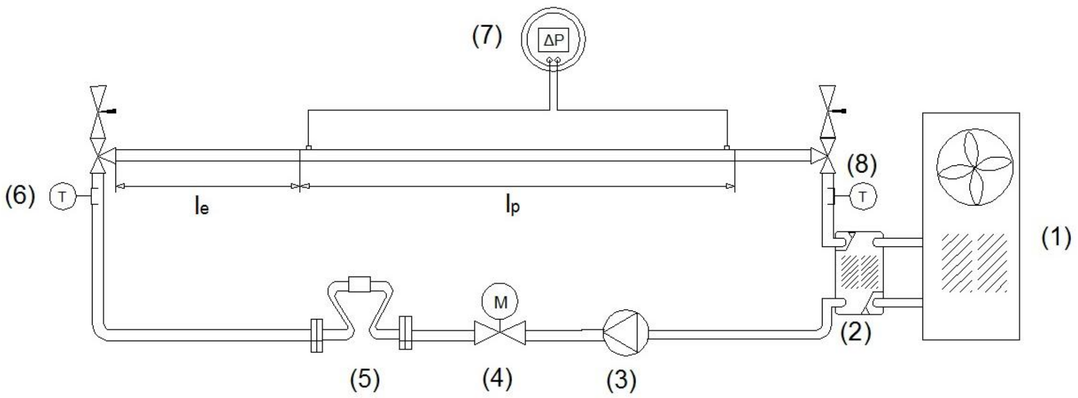


Figure 1. Schematic diagram of the experimental set up. (1) Cooling machine, (2) Plate heat exchanger, (3) In-line pump, (4) Electro-valve, (5) Coriolis mass flow-meter, (6), and (8) RTDs, (7) Differential pressure transducer.

The measurement sections consist of four pressure taps separated by 90º and connected to the suitable SMAR® LD-301 differential pressure sensors according to the fixed mass flow rate. The test section length is l_p = 200d and is preceded by a hydrodynamically developing region of l_e = 60d length. All the experimental data are collected through an Agilent® data acquisition model 34980A. The measurement errors are 0.075% for pressure measurements, 0.2% for mass flow rate measurements, and 0.1 and 1 mm in diameter measurement and testing section length measurements, respectively.

Once the target temperature is reached steady conditions have to be assured. Each wire-coil specimen was tested varying the operating mass flow rate in order to continuously cover the laminar, transition and turbulent region. Based on measuring the mass flow rate, the pressure drop, and the inlet and outlet fluid temperatures, the fluid properties are evaluated at the mean testing temperature $T_m = (T_{in} + T_{out})/2$. Reynolds number is computed according to Eq. (1) and friction factor coefficient by Eq. (2).

$$\mathrm{Re} = \frac{4G}{\mu \pi d} \tag{1}$$

$$f = \frac{\pi^2 \rho d^5 \Delta p}{32 G^2 l_p} \tag{2}$$

The total uncertainty of the friction factor coefficient was calculated according to Kline and McClintock [44] work based on a 95% confidence level. A maximum value of uncertainty of 1.5% for friction factor for Re=80 was shown.

4. Analysis of results

In order to validate the experimental procedure, isothermal flow tests were carried out to obtain the smooth tube friction factor for Reynolds numbers from 50 to 8000, covering laminar, transition and low turbulent flow regime. The experimental results are compared with the analytical solution for laminar flow f_{LS}=16/Re and the Blasius equation for turbulent flow $f_{TS}=0.079\cdot \mathrm{Re}^{-1/4}$. The average error reported was lower than 3%.

The smooth tube tests were employed to contrast the methodology that allows computing two critical Reynolds numbers: the first Re_{CL}, for which the transition region is reached from laminar flow, and the second Re_{CT}, that establish the end of transition and the beginning of low turbulent flow regime. To estimate both critical Reynolds numbers, the relative fluctuation in the friction factor was analysed as proposed in [45].

4.1 Tests in tubes fitted with wire-coil inserts. Friction factor

This paper reports the study of 23 helicoidal wire-coils with circular cross section and different geometric characteristics, covering a dimensionless pitch range of p/d=[0.25-3.37] and a dimensionless thickness range of e/d=[0.071-0.286], for Reynolds numbers from 50 to 8000, covering laminar, transition and low turbulent regimes. This interval widely includes the Reynolds numbers range in which wire-coils show better performance as a passive enhancement technique in heat exchangers Re=[200-2000] [29].

This section reports the results obtained for friction factor, grouping the studied wire-coils according to the dependence of the friction factor with Reynolds number. With this aim in mind, and taking into account the analysis of the results, a new dimensionless parameter is defined: the *Transition Shape Parameter* (TSP) (Eq. 3). The TSP only depends on the wire coil geometric characteristics and allows to predict the different evolution of the friction factor coefficient with Reynolds number in the transition region, compared to smooth tubes.

$$\mathrm{TSP} = \frac{(p/d)^5}{(e/d)^2} \tag{3}$$

	d (mm)	**p** (mm)	**e** (mm)	**p/d**	**e/d**	**p/e**	**TSP**
W1C	7.00	1.75	1.40	0.25	0.200	1.25	2.441E-02
W1B	7.00	1.75	0.70	0.25	0.100	2.50	9.766E-02
W1A	7.00	1.75	0.50	0.25	0.071	3.50	1.914E-01
W2B	7.00	3.50	0.70	0.50	0.100	5.00	3.125E+00
W2A	7.00	3.50	0.50	0.50	0.071	7.00	6.125E+00
W1D	7.00	7.00	2.00	1.00	0.286	3.50	1.225E+01
W2C	7.00	7.00	1.40	1.00	0.200	5.00	2.500E+01
W2D	7.00	8.50	2.00	1.21	0.286	4.25	3.234E+01
W3C	7.00	7.50	1.40	1.07	0.200	5.36	3.530E+01
W3A	7.00	7.00	0.50	1.00	0.071	14.00	1.960E+02
W1E	18.00	21.12	1.34	1.17	0.074	15.76	4.013E+02
W6E	18.00	25.31	1.84	1.41	0.102	13.76	5.260E+02
W1F	18.00	22.50	1.37	1.25	0.076	16.40	5.284E+02
W3B	7.00	10.50	0.70	1.50	0.100	15.00	7.594E+02
W4A	7.00	10.50	0.50	1.50	0.071	21.00	1.488E+03
W5E	18.00	33.57	1.79	1.87	0.099	18.75	2.282E+03
W3E	18.00	30.66	1.40	1.70	0.078	21.90	2.370E+03
W2F	18.00	30.96	1.37	1.72	0.076	22.63	2.606E+03
W4B	7.00	14.00	0.70	2.00	0.100	20.00	3.200E+03
W5A	7.00	14.00	0.50	2.00	0.071	28.00	6.272E+03
W4E	18.00	46.22	1.68	2.57	0.093	27.51	1.281E+04
W2E	18.00	48.32	1.45	2.68	0.081	33.32	2.148E+04
W3F	18.00	60.66	1.37	3.37	0.076	44.30	7.525E+04

Table 5. Wire-coil classification according to the Transition Shape Parameter

According to this definition, the TSP allows to establish a wire-coil classification. When a wire-coil insert with a low TSP is employed (TSP<10) as an enhancement device, the friction factor curve mimics the smooth tube behaviour. Consequently, an abrupt increase in the friction factor is obtained in the transition region. On the contrary, for wire-coils with a high TSP (TSP>750) the lack of the characteristic abrupt discontinuity that typically and clearly represents turbulence onset for the smooth tube is observed and a softer transition is reported. Finally, for intermediate values 10<TSP<750 the friction factor evolution presents different trends but dominated by the nondimensional thickness. Hence, for an e/d<0.1 the friction coefficient smoothly increases in the transition region, whereas for e/d=0.2 it remains constant in the transition region and for higher thicknesses e/d=0.286, a turbulent nature flow is exhibited from very low Reynolds numbers and there is a linear friction factor variation with a characteristic slope of turbulent flow. Table 5 summarizes the studied wire-coils classified according to their TSP values in ascending order.

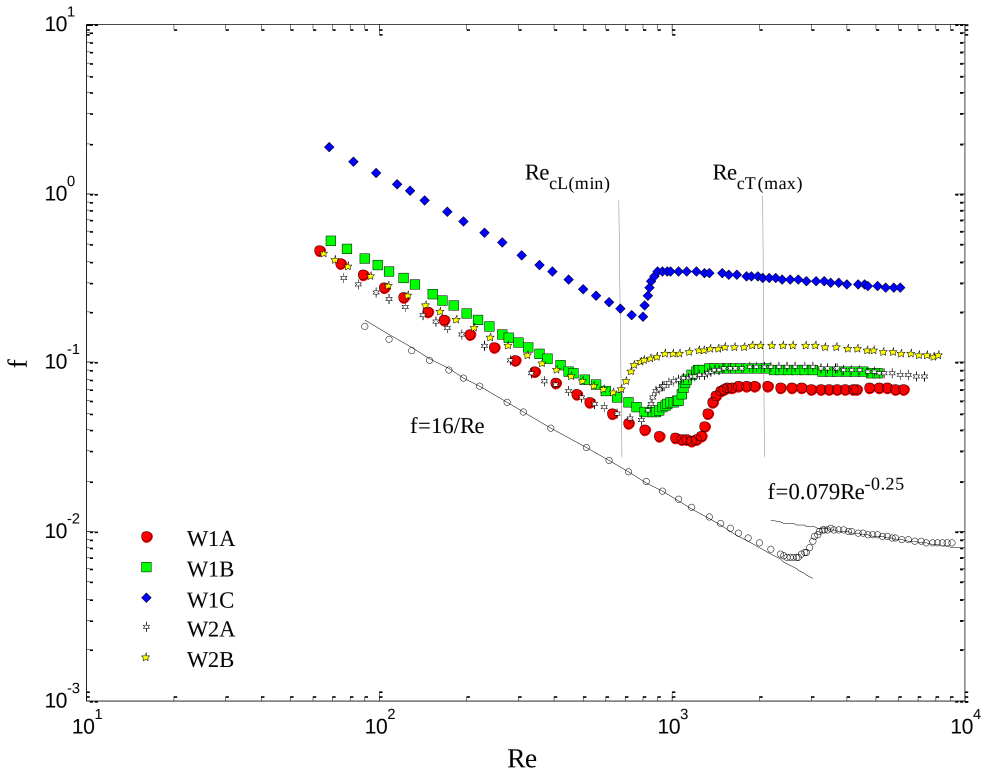


Figure 2. Fanning friction factor results in tubes fitted with wire-coil inserts with TSP<10

Fig. 2 depicts the Fanning friction factor for the studied wire-coils with TSP<10 and in comparison with smooth tube friction factor obtained experimentally. An increase in pressure drop under laminar and turbulent flow regimes in contrast to the smooth tube is observed.

In the laminar region, parallel curves are obtained regarding to smooth tube. The recirculations originated downstream by the helical roughness increase the pressure drop. Within low turbulent region, the friction factor coefficient is weakly dependent on Reynolds number. For this geometrical group, the most remarkable characteristic is the presence of a sudden transition to turbulent flow.

Fig. 3 depicts the Fanning friction factor for the wire-coils tested with TSP>750. For these wire-coils, the friction factor in laminar regime is very close to the smooth tube values, but a non-parallel trend is observed. The friction factor values are lower than the previously reported for TSP<10. This is founded on the lower swirl introduced. For turbulent flow, the friction factor is also lower and it depends on the Reynolds number. This is due to the increase in the wire-coil pitch. Flow overtakes the helical roughness with a higher angle, the wire-coil cross section is elliptic, and the downstream recirculations are reduced or even vanished. An outstanding characteristic is that transition occurs smoothly and extends over a broad Reynolds numbers region, in which friction factor does not show abrupt discontinuities. This behaviour of the wire-coils with a high TSP allows to simplify and make more reliable the design steps of an enhanced heat exchanger, due to the existence of a predictable friction factor coefficient for a wide range of Reynolds numbers.

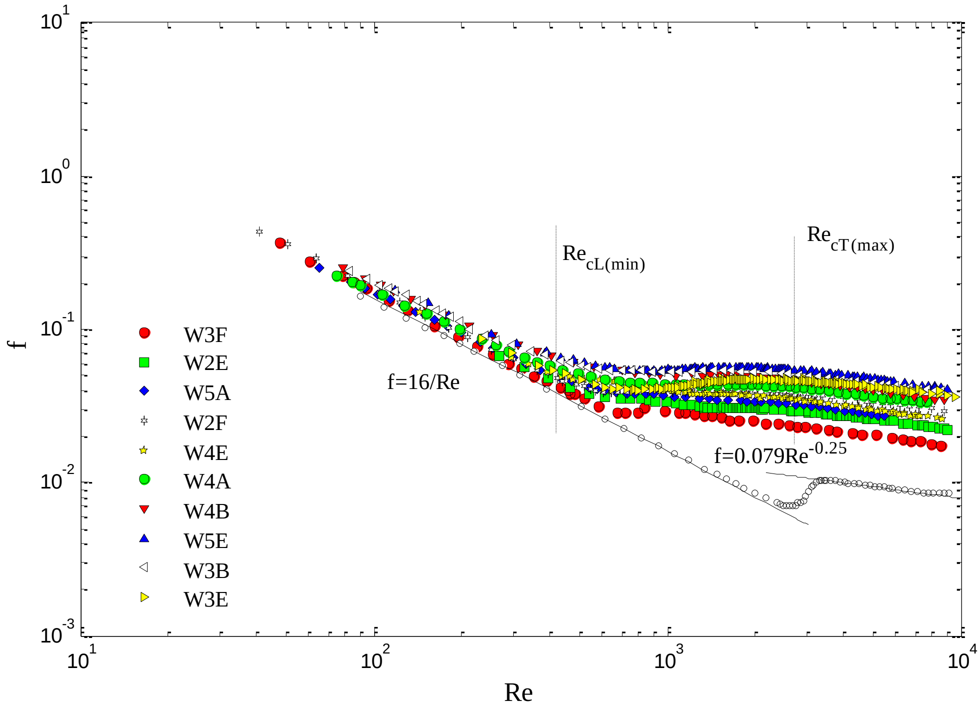


Figure 3. Fanning friction factor results in tubes with wire-coil inserts with TSP>750

In Fig. 4 the Fanning friction factor is represented for a wire-coils set in the geometrical range 10<TSP<750. This group of wire-coils can be subdivided according to nondimensional thickness, whereas the nondimensional pitch stops being the dominant geometric parameter. For e/d≤0.1, the behaviour in laminar regime resembles the wire-coils with TSP>750. However, in turbulent regime the friction factor is higher, due to the upper friction factor values reached at the end of transition region.

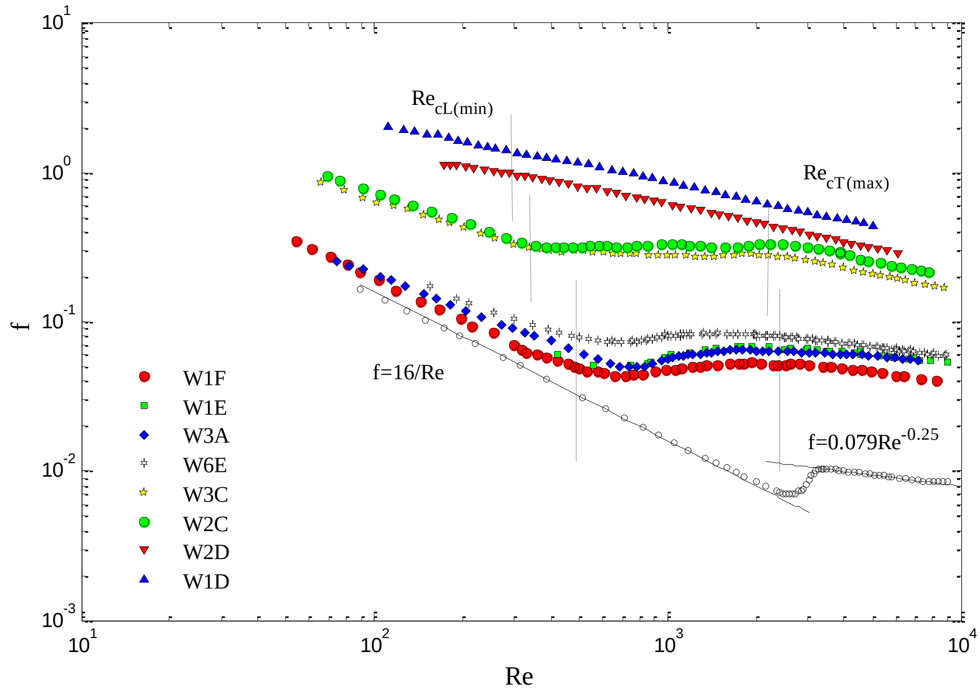
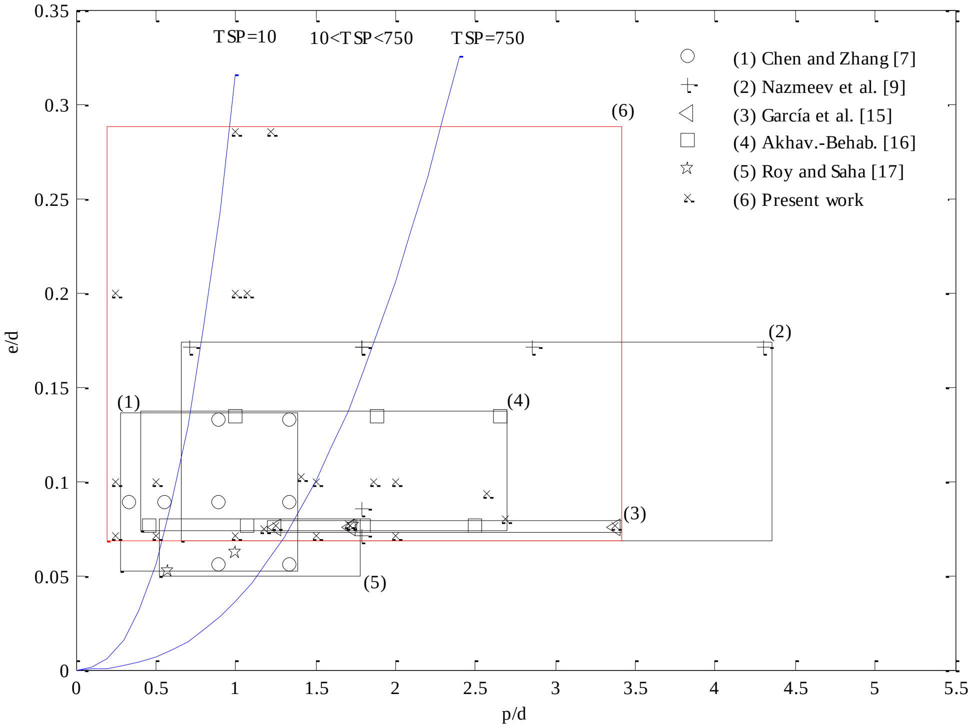


Figure 4. Fanning friction factor results in tubes with wire-coil inserts with 10<TSP<750

Nevertheless, for the highest nondimensional thickness wire-coils, the behaviour is completely different. For e/d=0.2, the friction factor significantly increases and presents a wide transition region in which the friction coefficient remains constant. In this type of insert, the flow is dominated by the helical roughness and the downstream recirculations. For the highest thickness, e/d=0.286, there is a turbulent flow nature from very low Reynolds numbers and there are no appreciable friction factor trend changes, yielding an almost linear evolution on a logarithmic scale with Reynolds number.

According to the experimental data reported in Figs. 2, 3 and 4, a wide and reliable experimental data set is available. This allows to stablish a wire-coil classification according to the TSP as a function of the geometric characteristics and make possible to propose a universal correlation set. Fig. 5 summarises the working range covered by this study in comparison with previous authors and divide the field of study according to the TSP limit values for the three established categories.



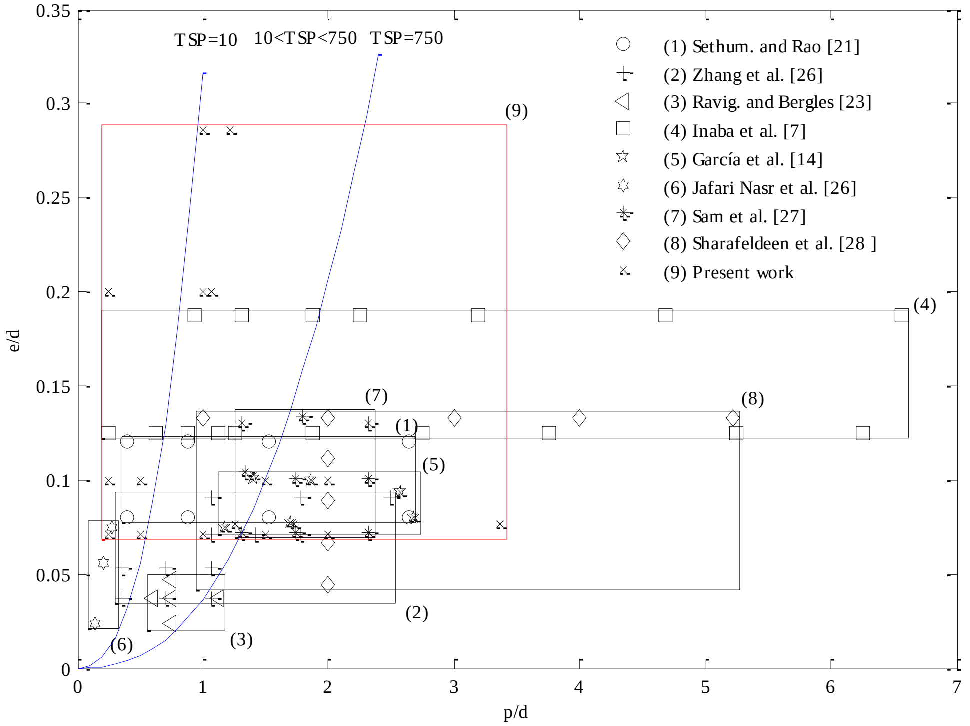


Figure 5. Working range for wire-coil inserts as a function of TSP. 5a) (Upper) Laminar flow regime studies. 5b) Turbulent flow regime studies

5. Data correlations

In this section, the correlations proposed are presented for the critical Reynolds numbers and for the friction coefficient as a function of Reynolds number and dimensionless pitch and thickness.

5.1 Critical Reynolds number for laminar flow

Firstly, the correlation for tubes fitted with wire-coil inserts is provided to obtain the critical Reynolds number Re_{CL} for which the laminar flow region ends. To obtain $Re_{CL,}$ the evolution of friction coefficient as a function of Reynolds number for the different wire-coils studied is analysed together with the experimental standard deviation of the friction factor itself [45]. In Fig. 6, the critical laminar Reynolds number is experimentally defined and estimated by means of the proposed correlation (Eq. 4), with a validity range of p/d=[0.25-3.37] and e/d=[0.071-0.286], and with an average and maximum error of 4.6% and 12.4%, respectively. It is observed how the critical laminar Reynolds number decreases as the dimensionless pitch increases, reaching an asymptotic value between 200 and 600, depending on the wire-coil thickness. Nazmeev et al. [9] proposed a correlation to obtain the critical Reynolds number, but the values provided are a 64% lower in average, and the trend as a function of the increase in dimensionless pitch is inverse.

$$Re_{CL}=5.710(p/d)^{-2.407}+144.229(p/d)^{-0.167}(e/d)^{-0.575} \tag{4}$$

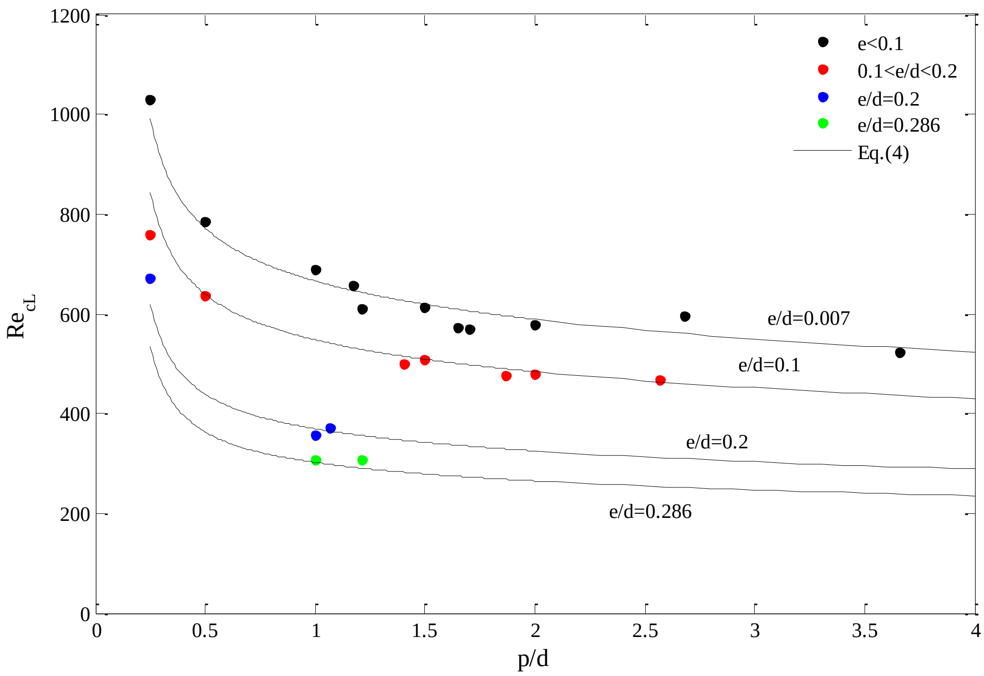


Figure 6. Critical laminar Reynolds number experimentally obtained and predicted by the proposed correlation (R^2=0.977)

5.2 Critical Reynolds number for turbulent flow

Fig. 7 represents the Reynolds number for which the turbulent flow regime begins (Re_{CT}). This value is experimentally obtained and predicted by the proposed correlation (Eq. 5), with a validity range of p/d=[0.25-3.37] and e/d=[0.071-0.2], and with an average and maximum error of 6.8% and 7.7%, respectively. The wire-coils with e/d=0.286 are not included, due to the turbulent flow nature from very low Reynolds numbers, and without a clearly defined transition region. For an increasing dimensionless pitch and regardless of the wire-coil thickness, the beginning of the turbulent flow regime occurs at increasing Reynolds numbers without reaching an asymptotic value for the p/d interval studied. This brings to light, as previously mentioned, that at increasing dimensionless pitch the transition from laminar to turbulent flow takes place more smoothly, and the transition region is extended covering a wider Reynolds number interval.

$$Re_{CT}=-347.213+2633.779(p/d)^{0.206} \quad (5)$$

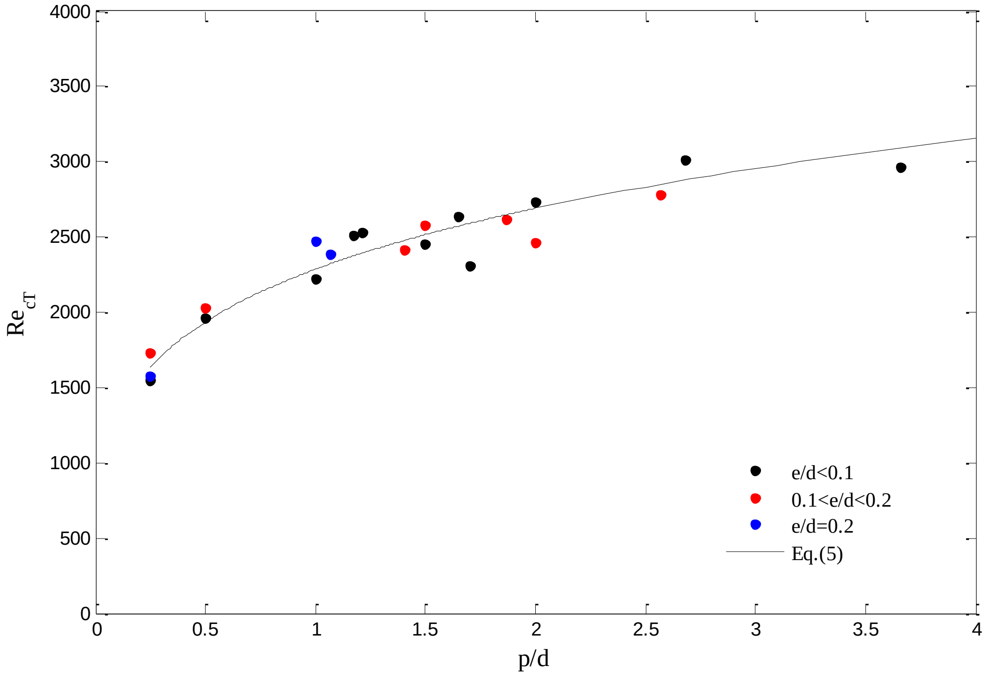


Figure 7. Critical turbulent Reynolds number obtained experimentally and predicted by the proposed correlation (R^2=0.92)

5.3 Correlations for the friction factor in tubes fitted with wire-coil inserts

In this section, the correlations derived to compute friction factor as a function of the wire-coil geometric parameters p/d and e/d and the Reynolds number are presented. For practical purposes, once the wire-coil is selected with their geometric characteristics by using Eq. (4) and (5), Re_{CL} and Re_{CT} are obtained, being usable the corresponding correlations in laminar region within $Re<Re_{CL}$, in the turbulent region within $Re>Re_{CT}$ and in the transition region within $Re_{CL}<Re<Re_{CT}$.

a) Low TSP group (TSP<10)

For the wire-coils group with TSP<10, there is a slight difference in the evolution of the friction factor in the transition region, compared to the smooth tube. Correlations for the friction factor in laminar, transition and turbulent flow regimes are proposed. Due to the abrupt discontinuity in the transition region, an accurate prediction is not viable affecting the complexity of the proposed correlation (

Table **6**). In the laminar region, parallel curves are obtained as a function of the geometric characteristics of the inserted wire-coil, whereas for the turbulent region a notable increase in the friction factor is observed but with a lower slope in comparison with the smooth tube. Fig. 8 compares the proposed correlations for each flow region with the experimental data.

Regime, range and correlation proposed for TSP<10		R^2	Av. Dev.	Max. Dev.
Laminar $Re<Re_{CL}$ $f_{L(L)}=2439.936Re^{-0.969}(p/d)^{-1.033}(e/d)^{2.928}+14.554Re^{-0.894}$	(6)	1.000	3.9%	6.4%
Transition $Re_{CL}<Re<Re_{CT}$ $f_{Tr(L)}=-4.68\cdot10^5Re^{-1.261}(p/d)^{-0.0004}(e/d)^{1.91}$ $+2.51\cdot10^5Re^{-1.124}(p/d)^{+0.078}(e/d)^{1.998}+0.052$	(7)	0.971	16,5%	23.4%
Turbulent $Re>Re_{CT}$ $f_{T(L)}=1442.197Re^{-0.173}(p/d)^{1.348}(e/d)^{3.393}+0.091Re^{-0.037}$	(8)	0.998	3.1%	6.9%

Table 6. Proposed correlations for wire-coil inserts with TSP<10. Low TSP group

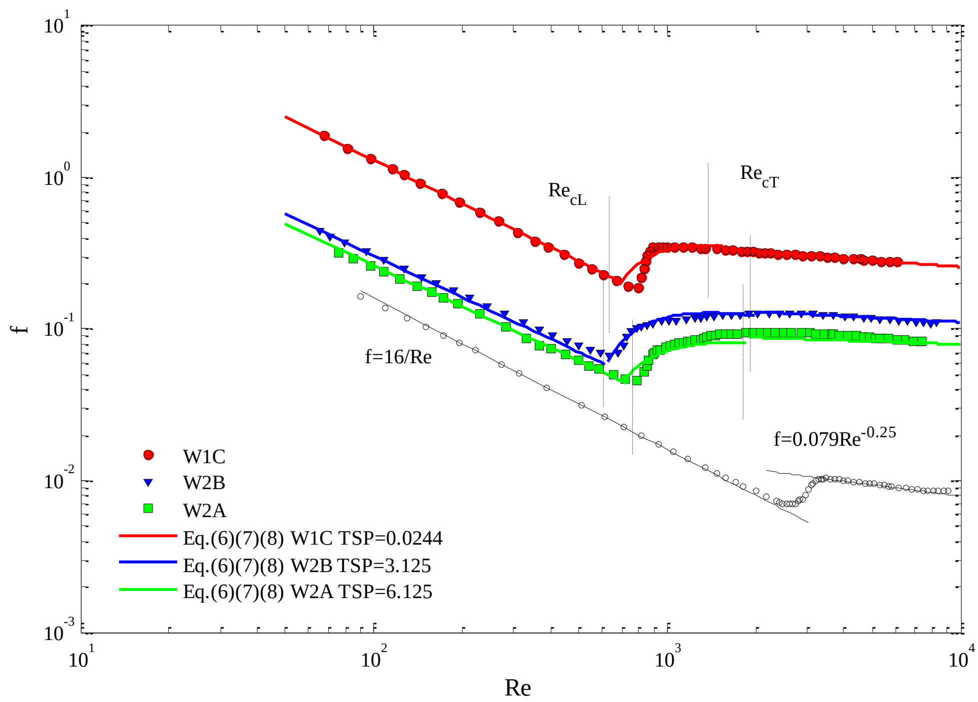


Figure 8. Comparison between experimental data and proposed correlation. Low TSP Group

b) **High TSP Group** (TSP>750)

The TSP>750 wire-coils group is characterized by a smooth transition, a diverging laminar region with increasing Reynolds numbers and a turbulent region with a moderate rise in friction factor regarding the smooth tube. For this range of TSP numbers, there is a specific friction factor evolution. The transition from laminar to turbulent takes place smoothly and along a wide range of Reynolds numbers. The proposed correlations are summarized in Table 7.

Regime, range and correlation proposed for TSP>750		R^2	Av. Dev.	Max. Dev.
Laminar $Re<Re_{CL}$ $f_{L(H)}=40.568Re^{-0.924}(p/d)^{-0.071}(e/d)^{0.426}$	(9)	0.993	6.5%	9.3%
Transition $Re_{CL}<Re<Re_{CT}$ $f_{Tr(H)}=1.12Re^{-0.048}(p/d)^{-0.449}(e/d)^{1.061}$	(10)	0.960	9,2%	22.9%
Turbulent $Re>Re_{CT}$ $f_{T(H)}=12.907Re^{\left(-0.377(p/d)^{-0.483}\right)}(p/d)^{-1.794}(e/d)^{0.965}+0.297(p/d)^{-9.528}$	(11)	0.955	8.4%	23.6%

Table 7. Proposed correlations for wire-coil inserts with TSP>750. Group High TSP

In Fig. 9, the proposed correlations are compared for each region with the experimental data. The proximity of the curves in the laminar regimes diverging for increasing Reynolds numbers is observed. In the turbulent regime, based on the wire coil geometry, approximately parallel curves are obtained, but with a decreasing slope as Reynolds number rises. For these wire-coils, the friction factor coefficient remains almost constant within the transition region.

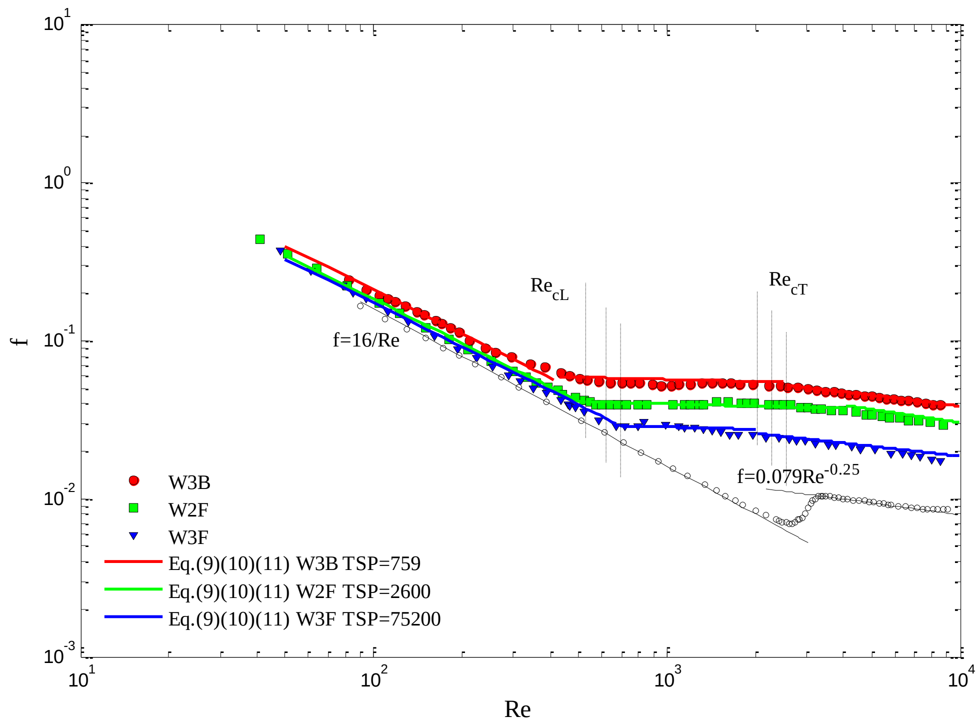


Figure 9. Comparison between experimental data and proposed correlation. High TSP group

c) **Intermediate TSP Group** (10<TSP<750)

This group comprises the wire-coils with an intermediate behaviour between the two previous groups. It contains the wire-coils in which the TSP ranges from 10 to 750. Here, the friction factor evolution exhibits different behaviours based on wire-coil dimensionless thickness. For the wire-coil set studied there are three subgroups. The first subgroup comprises those wire-coils with $e/d \leq 0.1$, with a similar behaviour to high TSP group. For this subgroup, the transition still being smooth, but the friction factor slightly increases with increasing Reynolds numbers, and, in turbulent flow regime, the friction factor coefficient is significantly higher. The second subgroup contains the wire-coils with e/d=0.2 whose main characteristic is the very broad transition region. Friction factor coefficient remains practically constant, covering the range from $300 \leq Re \leq 3000$, and can be computed as the average value obtained using the laminar and turbulent regions correlations for critical Reynolds numbers Re_{CL} and Re_{CT}, respectively. Finally, the third subgroup is comprised by the e/d=0.286 wire-coils, which present a turbulent behaviour for the whole Reynolds number range studied. The proposed correlations for each region are summarized in Table 8.

Regime, range and correlation proposed for 10<TSP<750		R^2	Av. Dev.	Max. Dev.
Laminar $Re<Re_{CL}$				
$e/d \leq 0.1$ $f_{L(I)}=163.84Re^{-0.828}(p/d)^{-0.516}(e/d)^{1.077}$	(12)	0.990	7.7 %	12.1 %
$e/d=0.2$ $f_{L(I)}=13.66Re^{-0.635}(p/d)^{-1.49}$	(13)	0.997	1.5 %	1.8 %
Transition $Re_{CL}<Re<Re_{CT}$				
$e/d \leq 0.1$ $f_{Tr(I)}=0.163Re^{-0.32}(p/d)^{5.547}(e/d)^{1.057}+1.294Re^{0.299}(p/d)^{3.838}(e/d)^{1.606}$	(14)	0.971	6.7 %	14.1%
$e/d=0.2$ $f_{Tr(I)}=\text{Constant}$				
Turbulent $Re>Re_{CT}$				
$e/d \leq 0.1$ $f_{T(I)}=7.926Re^{-0.182}(p/d)^{-0.848}(e/d)^{1.267}$	(15)	0.990	7.7 %	14.9 %
$e/d=0.2$ $f_{T(I)}=113.469Re^{-0.409}(p/d)^{-1.819}(e/d)^{1.645}$	(16)	0.996	3.3 %	4.0 %
$Re>Re_{CL}$ $e/d=0.286$ $f_{T(I)}=\text{Eq. (16)}$				

Table 8. Proposed correlations for wire-coil inserts with 10<TSP<750. Intermediate TSP group.

In Fig. 10, the proposed correlations are compared with the experimental data for each flow region and subgroup of wire-coils. The need to obtain correlations available for each wire-coils subgroup is noticeable due to the different experimental data trend observed. For e/d=0.2, the friction factor coefficient in the transition region was obtained by averaging the limit values for Re_{CL} replacing values in Eq. (13) and Re_{CT} replacing values in Eq. (16). For the wire-coils e/d=0.286, the Eq. (16) is used in the whole interval of Reynolds number studied. As aforementioned, the wire-coils with a high thickness exhibit a fully turbulent flow behaviour in the entire Reynolds numbers range studied.

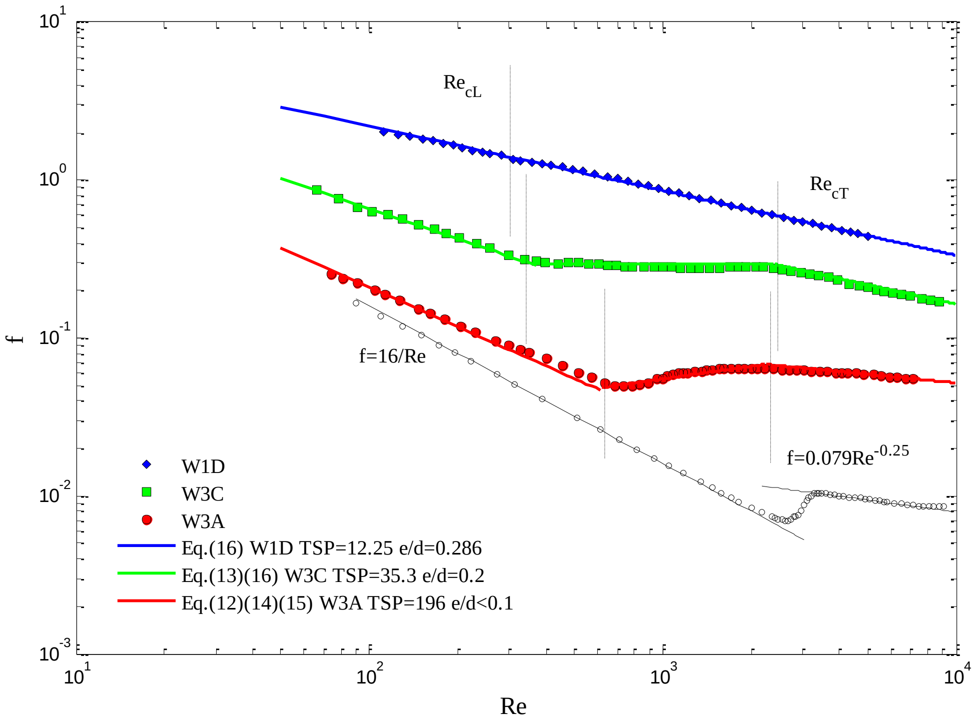


Figure 10. Comparison between experimental data and proposed correlation. Group Intermediate TSP

5.4 Comparison with other correlations

5.4.1 Comparison with correlations for laminar flow

The number of available correlations for laminar flow is scarce. A specific wire-coil will be selected to analyse the agreement between the correlations published and the correlations proposed in the present study. The summary of the correlations is shown in Table 1. The selected wire-coil for comparative purposes is the W3A (p/d=1, e/d=0.071 and TSP=196), as this insert meet the validity requirements in terms of p/d and e/d for all the correlations.

Fig. 11 shows a comparison of the correlations available in the open literature for wire coils working in the laminar region. The Fanning friction factor experimentally obtained for W3A, and the proposed correlation in the present work (Eq. 12) are compared with the correlations published in open literature. The correlation from Chen and Zhang [7] was obtained under non-isothermal flow conditions and using a working fluid with Pr=300. This correlation retrieves the worst results. The slope is very different from the proposed correlation in this work Eq. (12). The correlation from Nazmeev et al. [9] over-predicts the friction factor coefficient by over a 50%, and the slope is slightly higher. Roy and Saha correlation [17] presents a unit inconsistency that has to be taken into consideration. As presented in Table 1, it provides poor results, since the friction coefficient intersects the smooth tube line. Finally, the correlations from García et al. [15], and Akhavan-Behabadi [16] were not used due to their lack of generality.

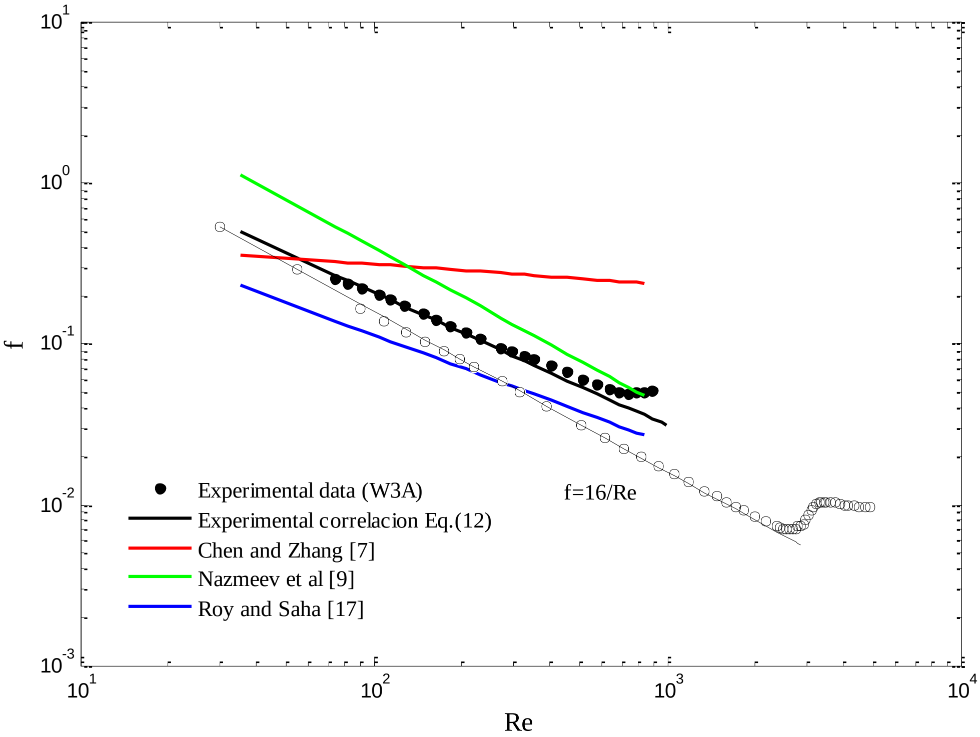


Figure 11. Correlations comparison valid for laminar region. Wire-coil with TSP=196

As a conclusion, the available correlations do not predict adequately the experimental data behaviour, and new correlations are required to estimate accurately the friction factor coefficient as a function of the geometric characteristics of a wire-coil insert. The proposed correlations developed in the present work (Eqs. (6), (9) (12) and (13)) significantly contribute to this aim.

5.4.2 Comparison of correlations for turbulent flow

In turbulent regime, there is a larger number of available studies. The proposed correlations in the open literature cover a broader range of dimensionless pitch and thickness. Thus, two wire-coils of low and intermediate TSP were chosen for comparative purposes. This enables the use of the most suitable insert attending to its geometric characteristics, according to the application range of the analysed correlation. The selected wire-coils were the W6E and the W2B. The W6E is defined by p/d=1.41, e/d=0.102 and TSP=526, whereas W2B by p/d=0.5, e/d=0.1 and TSP=3.125, therefore, they are significantly different from one another.

Fig. 12 plots the correlations available for wire coils in the turbulent regime. The Fanning friction factor experimentally obtained for W6E, and the proposed correlation in the present work (Eq. 15) are compared with the correlations published in open literature. The correlations by Inaba et al. [7] and Zhang et al. [22] under predict the experimental values. Their trends are very similar and show a different slope regarding the data tested. The predictions by Sethumadhavan and Rao [21] and Ravigururajan and Bergles [34] also present lower friction factors, but follow the experimental data trend. The correlations defined by San et al. [27] and Sherafeldeen et al. [28] over predict the friction factor coefficient. However, the San et al. correlation [27] presents a slightly higher slope, probably due to the larger validity of Reynolds numbers range. The correlation in [28] predicts a much lower slope. This may be due to the narrow Reynolds numbers validity range, and to the dimensionless pitch wire-coils studied by the authors that ranges between 1 and 5. Finally, it should be underlined that the correlation defined by García et al. [14], as the one proposed in the present study (Eq. 15), perfectly fit the experimental data obtained. However, the correlation in [14] is valid for a group of wire-coils with more limited geometric characteristics, whereas the new correlation proposed in the present work covers a much wider geometrical range.

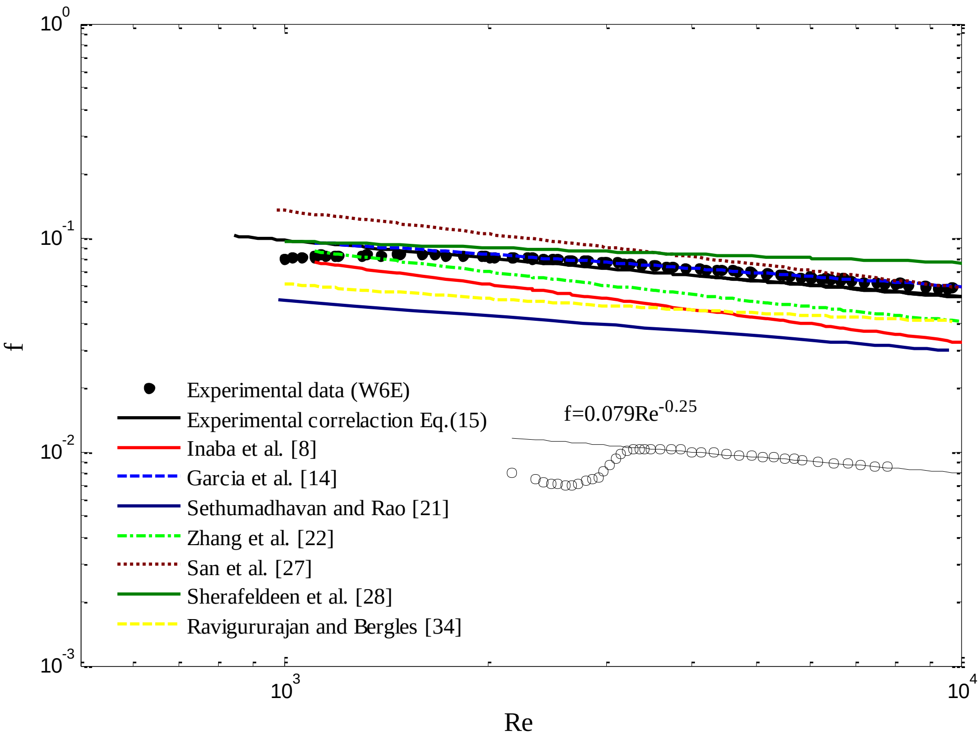


Figure 12. Correlations comparison valid for low turbulent region. Wire-coil with TSP=526

Fig. 13 shows the correlations comparison valid for low turbulent region. The Fanning friction factor experimentally obtained for W2B (TSP=3.125) and the proposed correlation in the present work (Eq. 8) are compared with the correlations published in open literature. The specimen W2B exhibits very different hydraulic behaviour to the previously analysed W6E. For this type of wire-coils, the correlations proposed by Inaba et al. [7], Zhang et al. [22], Sethumadhavan and Rao [21], Ravigururajan and Bergles [34] and Jafari Nasr et al. [26] are applicable. Although, the last correlation is slightly out of range. All the correlations, excluding [34], provide acceptable results in reasonable agreement with the proposed correlation by the authors (Eq. 8). This may be due to the fact that is a very general correlation obtained to be used for very different enhancement techniques (ribbed tubes and wire coil inserts), which contribute to a non-accurate prediction of friction factor. The present work, focused on wire-coil inserts with circular cross-section, allow to obtain more accurate results for this specific geometry.

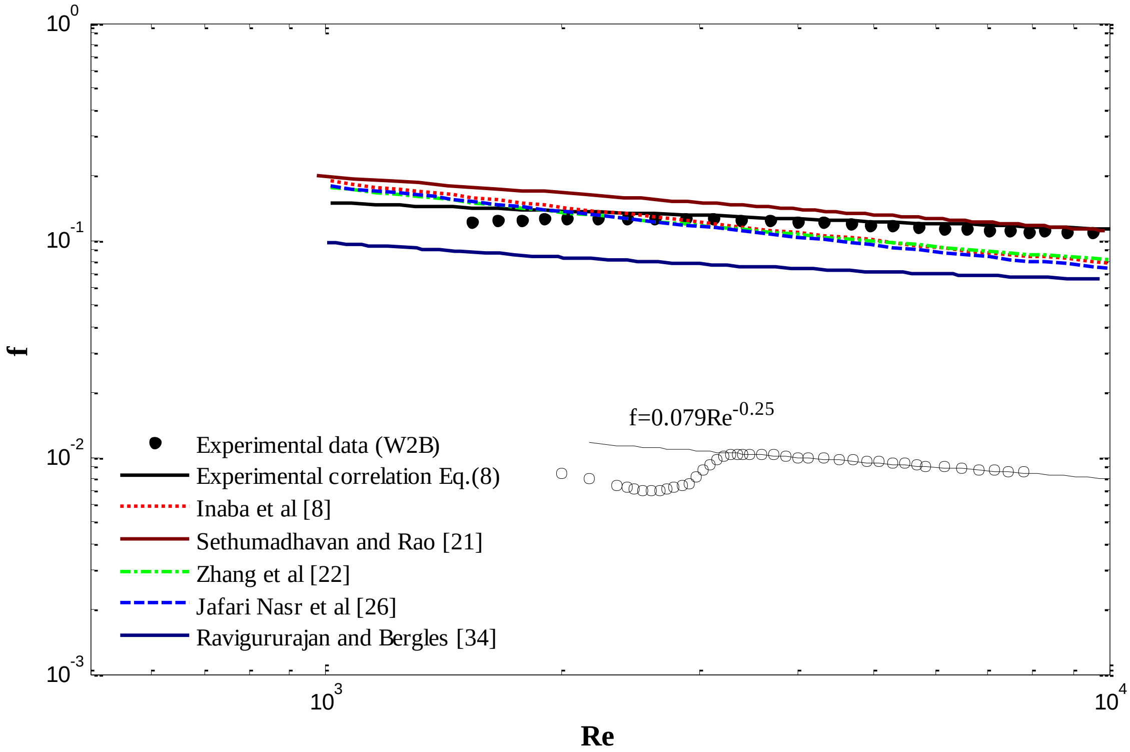


Figure 13. Correlations comparison valid for low turbulent region. Wire-coil with TSP=3.125

For the transition region, a great interest area for employing wire-coils, a comparison was not carried out, due to the lack of available correlations in the open literature. Nevertheless, attending to Fig. 8, 9 and 10, the correlations proposed in this work show a good agreement with the experimental data.

The extensive number of wire-coils studied with a wide range of p/d and e/d and the vast experimental data obtained for each specimen covering laminar, transition and low turbulent regimes has allowed to identify three different patterns of flow development in the transition region. The dimensionless *Transition Shape Parameter* defined is able to distinguish these patterns attending to the wire-coil geometric characteristics and to classify these inserts. The set of correlations derived for critical Reynolds numbers and for friction factor, allow to obtain accurately pressure drop in enhanced heat exchanger under any operating condition in which these inserts can be employed. The approach described in the present paper represents a major difference regards to previous studies.

6. Conclusions

- A group of 23 helicoidal wire-coils was studied with different geometric characteristics covering the intervals p/d=[0.25-3.37] and e/d=[0.071-0.286], for Reynolds numbers ranging from 50 to 8000 under laminar, transition and low turbulent flow regimes. This range widely covers the Reynolds numbers in which wire-coils show better performance as an enhancement passive technique in shell and tube heat exchanger applications Re=[200-2000].

- A novel non-dimensional parameter is defined: the Transition Shape Parameter (TSP), able to predict the degree of change of the friction factor evolution with Reynolds number in the transition region, compared to the smooth tube. This new parameter allows to categorize wire-coils in three groups: Low, Intermediate and High TSP. The Low TSP (TSP<10) group presents an abrupt transition and the friction factor evolution mimics the smooth tube, whereas the High TSP group (TSP>750) presents a transition region very softened with a significant variation in friction factor evolution regarding smooth tube. This phenomenon contributes to an accurately prediction of the friction factor coefficient. Finally, the Intermediate TSP (10<TSP<750) includes three wire-coil subgroups characterized by a dependent hydraulic behaviour on its dimensionless thickness.

- New correlations to predict the critical Reynolds numbers of the beginning (Re_{CL}) and ending of the transition region (Re_{CT}) are proposed. These correlations depend on the geometrical characteristics of the wire-coils and play an important role in selecting the most appropriate correlation of the friction factor as a function of the Reynolds number.

- A set of Fanning friction factor experimental correlations was obtained, for laminar, transition and low turbulent regions and compared with those proposed by other authors. The applicability limit values are established in terms of critical Reynolds numbers and the defined Transition Shape Parameter (TSP).

- To the best of the authors knowledge, this work provides the first correlation set for wire-coil inserts within the transition region. This fact is of special relevance, as wire-coils exhibit optimal thermohydraulic performance in this region, and may contribute to extend the employment of wire-coils as heat transfer enhancement devices.

Acknowledgement

The authors gratefully acknowledge the “Agencia de Ciencia y Tecnología de la Región de Murcia” (Fundación Séneca: Project with Ref. 15297/PI/10) and the Spanish Ministry of Science (Project with Ref. ENE2011-28571-C02-01) for supporting this research.

References

[1] Webb, R.L., and Kim, N. (2005) Principles of Heat Transfer. Taylor and Francis, 2ª Ed.

[2] Liu, S., and Sakr, M. (2013) A Comprehensive Review on Passive Heat Transfer Enhancements in Pipe Exchangers. Renewable and Sustainable Energy Reviews, 19: 64 – 81
https://doi.org/10.1016/j.rser.2012.11.021

[3] Sheikholeslami, M., Gorji-Bandpy, M., Ganji, D.D. (2015) Review of Heat Transfer Enhancements Methods: Focus on Passive Methods Using Swirl Flow Devices. Renewable and Sustainable Energy Reviews, 49: 444 – 469
https://doi.org/10.1016/j.rser.2015.04.113

[4] Uttarwar, S.B., Raja Rao, M. (1985) Augmentation of Laminar Flow Heat Transfer in Tubes by Means of Wire-coil Inserts. Trans ASME 107: 930–935.
doi:10.1115/1.3247523

[5] Obot, N.T., Esen, E.B., Rabas, T.J. (1990) The Role of Transition in Determining Friction and Heat Transfer in Smooth and Rough Passages. Int. J. Heat and Mass Transfer 33, 10: 2133-2143.
https://doi.org/10.1016/0017-9310(90)90115-B

[6] Oliver, D.R., Shoji, Y. (1992) Heat Transfer Enhancement in Round Tubes Using Three Different Tube Inserts: non-Newtonian Liquids. Trans. IChemE., 70: 558-564.
ISSN : 0263-8762 CODEN : CERDEE

[7] Chen, L., Zhang, H.J. (1993) Convection Heat Transfer Enhancement of Oil in a Circular Tube With Spiral Spring Inserts. Heat Transfer Measurements and Analysis ASME 249: 45-50.

[8] Inaba, H., Ozaki, K., Kanakoa, S. (1994) A Fundamental Study of Heat Transfer Enhancement and Flow-Drag Reduction in Tubes by Means of Wire-coil Insert. Japan Soc. Mech. Eng. 60: 240–247.
doi: 10.1299/kikaib.60.1005

[9] Nazmeev, Y.G., Konakhin, A.M., Kumirov, B.A., Shinkevich, O.P. (1994) An Experimental Study of Heat Transfer under Laminar Flow Conditions in Tubes with Spiral-Wire Inserts. Thermal Engineering 41, 11: 898–901.

[10] Tauscher, R., Mayinger, F., (1997) Enhancement of Heat Transfer in a Plate Heat Exchanger by Turbulence Promoters. Proceedings of the Int. Conf. on Compact Heat Exchangers for the Process Industries, Begell House, New York pp. 243-260.
doi: 10.1007/978-94-015-9159-1_12

[11] Bergles, A.E. (2002) ExHFT for Fourth Generation Heat Transfer Technology. Experimental Thermal and Fluid Science, 26: 335-344.
https://doi.org/10.1016/S0894-1777(02)00145-0

[12] Wang, L., Sunden, B. (2002) Performance Comparison of Some Tube Inserts. Int. Comm. of Heat and Mass Transfer, 29:45-56.
doi: 10.1016/S0735-1933(01)00323-2

[13] Dewan, A., Mahanta, P., Sumithra Raju, K., Suresh Kumar, P. (2004) Review of Passive Heat Transfer Augmentation Techniques. Proceedings INSTN Mechanical Eng., 218, Part A: J. Power and Energy.
https://doi.org/10.1243/0957650042456953

[14] García, A., Vicente, P.G., Viedma. A. (2005) Experimental Study of Heat Transfer Enhancement with Wire-coil Inserts in Laminar, Transition, and Turbulent Regimes at Different Prandtl Numbers. Int. J. Heat and Mass Transfer, 48: 4640–4651
https://doi.org/10.1016/j.ijheatmasstransfer.2005.04.024

[15] García, A., Solano, J.P., Vicente, P.G., Viedma. A. (2007) Flow Patterns Assessment in Tubes with Wire-coil Inserts in Laminar and Transition Regimes. Int. J. of Heat and Fluid Flow, 28: 516-525
https://doi.org/10.1016/j.ijheatfluidflow.2006.07.001

[16] Akhavan-Behabadi MA, Kumar R, Salimpour MR, Azimi R (2010) Pressure drop and heat transfer augmentation due to coiled wire inserts during laminar flow of oil inside a horizontal tube. Int J Therm Sci 49:373–381
https://doi.org/10.1016/j.icheatmasstransfer.2015.02.013

[17] Roy, S., Saha, S.K., (2015) Thermal and Friction Characteristics of Laminar Flow Through a Circular Duct Having Helical Screw-tape with Oblique Teeth Inserts and Wire-coil Inserts. Experimental Thermal and Fluid Science 68: 733-743
https://doi.org/10.1016/j.expthermflusci.2015.07.007

[18] Kumar, P., Judd, R.L. (1970) Heat Transfer with Coiled Wire Turbulence Promoters. The Canadian Journal of Chemical Engineering 48: 378 – 383
doi: 10.1002/cjce.5450480406

[19] Klaczak, A. (1973) Heat Transfer in Tubes with Spiral and Helical Turbulators. Journal of Heat Transfer 95: 557 – 559
doi: 10.1115/1.3450114

[20] Chiou, J.P. (1987) Experimental Investigation of the Augmentation of Forced Convection Heat Transfer in a Circular Tube Using Spiral Spring Inserts. Journal of Heat Transfer ASME 109: 300-307 doi:10.1115/1.3248080

[21] Sethumadhavan, R., Raja Rao, M. (1983) Turbulent Flow Heat Transfer and Fluid Friction in Helical-Wire-Coil-Inserted Tubes. Int. Journal of Heat and Mass Transfer 26: 1833 – 1845 https://doi.org/10.1016/S0017-9310(83)80154-9

[22] Zhang, Y.F., Li, F.Y., Liang, Z.M. (1991) Heat Transfer in Spiral Coil-Inserted Tubes and Its Application. Advanced Heat Transfer Augmentation Mixed Convect. ASME HTD 169: 31 - 36

[23] Rabas, T.J. (1994) Prediction Methods for Single Phase Turbulent Flow Inside Tubes with Wire-Coil Inserts. Optimal Design of Thermal Systems Components ASME HTD 279: 91 – 97

[24] Ravigururajan, T.S., Rabas, T.J. (1996). Turbulent Flow in Integrally Enhanced Tubes, Part 2: Analysis and Performance Comparison. Heat Transfer Engineering, 17: 30 – 40 http://dx.doi.org/10.1080/01457639608939871

[25] Naphon, P. (2006) Effect of Coil-Wire Insert on Heat Transfer Enhancement and Pressure Drop of the Horizontal Concentric Tubes. Int. Comm. In Heat and Mass Transfer 33: 753 – 763 https://doi.org/10.1016/j.icheatmasstransfer.2006.01.020

[26] Jafari Nasr, M.R., Habibi Khalaj, A., Mozaffari, S.H. (2010) Modelling of Heat Transfer Enhancement by Wire-coil Inserts Using Artificial Neural Network Analysis. Applied Thermal Engineering 30: 143-151
https://doi.org/10.1016/j.applthermaleng.2009.07.014

[27] San, J.Y., Huang, W.C., Chen, C.A. (2015) Experimental Investigation on Heat Transfer and Fluid Friction Correlations for Circular Tubes with Coiled-Wire Inserts. Int. Comm. In Heat and Mass Transfer, 65: 8-14
https://doi.org/10.1016/j.icheatmasstransfer.2015.04.008

[28] Sharafeldeen, M.A., Berbish, N.S., Moawed, M.A. · R. K. Ali. (2017) Experimental Investigation of Heat Transfer and Pressure Drop of Turbulent Flow Inside Tube with Inserted Helical Coils. Heat Mass Transfer 53 (4): 1265–1276
doi:10.1007/s00231-016-1897-z

[29] García, A., Solano, J.P., Vicente, P.G., Viedma, A. J. The influence of artificial roughness shape on heat transfer enhancement: Corrugated tubes, dimpled tubes and wire-coils. Applied Thermal Engineering, 35: 196-201, 2012.
https://doi.org/10.1016/j.applthermaleng.2011.10.030

[30] Saha, S.K. (2010) Thermal and Friction Characteristics of Laminar Flow Through Rectangular and Square Ducts with Transverse Ribs and Wire-coil Inserts. Experimental Thermal and Fluid Science 34: 63-72
https://doi.org/10.1016/j.expthermflusci.2009.09.003

[31] Chandrasekar, M., Suresh, S., Chandra Bose, A (2010) Experimental Studies on Heat Transfer and Friction Factor Characteristics of Al2O3/Water Nanofluid in a Circular Pipe under Laminar Flow with Wire-coil Inserts. Experimental Thermal and Fluid Science 34: 122-130 https://doi.org/10.1016/j.expthermflusci.2009.10.001

[32] Saeedinia, M., Akhavan-Behabadi, M.A., Nasr, M. (2012) Experimental Study on Heat Transfer and Pressure Drop of Nanofluid Flow in a Horizontal Coiled Wire Inserted Tube under Constant Heat Flux. Experimental Thermal and Fluid Science 36: 158 – 168
https://doi.org/10.1016/j.expthermflusci.2011.09.009

[33] Martínez, D.S., García, A., Solano, J.P., Viedma. A (2010) Heat Transfer Enhancement of Laminar and Transitional Newtonian and non-Newtonian Flows in Tubes with Wire-coils Inserts. Int. J. of Heat and Mass Transfer 76: 540-548
https://doi.org/10.1016/j.ijheatmasstransfer.2014.04.060

[34] Ravigururajan, T.S., Bergles, A.E. (1996) Development and Verification of General Correlations for Pressure Drop and Heat Transfer in Single-Phase Turbulent Flow in Enhanced Tubes. Experimental Thermal and Fluid Science 13: 55 – 70
https://doi.org/10.1016/0894-1777(96)00014-3

[35] Promvonge, P. (2008) Thermal Performance in Circular Tube Fitted with Coiled Square Wires. Energy Conversion and Management, 49: 980 – 987
https://doi.org/10.1016/j.enconman.2007.10.005

[36] Gunes, S., Ozceyhan, V., Buyukalaca, O. (2010) Heat Transfer Enhancement in a Tube with Equilateral Triangle Cross Sectioned Coiled Wire Inserts. Experimental Thermal and Fluid Science, 34: 684 – 691
https://doi.org/10.1016/j.expthermflusci.2009.12.010

[37] Gunes, S., Ozceyhan, V., Buyukalaca, O. (2010) The Experimental Investigation of Heat Transfer and Pressure Drop in a Tube with Coiled Wire Inserts Placed Separately from the Tube Wall. Applied Thermal Engineering, 30: 1719 – 1725
https://doi.org/10.1016/j.applthermaleng.2010.04.001

[38] Eimsa-ard, S., Nivesrangsan, P., Chokpoemphun, S., Promvonge, P. (2010) The Influence of Combined Non-Uniform Wire-coil and Twisted Tape Inserts on Thermal Performance Characteristics. Int. Comm. In Heat and Mass Transfer, 37: 850 – 856
https://doi.org/10.1016/j.icheatmasstransfer.2010.05.012

[39] Eimsa-ard, S., Koolnapadol, N., Promvonge, P. (2012) Heat Transfer Behaviour in a Square Duct with Tandem Wire-coil Element Insert. Chinese Journal of Chemical Engineering, 20(5): 863 – 869
https://doi.org/10.1016/S1004-9541(12)60411-X

[40] Saha, S.K. (2010) Thermal and Friction Characteristics of Turbulent Flow Trough Rectangular and Square Ducts with Transverse Ribs and Wire-Coil Inserts. Experimental Thermal and Fluid Science, 34: 575 – 589
https://doi.org/10.1016/j.expthermflusci.2009.11.010

[41] Chang, S.W., Gao, J.Y., Shih. H.L. (2015) Thermal Performances of Turbulent Tubular Flows Enhanced by Ribbed and Grooved Wire-coils. International Journal of Heat and Mass Transfer, 90: 1109 – 1124
https://doi.org/10.1016/j.ijheatmasstransfer.2015.07.070

[42] Keklikcioglu, O., and Ozceyhan, V. (2016) Experimental Investigation on Heat Transfer Enhancement of a Tube with Coiled-Wire Inserts Installed with a Separation from the Tube Wall. Int. Comm. In Heat and Mass Transfer, 78: 88 – 94
https://doi.org/10.1016/j.icheatmasstransfer.2016.08.024

[43] Naik, M.T., Fahad, S.S., Sundar, L.S., Singh, M.K. (2014) Comparative Study in Turbulent Flow Using CuO/Water Nanofluid. Experimental Thermal and Fluid Science, 57: 65 – 76
https://doi.org/10.1016/j.expthermflusci.2014.04.006

[44] Kline, S.J., and McClintock, F.A., Describing Uncertainties in Single Sample Experiments, Mech. Eng., vol. 75, pp. 3-8, 1953.

[45] Meyer, J.P., Olivier, J.A. Transitional flow inside enhanced tubes for fully developed and developing flow with different types of inlet disturbances: Part I – Adiabatic pressure drops. International Journal of Heat and Mass Transfer, 54: 1587-1597, 2011. https://doi.org/10.1016/j.ijheatmasstransfer.2010.11.027

Highlights

- 23 Wire-coils were tested for: p/d=[0.25-3.37], e/d=[0.071-0.286] and Re=[50-8000]
- Wire-coil were categorized with a new dimensionless Transition Shape Parameter
- TSP is able to distinguish three different patterns on transition to turbulence region
- Critical Reynolds and friction factor correlations for all flow regimes are given