

EXPERIMENTAL INVESTIGATION ON HEAT TRANSFER AND FRICTIONAL CHARACTERISTICS OF WIRE COILS INSERTS IN TRANSITION FLOWS AT DIFFERENT PRANDLT NUMBERS

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ABSTRACT

Helical-wire-coils inserted in a round tube have been experimentally studied in order to obtain their thermohydraulic behaviour in laminar, transition and turbulent flows. Using water and propylene glycol mixtures at different concentrations, a wide range of flow conditions was covered: Reynolds Number from 100 to 90 000 and Prandtl number from 2.8 to 200. Six Wire coil inserts were tested, with a geometric range of helical pitch $1.17 < p/d < 2.68$, wire diameter $0.07 < e/d < 0.10$, pitch to wire diameter $14 < p/e < 33$ and helix angle $30^\circ < \alpha < 53^\circ$. Wire coils were tightly attached to the inner tube surface. Experimental correlations of Fanning friction factor and Nusselt number as functions of flow and dimensionless geometric parameters are proposed. Results show that wire coils increase pressure drop up to 8 times and heat transfer up to 4 times compared to the empty smooth tube. Moreover these insert devices accelerate transition to critical Reynolds numbers down to 700. Transition to turbulent flow occurs softly without instabilities in flow, due to the swirl flow induced by the wires. CRITERIOS DE MEJORA HIPOTESIS MECANISMO

1 Introduction

In the last decades, considerable effort has been done to develop heat transfer enhancement techniques in order to improve overall performance of heat exchangers. The interest in these techniques is closely tied to energy prices, and with the actual rise in energy cost it is expected that heat transfer enhancement field will experience a new growth phase. Although there is need to develop novel technologies, experimental work on the former it is still necessary, since the knowledge of its performance presents large degree of uncertainty thus making difficult their transfer to industrial practice.

Tubeside enhancement techniques can be classified according to the following criterion: (1) additional devices which are incorporated into a plain round tube (twisted tapes, wire coils) and (2) non plain round tube techniques such as surface modification of a plain tube (corrugated and dimpled tubes) or manufacturing of special tube geometries (internally finned tubes).

In applications like petrochemical industry where specifications codes are required, insert devices can be used since they do not modify round tube mechanical properties as integral roughness do. They can be used when it is required to increase the heat transfer rate of an existing heat exchanger: there is no need to replace the tube bundle and they can be installed in a routine maintenance stoppage.

Wire coils inserts are currently used in applications as oil cooling devices, preheaters or fire boilers. They show several advantages with respect to other enhancement techniques:

1. Low cost
2. Easy installation and removal
3. Preservation of original plain tube mechanical strength
4. Possibility of installation in an existing smooth tube heat exchanger

Figure 1 shows a sketch of a wire coil inserted in tight contact with the inner tube wall, where p stands for helical pitch, e for the wire-diameter and d is the tube inside diameter. This parameters can be arranged to define the wire geometry in non-dimensional form: pitch to diameter ratio p/d , wire-diameter to tube-diameter ratio e/d and pitch to wire-diameter ratio p/e .

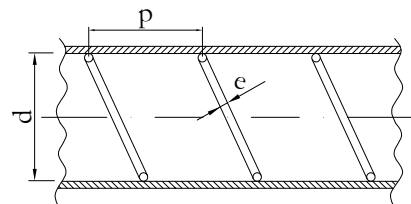


Figure 1 Sketch of a helical-wire-coil inserted in a tube.

The tubeside flow pattern is modified by the presence of a helically coiled wire as follows:

1. If the wire coil acts as a *swirl flow generator*, a helical flow at the periphery of the flow is produced. This rotating flow is superimposed upon the axially directed central core flow and promotes centrifugal forces that aid convection in case of heating.
2. If the wire coil acts as a *turbulence promoter*, flow turbulence level is increased by a separation and reattachment mechanism. Moreover, when wire coils are in contact with the tube wall, they act as roughness elements disturbing the existing laminar sublayer.

Wire coils increase heat transfer rate through one or two of the mechanisms mentioned above, depending on flow conditions and wire geometry. However, it is expected that wire coils will act as random roughness at high Reynolds numbers.

Experimental works centred on wire coils inserts are scant in comparison to those on twisted tapes. This fact has been noted

from the works of Kumar and Judd ?? or Sethumadhavan and Rao ?? to the more recent of Silva *et al* ?? or Shoji *et al* ?. Although wire coils is an interesting insert device, reliable correlations are needed to extend the use of this technique. Twisted tapes may not necessarily be the best insert device (Webb ??), but they are more used than wire coils because design equations are well established in laminar, transition and turbulent flow.

Table 1 summarizes the most substantial experimental works carried out on wire coils in single-phase flow of newtonian fluids. Most of these works were focused in turbulent flow employing air or water as the only test fluid and heat transfer dependence on Prandtl number was not established. In turbulent flow, only the work from Sethumadhavan & Rao ?? extends Prandtl range by employing water and glycerol as test fluids. In laminar and transition flows the only studies available in the open literature are Uttarwar & Rao ?? and Inaba *et al* ?. For these regimes insert devices are supposed to be an effective technique, and current data available on wire coils is completely insufficient.

Uttarwar & Rao ?? studied 7 wires employing servotherm oil as test fluid, covering a moderate Reynolds number range from 30 to 700. Their heat transfer results are affected by the entry region (Webb ??), and they didn't provide a friction factor correlation. Inaba *et al* ?? is the only experimental work that present results in the laminar-transition-turbulent region, covering a Reynolds number range from 200 to 6000.

Wire coils have been studied mainly in turbulent flow of water or air. In order to compare the experimental results from different authors, the proposed correlations have been solved for a wire coil of geometry $p/d = 1.2$ and $e/d = 0.1$ at flow conditions: $Pr = 6$ and 150 and $Re = 4000 - 90000$.

A considerable scatter among friction factor correlations plotted in figure 2 is observed, with differences up to a factor of three between predictions of Inaba *et al* ?? and Zhang ?? . Rabas ?? compiled friction factor and heat transfer data taken from several sources and concluded that there was no obvious explanation to select any of the friction factor correlations proposed by the different authors. Moreover, there is a marked lack of pressure drop data since many authors simply don't provide them.

Nusselt number correlations are plotted in Figure 3. Results present less scatter than friction data, but disagreements reach up to factors of 2 at $Pr = 150$. Differences increase at high Pr , since most of heat transfer data were obtained at moderate Prandtl numbers.

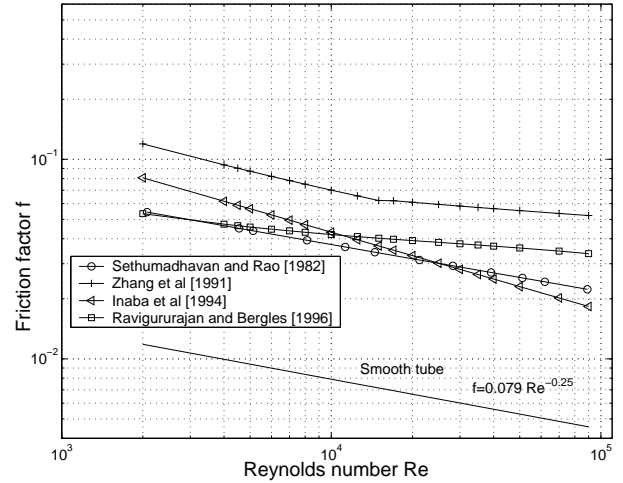


Figure 2 Comparison among experimental correlations proposed to determine Fanning friction factor in turbulent flow for a Wire coil of $p/d = 1.2$ and $e/d = 0.1$.

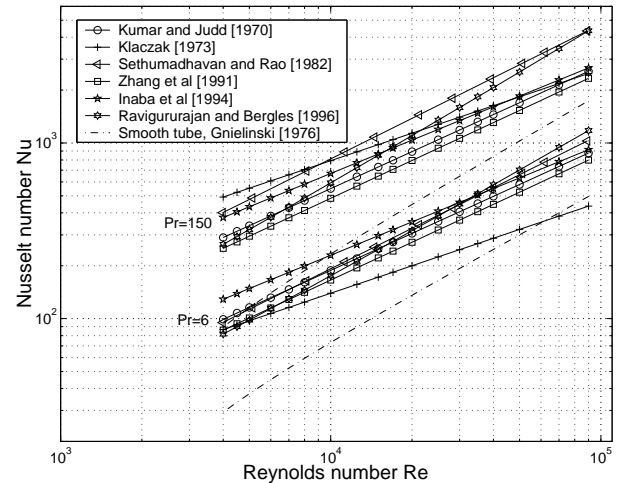


Figure 3 Comparison among experimental correlations proposed to determine Nusselt number in turbulent flow for a Wire coil of $p/d = 1.2$ and $e/d = 0.1$, at $Pr = 6$ and 150 .

The aim of current work is to extend experimental data relating to thermohydraulic behaviour of helical-wire-coil inserted in a tube. Heat transfer and pressure drop data have been obtained for laminar-transition-turbulent flow in a wide flow range: $150 < Re < 90,000$ and $5 < Pr < 200$. The experimental correlations proposed in this paper will aid to determine which of the available correlations are more suitable to predict heat transfer and pressure drop of wire coils outside of researchers' flow and geometrical experimental ranges. Geometrical range studied at the present work is compared to those from other experimental investigations in Figure 4.

Paper	N_{wire}	d [mm]	p/d	e/d	p/e	$Re \times 10^3$	Test Fluid, Pr
Kumar & Judd []	15	12.2	1.05 - 5.50	0.11 - 0.15	8.0 - 47	7.0 - 100	Water, 6
Klaczak []	13	6.8	0.68 - 2.88	0.10 - 0.22	6.6 - 13	1.7 - 20	Water, 2.5 - 9.0
Sethumadhavan & Rao []	8	25.0	0.40 - 2.64	0.08 - 0.12	3.3 - 33	4.0 - 100	Water - Glycerol 5.2 - 32
Uttarwar & Rao []	7	25.2	0.40 - 2.62	0.08 - 0.13	5.0 - 33	0.03 - 0.7	Servotherm oil, 300 - 675
Ravigururajan & Bergles []	5	68	0.60 - 1.12	0.023-0.047	16 - 32	5.0 - 25	Air,
Inaba et al []	19	16	0.3 - 6.5	0.12 - 0.19	1.6 - 52	0.2 - 6	Water,

Table 1 Experimental range covered by the studies published in the literature available [2-6].

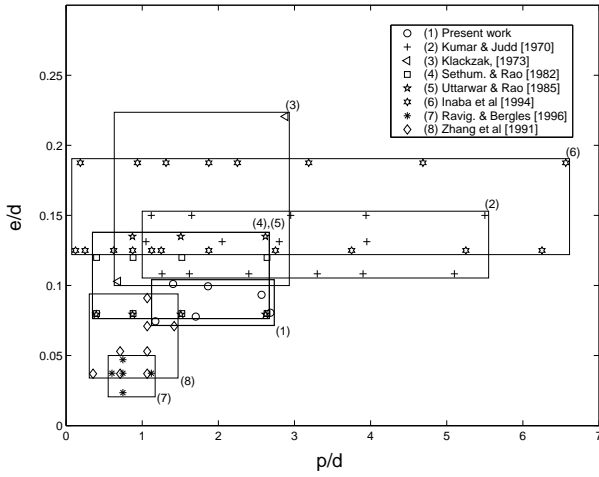


Figure 4 Dimensionless pitch p/d vs. dimensionless wire diameter e/d . Present work geometrical range in comparison to papers [2-8]

2 Tested tubes (FALTA)

3 Experimental set-up (FALTA)

Fluid	Temp.	Re	Pr
100 % WT	65°C	4000 – 90000	2.8
100 % WT	40°C	1500 – 60000	4.3
50 % WT - 50% PG	65°C	500 – 20000	18
50 % WT - 50% PG	40°C	250 – 10000	36
10 % WT - 90% PG	65°C	100 – 7000	75
10 % WT - 90% PG	40°C	80 – 3000	160

Table 2 Test fluids and experimental flow range

4 Results and discussion

4.1 Pressure drop

Isothermal pressure drop experiments were carried out employing water and propylene glycol mixtures as test fluids to obtain Fanning friction factors in a continuous Reynolds number range from 200 to 90000. Previously to perform experiments over the wire coils, the smooth empty tube was tested so as to adjust the experimental setup and check its uncertainties. Smooth tube friction factor results are compared to the analytical solution ($f_s = 16Re^{-1}$) in the laminar region and to the widely known Blasius equation ($f_s = 0.079Re^{-0.25}$) in the turbulent region. The measurements deviation ($< 3\%$) are in accordance with the uncertainty analysis, and assures a proper instrumentation adjustment.

Results are presented in Fig. 5 for the 6 wire coils and the smooth tube in laminar, transition and turbulent flow. At Reynolds numbers below 500, friction factor values are proportional to Re^{-1} , which means a pure laminar flow. Transition to turbulence flow occurs in a gradual way, without instabilities. At Reynolds numbers above 3000, friction factor tendency points to a pure turbulent flow. In the high Reynolds number region ($Re > 20000$), fanning factors of wires with the lowest values of pitch to wire-diameter ratio ($p/e < 19$, Wires 01, 03, 05 and 06) tend to become independent of Re , a similar trend that a rough surface. This is in accordance with the early work of Takhesima *et al* (??), but contradicts Sethumadhavan and Rao results (??) who did not find friction factors independent of Reynolds number even for a wire of $p/e = 5$ at $Re=100000$.

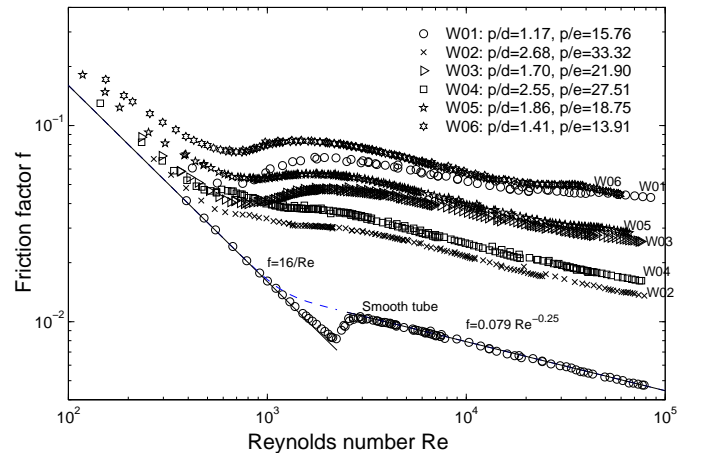


Figure 5 Fanning friction factor vs. Reynolds number. Wire coils inserts in laminar transition and turbulent flows.

Friction factor experimental results from the 6 wires at Reynolds numbers from 2000 to 30000 have been correlated by the following equation

$$f_a = 5.76(e/d)^{0.95}(p/d)^{-1.21}Re^{0.217} \quad (1)$$

Since friction factor is proportional to $(e/d)^{0.95}$ and to $(p/d)^{-1.21}$, pitch to wire-diameter ratio p/e can be used as the only parameter that characterizes tube roughness' influence on friction factor. The following general equation is finally proposed

$$f_a = 9.35(p/e)^{-1.16}Re^{-0.217}. \quad (2)$$

Eq. (2) leads to a deviation of 8 % for 95% of friction factor experimental data in the region: $Re = 2000 - 30000$. At high Reynolds turbulent flow, ($Re = 30000 - 80000$), the use of this equation overpredicts up to 15 % the experimental values.

Fig. 6 shows friction factor augmentation (f_a/f_s) produced by the wire coils. In pure laminar flow ($Re < 500$), moderate friction factor augmentations between 1,2 and 1,8 are observed. At pure turbulent flows these values are much higher and stay between 2.5 for W01 and 9 for W02 at $Re = 80000$.

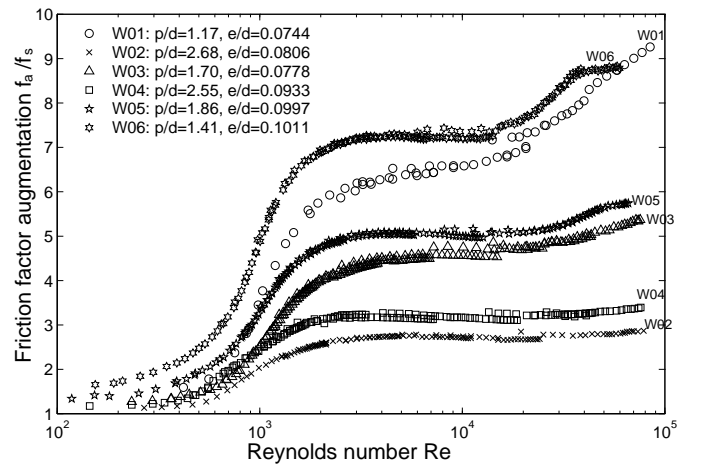


Figure 6 Fanning friction factor augmentation vs. Reynolds number. Wire coils inserts in transition and turbulent flows.

An equation for friction factor augmentation for Reynolds numbers from 2000 to 30000 has been obtained as the ratio between Eq. (2) and Blasius equation

$$f_a/f_s = 118.35(p/e)^{-1.16}Re^{0.033}. \quad (3)$$

Eq. (3) shows that pressure drop augmentation in the range $2000 < Re < 30000$ depends mainly on wire coil geometry with a slight dependence on Re .

4.1.1 Results discussion

This experimental work extends the amount of data available on pressure drop produced by wire coils. Around 900 experimental friction factor data have been obtained for 6 wire coils of geometries p/d from 1.17 to 2.68 and e/d from 0.75 to 0.1 in a Reynolds number range from 100 to 90000. Additionally, a friction factor correlation has been proposed in the Reynolds number range from 2000 to 30000 (Eq. 2).

A review of the open literature shows that many authors do not correlate their experimental friction factor results. Moreover, there is a substantial scatter of the data from the few sources available. Rabas [??] suggested as possible causes: the vibrations of the coil and the tube and the clearance that sometimes exists between the coil and the tube wall.

Fig. 7 compares Eq. (2) to the correlations proposed by other sources in turbulent regime for a wire coil of geometry $p/d = 1.2$ and $e/d = 0.1$. The correlations proposed by Sethumadhavan and Rao [??], Ravigururajan and Bergles [??] and Inaba *et al* [??] underpredicts the results of the present work. Rabas [??] reviewed data from different open and private sources and concluded that the friction factor correlation of Ravigururajan and Bergles [??] underpredicted most of that data. Less discrepancies (around 25 %) have been found with the graphical results from Kumar (??) and a good agreement exists with Zhang *et al* [??] whose wire diameter range covers the one achieved in the present work.

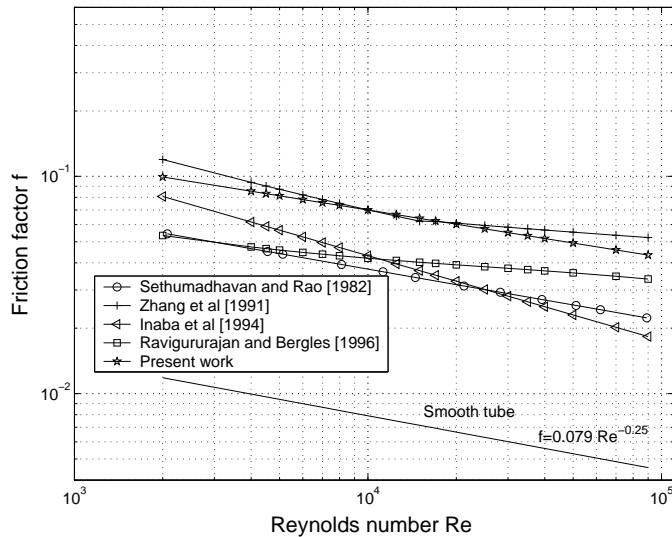


Figure 7 Fanning friction factor augmentation vs. Reynolds number. Wire coils inserts in transition and turbulent flows.

Wire coils have been tested in the laminar and transition regimes in order to analyze the benefits offered by this technique for viscous fluids. At pure laminar flow ($Re < 500$), Fig. 5 shows that friction factor increases with hydraulic diameter D_h with values of f_a/f_s between 1.2 and 1.8. This fact was observed by Uttarwar *et al* [??] and clearly suggests that wire-coil inserted tubes behave essentially as a smooth tube in the laminar regime.

Transition to turbulent flow takes place at low Reynolds numbers ($Re \approx 700$) and in a gradual way. Fig. 5 shows that the critical Reynolds number is not clearly marked suggesting that

a swirl flow mechanism exists: in twisted tapes, where a rotating component is clearly induced, transition from laminar to turbulent flow is as well produced continuously and it is even not possible to determine the point where transition occurs (Manglik [??]). This behaviour differs from what the authors found in corrugated and dimpled tubes, where sudden transitions were observed and the critical Reynolds numbers were defined by a local minimum in the friction factor curve (authors [??] and [??]).

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4.2 Heat Transfer

Heat transfer studies under uniform heat flux conditions were carried out for a smooth empty tube and for this tube with 6 different wire coil inserts. Following the procedure described at section 3, a wide range of flow conditions was covered: $Re = 80 - 90000$, $Pr = 2,8 - 160$.

The set of tests started with the empty smooth tube. These experiments were employed to check the experimental set-up, verify the procedure and confirm the calculated uncertainties. Fig. 8 shows Nusselt number results vs. Reynolds number for the smooth tube in laminar, transition and turbulent regimes. In laminar flow, heat transfer was produced under mixed convection. Local Nusselt numbers were measured in the fully developed region and thus they depend only on Rayleigh number. Results at Reynolds below 2300 are compared with Petukhov equation

$$Nu_s = 4,36[1 + (Ra/18000)^{4}]^{0,045}. \quad (4)$$

Experimental results are in good agreement with Eq. 4. Heat transfer experiments were carried out at Rayleigh numbers between 2 and $3.5 \cdot 10^7$, which corresponds to $Nu_s = 15.4$ and 17 (horizontal lines in Fig. 8).

Turbulent Nusselt number results in Fig. 8 are compared to Gnielinski [?] equation,

$$Nu_s = \frac{(f_s/2)(Re - 1000)Pr}{1 + 12.7\sqrt{f_s/2}(Pr^{2/3} - 1)}. \quad (5)$$

Experimental results are slightly higher than those predicted by Eq. (5) (1 to 6 percent above). To determine accurately the real heat transfer augmentation produced by the wire coils, the following equation is proposed:

$$Nu_s = 0.0147(Re - 1000)^{0.86}Pr^{0.39}. \quad (6)$$

This equation correlates 95% of the measured smooth tube Nusselt numbers within $\pm 5\%$.

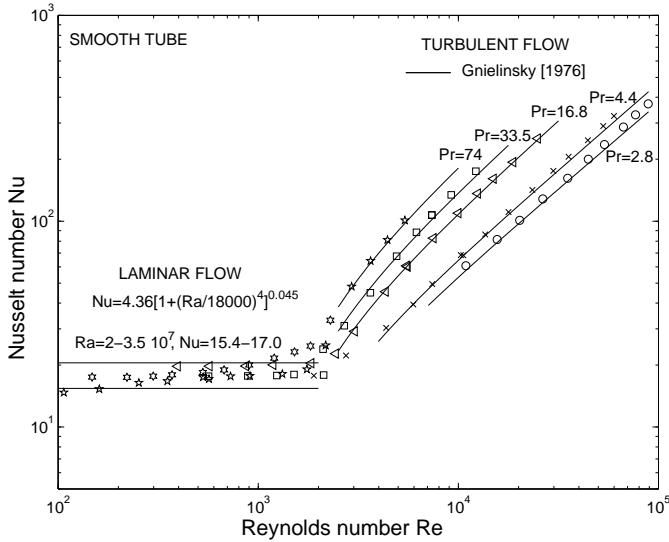


Figure 8 Nusselt number vs. Reynolds number in laminar-transition-turbulent flow. Experimental smooth tube results compared with Pethukhov and Gnielinski equations.

Laminar, transitional and turbulent heat transfer experiments were carried out for the wire coil inserts described in Table ???. Around one hundred experimental points were taken for each wire coil in order to determine Re and Pr influence on Nu_a . Fig. 9 shows Nusselt numbers measured for wire coil 05, as an example of the experimental work carried out on the six wire coils.

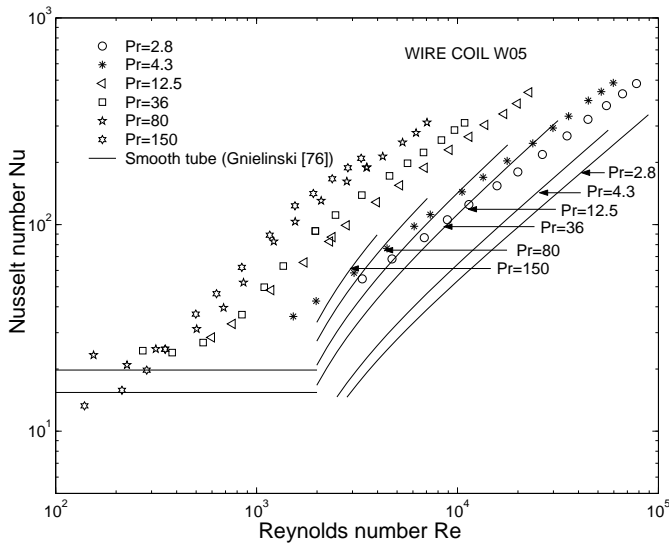


Figure 9 Nusselt number vs. Reynolds number. Wire Coil 05.

Heat transfer results for the set of wire coils are shown in Fig 10. For the sake of clarity, only Nusselt numbers at $Pr = 4.3$ and 75 are presented. At pure laminar regime ($Re < 500$), Nusselt numbers are close to smooth tube results under mixed convection. In fact, appreciable circumferential temperature differences were measured in the tube wall, which indicates that the fbw is affected by the bouyancy forces. A smooth transition to turbulent fbw is observed and at Reynolds numbers above 1000 Nusselt numbers shows a tendency of a pure turbulent fbw.

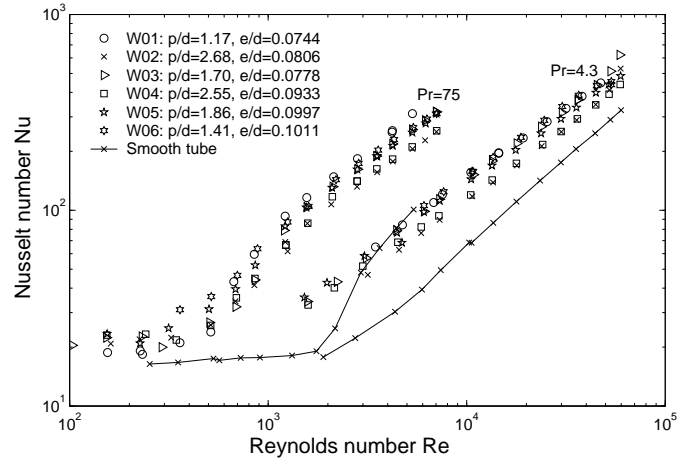


Figure 10 Nusselt number vs. Reynolds number. Wire Coil 01-06 at $Pr=4.3$ and 75 .

A Nusselt number equation in the the form $Nu_a = Nu_a(Re, Pr, e/d, p/d)$ have been obtained via curve-fitting of heat transfer results for the six wire coils (≈ 350 points):

$$Nu_a = 0.303(e/d)^{0.12}(p/d)^{-0.377}Re^{0.72}Pr^{0.37}. \quad (7)$$

Eq. (7) shows that the wire coil diameter makes a slight influence on heat transfer. Thus heat transfer in wire coil inserts is mainly influenced by the reduced pitch p/d . The following general equation correlates 95% of experimental data within a deviation of 9%

$$Nu_a = 0.132(p/d)^{-0.372}Re^{0.72}Pr^{0.37}. \quad (8)$$

Nusselt number augmentation is defined by the ratio between Nu_a and Nu_s at the same Reynolds and Prandtl numbers. Fig. 11 shows Nu_a/Nu_s for wire coil 05. In the transition region ($500 < Re < 3000$), heat transfer augmentation depends strogly on Prandtl number. In this region, fbw regime in a smooth tube is laminar and heat transfer does not depend neither on Reynolds or Prandtl number. However, if a wire coil is inserted, fbw becomes turbulent and Nusselt number depends on both nondimensional numbers ($Nu \propto Re^{0.72}$ $Nu \propto Pr^{0.37}$). For $Re > 3000$ experimental measurements show that the Prandtl number influence on heat transfer augmentation is negligible.

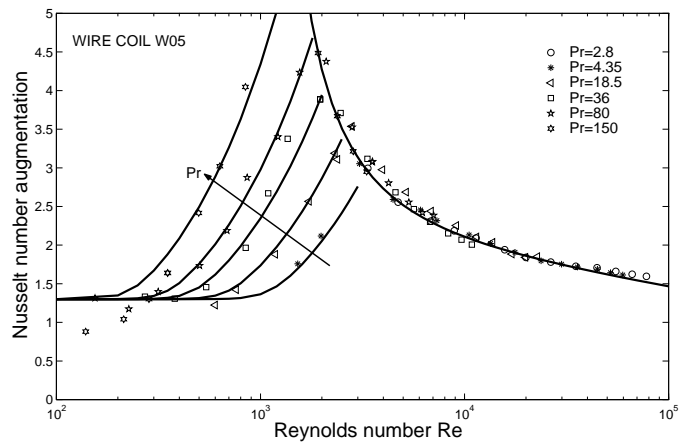


Figure 11 Nusselt number vs. Reynolds number. Wire Coil 05.

Fig. 12 shows Nusselt number augmentation produced by all wire coils at $Pr = 4.3$ and 75 . At Reynolds numbers $Re < 500$ Nu_a/Nu_s below 1.4 are obtained in all cases. In turbulent fbw Nu_a/Nu_s decreases with Reynolds number: $Nu_a/Nu_s = 2 - 2.8$ at $Re = 5000$ and $Nu_a/Nu_s = 1.5 - 2.1$ at $Re = 20000$.

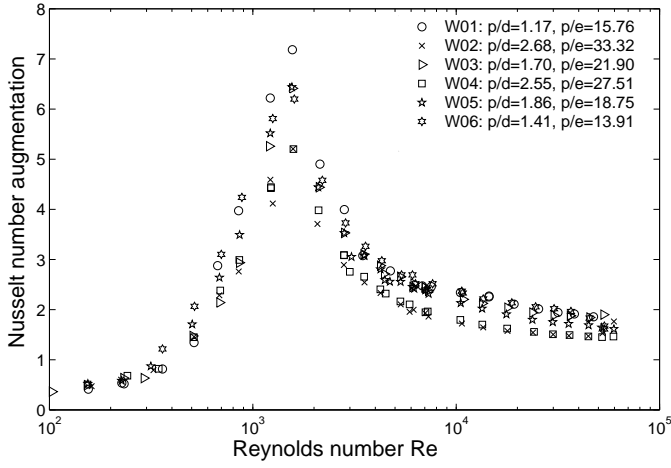


Figure 12 Nusselt number vs. Reynolds number. Wire Coil 05.

4.2.1 Results discussion

Experimental results have shown that heat transfer augmentation Nu_a/Nu_s decreases with Reynolds numbers. The measurements show Nusselt number augmentations similar to those found by Sethumadhavan and Rao and Kumar and Judd mas ???.

Results indicate that wire diameter to tube diameter ratio e/d has a negligible influence on heat transfer, just as Sethumadhavan and Rao and Kumar and Judd mas ??? reported within a similar e/d range.

Fig. 13 shows the proposed Nusselt number correlation (Eq. ??) for a wire of $e/d = 0.1$ and $p/d = 1.2$ at Prandtl numbers 6 and 150 in comparison to the correlation proposed by other sources. At $Pr = 6$, results from Eq. (??) are very close to those predicted by Kumar and Judd [?] and in good agreement with Sethumadhavan and Raja Rao and Zhang *et al.*. At $Pr = 150$ the agreement with Kumar and Judd [?] remains but Eq. (??) consistently underpredicts results from Sethumadhavan and Raja Rao. This work and the one carried out by Sethumadhavan and Raja Rao are the only that have tried to determine Prandtl number influence on heat transfer and have different conclusions: Sethumadhavan and Raja Rao obtained $Nu \propto Pr^{0.45}$ while at this work concludes $Nu \propto Pr^{0.37}$.

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Rest of works only employed water or air as test fluids and the use of their correlations is not recommended at high Prandtl numbers.

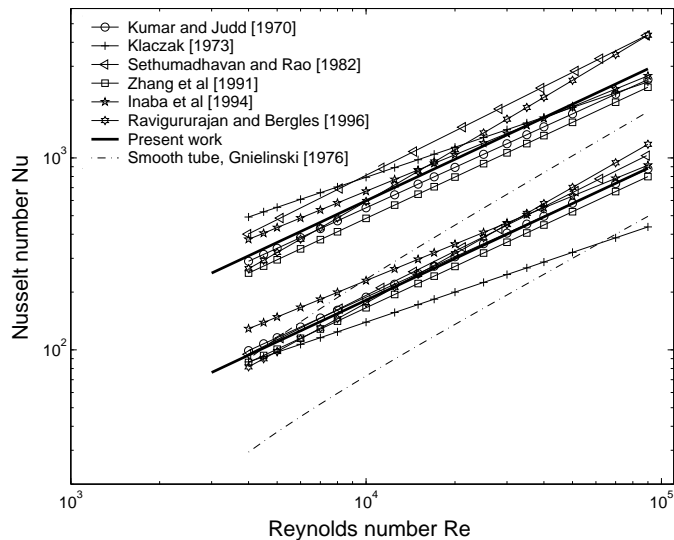


Figure 13 Nusselt number vs. Reynolds number. Wire Coil 05.

5 Performance evaluation, roughness optimization

Bergles *et al.* [?] and Webb [?] proposed several performance criteria to evaluate the thermohydraulic performance of the enhancement techniques. In this paper, criteria $R3$ and $R5$ outlined by Bergles *et al.* [?] are calculated to quantify the benefits from wire coil inserts.

The criterion $R3$ is defined by $R3 = Nu_a/Nu_o$ where Nu_a is the heat transfer obtained with the wire coils and Nu_o is the heat transfer obtained with an smooth tube for equal pumping power and heat exchange surface area. To satisfy the constrain of equal pumping power, Nu_o is evaluated at the equivalent smooth tube Reynolds number Re_o , which matches

$$f_a Re_a^3 = f_o Re_o^3 \Rightarrow Re_o^3 = \frac{f_a Re_a^3}{f_o} \quad (9)$$

Fig. 14 shows the performance parameter $R3$ for the six wire coils inserts studied at Prandtl number 7.

Comentarios

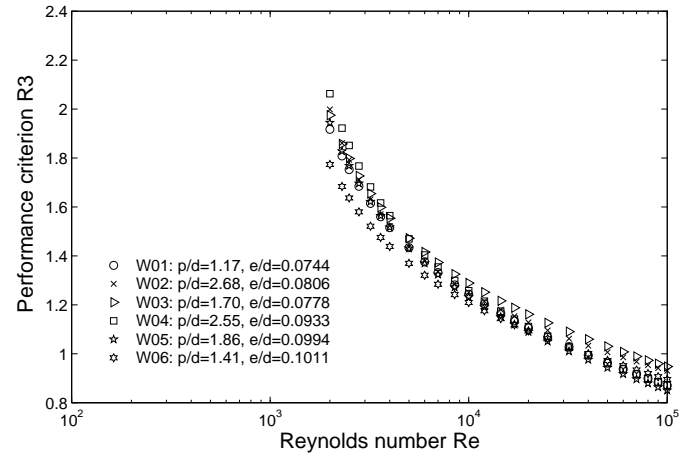


Figure 14 Performance evaluation criterion R3

Criterion $R5$ yields the surface reduction obtained by a heat exchanger design if wire coil inserts are used. This surface reduction is determined for equal pumping power and heat duty. Tube diameter is supposed to be constant and surface reduction can be obtained by reducing the number of tubes N , and/or tube length l . The equivalent smooth tube Reynolds number Re_o is obtained by:

$$f_o Re_o^3 / Nu_o = f_a Re_a^3 / Nu_a \Rightarrow Re_o^3 = \frac{f_a Re_a^3 Nu_o}{f_o Nu_a} \quad (10)$$

f_a and Nu_a are calculated at a given Re_a by Eqs. (??) and (??), respectively. f_o is calculated by Blasius equation and Nu_o by Eq. (6). Re_o is calculated by an iterative method in Eq. (10). The relation between amounts of tubes N_a/N_o and their relative lengths l_a/l_o should be calculated in order to have a constant pumping power.

Results are shown in Fig. 15. As expected, $R5$ increases parallel to Re_o increase.

Comentarios

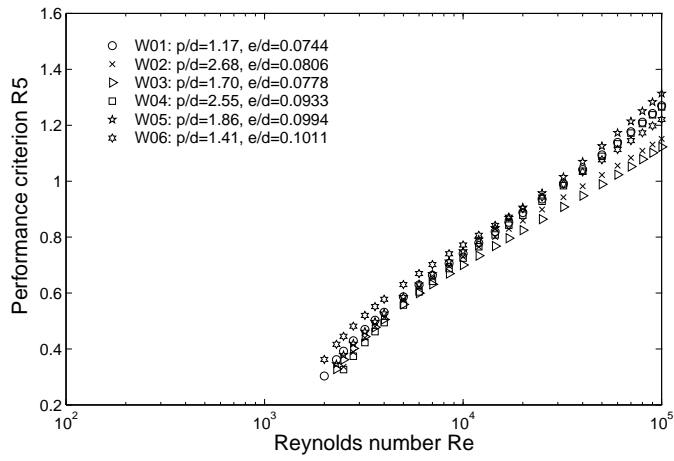


Figure 15 Performance evaluation criterion R5

6 Conclusions

1. A comprehensive experimental study has been carried out on
2. General correlations were drawn
3. Measurements were taken at 5 different Prandtl numbers in
4. According to performance evaluation criterion R3 suggested by Bergles *et al.* [?], an optimization analysis was carried out. At low
5. The present study significantly augments the reduced experimental data carried