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Experimental correlations on critical Reynolds numbers and friction factor in tubes with wire-coil inserts in laminar, transitional and low turbulent flow regimes

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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.

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.

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Nomenclature

c_p	specific heat [J/kg K]
d	internal tube diameter [m]
d_h	hydraulic diameter [m]
e	wire-coil diameter [m]
f	Fanning friction factor [–]
f_D	Darcy-Weissbach friction factor [–]
G	mass flow rate [kg/s]
k	thermal conductivity [W/mK]
l_e	entrance pipe length in test pressure [m]
l_p	distance between pressure tapes in pressure tests [m]
p	wire-coil pitch [m]
Δp	pressure drop [Pa]
t	static temperature [°C]
t_m	mean static fluid temperature in pressure tests [°C]

Special characters

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

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

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 and 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

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

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)	$f = 95.049Re^{-0.129}\,Pr^{-0.23}(p/d)^{0.848}(p/e)^{-1.428}$ Non-isothermal
Nazmeev et al. (1994) [9]	7	40–2000	0.71–4.3	0.071–0.17	14	Transformer oil	$Re^* = 415(p/d)^{0.73}\exp(-7.8\cdot(e/d))$ $f_D = 64/Re\cdot\exp[(-p/d)^{0.5}]\cdot\exp[5.5(e/d)^{0.4}]$ for $Re < Re^*$ $f_D = 530/Re^{0.36}(e/d)^{1.4}\exp[(-p/d)^{0.65}]$ 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 = 2 mm [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	$f\cdot Re = 3.55827Re^{0.32281}(\sin\alpha)^{0.25811}(e)^{0.33739}$ with "e" in (mm)