Experimental study of fouling mitigation and heat transfer enhancement with wire coil inserts

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Abstract

Tube inserts are used as heat transfer enhancement devices in applications: retrofitting and new design of shell and tube heat exchangers. In this paper, Helical-wire-coils fitted inside a round tube have been experimentally studied in order to characterize their thermo-hydraulic and fouling behaviors in turbulent flow regime. The present study introduces a new experimental method to reveal for the fouling process of $CaCO_3$ (Crystallization mechanism for water) and to study the effect of wire coil inserts on fouling resistance of $CaCO_3$, heat transfer coefficient and friction factor.

The fouling experiments were performed with the Reynolds number set at 12,824 which is correspondent to the flow velocity of 0.66 m/s in the test section. The inlet bulk temperature was 39 ^oC and with average total hardness 245. By adding of calcium chloride ($CaCl_2$) and bicarbonate sodium ($NaHCO_3$) continuously to water tank, the average total hardness keep almost constant. Fouling resistance results report from three wire coil inserts within a geometrical range of helical pitch $0.1375<p/d<0.2813$ and wire diameter $0.0238<e/d<0.0750$. The heat transfer and pressure drop are results from wire coils are shown in turbulent flow regime within a wide flow range: $4000<Re<52000$ and almost constant Prandtl number (Pr=3.15-4.55). We proposed a mathematical restatement on Kern and Seaton fouling model for plain and enhanced tube (with wire coil type1). Also Nusselt number and isothermal friction factor correlations are proposed for turbulent regime in terms of Reynolds number ($Re>4500$) and inserts geometry.

Keywords: Wire coil inserts- Fouling mitigation- Heat transfer enhancement- Friction factor.

Introduction

1-1- Water fouling (scaling)

Deposition of scale is a chemical process due to the concentrations of dissolved salts in the cooling water exceeding their solubility limits and precipitate on to surfaces in contact with the water. The most common scale formers, calcium salts, exhibit reverse solubility in that they become less soluble as the temperature of the water increases. This property causes scale formation in the most sensitive area, particularly in the heat transfer surfaces of production equipment. One of the most common forms of scales is calcium carbonate ($CaCO_3$) [1-5]. Most of the research done in the field of precipitation fouling of cooling tower water was on calcium carbonate [6]. When scale deposits in a heat exchanger surface, it is traditionally called fouling.

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The effect of temperature and flow velocity on fouling resistance has been extensively studied, from which the fouling mechanisms were speculate or modeled [1, 4-5]. To understand the behavior of the fouling, researchers measured the fouling resistance as a function of time. The analytical and semi-analytical models were developed based on these experimental studies to estimate fouling resistance. These models did not always give good agreement with experimental results. Hasson et al. [7] presented a fouling model to predict the fouling rate in a heat exchangers considering $CaCO_3$ deposition only. Since their analytical model did not consider the removal mechanism, the model is applicable to low velocity flows where the removal process is negligibly small.

The scale deposits produced from precipitation fouling are often very hard and difficult to remove. Webb and Li [8] stated that the main source of fouling in cooling water systems is the precipitation of calcium carbonate. Since water contains bicarbonate ions and not carbonate ions, the following three-step reactions describe the actual process of CaCO3 precipitation:

$$(\text{Reaction 1}) \qquad HCO_3^-{}_{(aq)} \leftrightarrow OH^-{}_{(aq)} + CO_2{}_{(aq)} \qquad (1)$$

$$(\text{Reaction 2}) \qquad OH^-{}_{(aq)} + HCO_3^- \leftrightarrow CO_3^{2-}{}_{(aq)} + H_2O \qquad (2)$$

$$(\text{Reaction 3}) \qquad Ca^{2+}{}_{(aq)} + CO_3^{2-}{}_{(aq)} \leftrightarrow CaCO_3{}_{(s)} \qquad (3)$$

1-2- Wire coil tube inserts

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

Depending on the wire coil geometry and on the Reynolds number, two different types of flows can occur: rotating flow and separated flow. The first one occurs at the tube periphery due to the helix angle and affects to a greater or lesser extent the thickness of the flow. A separated flow can occur due to the fluid crossover through the wire. The tubeside flow pattern is modified by the presence of a helically coiled wire as follows:

1- If the wire coils are in contact with the tube wall ($d_{insert}= d_{tube}$), they act as roughness elements and disturb the existing laminar sublayer. It is useful for heat transfer enhancement applications because the laminar sublayer is a resistance for heat transfer. Also, contacting with the tube wall quicken fouling (scaling) on tube surface.

2- If the wire coils are in contact with the tube wall ($d_{insert}<d_{tube}$), their role on heat transfer enhancement is not noticeable in comparison to it on scaling mitigation, specially when parameters e/d and p/d are as it can vibrate, because it increases removal rate of scale.

More researchers have been conducted with regards to heat transfer enhancement (wire coil effect on the heat transfer coefficient and pressure drop) as proven by a large number of papers in the literature [9-12]. Table 2 shows the published heat transfer coefficient and pressure drop data and their limitations for wire coil inserts [13], although it update. However until now, no researcher surveys their effects on the fouling mitigation with their effects on the heat transfer coefficient and pressure drop, simultaneously.

The main aim of the present paper is to study the effect of wire coil inserts on crystallization fouling (scaling) mitigation for water solutions with 245 ppm hardness. Also, it is reported the experimental data on wire coil inserts thermohydraulic behavior.

Nomenclature

A_f	cross section of tube (m^2)
A_I	carbon steel tube inner surface area (m^2)
d	tube diameter (m)
d_h	hydraulic diameter at inner tube (m)
e	wire diameter (fig. 1) (m)
h	heat transfer coefficient (w m^{-2} °C^{-1})
K_b	thermal conductivity of carbon steel block (J$m^{-1}s^{-1}$ °C^{-1})
K_{pipe}	thermal conductivity of tube (J$m^{-1}s^{-1}$ °C^{-1})
L	length of heating section (Carbon stell block) (m)
m	mass rate (kg/s)
p	pitch (for wire coil tube insert) (m)
ΔP	pressure drop (Pa)
Q	heat transfer rate (W)
r	radius (m)
R_f	fouling resistance (m^2.K/W)
$R_{f¥}$	fouling resistance at infinite time – the asymptotic value (m^2.K/W)
S	slope
T	temperature (°C)
T_b	bulk mean temperature (°C)
T_I	inner surface temperature of carbon steel block(or outer surface temperature of tube) (°C)
T_i	temperature for ith situation in carbon steel block
T_w	wall temperature (^{o}C)
t	time (Sec)
u	fluid velocity (m/s)

Dimensionless groups

f	friction factor
Nu	Nusselt number
Re	Reynolds number
Re_{Dh}	Reynolds number based on hydraulic diameter
Pr	Prandtl number

Greek symbol

b	a constant dependent on the system properties
r	density (kg/m^3)
m	viscosity (kg $m^{-1}s^{-1}$)

Subscripts

i	ith situation in carbon steel block (fig. 3)
I	inner surface of carbon steel block
d	deposition
r	removal
s	surface
W	wall

Table 1 Characteristic dimensions of the helical wire coils

wire coil no.	d [mm]	d_{insert} [mm]	p [mm]	e [mm]	p/d [-]	e/d [-]	p/e [-]
smooth tube	16	-	-	-	-	-	-
Type 1	16	13.8	2.2	0.38	0.1375	0.02375	5.79
Type 2	16	13.8	3.4	0.9	0.2125	0.05625	3.78
Type 3	16	13.8	4.5	1.2	0.2813	0.07500	3.75
Type 4	16	16	4.5	1.2	0.2813	0.07500	3.75

Table 2 Published data and their limitations for wire coil tube inserts [13] (Also, It is updated)

Investigator(s)	Re	Pr	Geometrical Characteristics	
			p/d_i	e/d_i
Sams (1956)	10^4-10^5	0.7	0.0475-5.317	0.0317-0.063
Kumar-Judd (1970)	7×10^3-10^5	5	1.00-5.50	0.104-0.144
Klaczak (1973)	1700-2×10^4	2.5-9	0.684-2.882	0.1029-0.2206
Sethumadhavan-Raj Rao (1983)	3×10^3-10^5	5.2-32	0.4-5.2	0.08-0.236
Uttarwar-Raj Rao (1985)	30-2×10^3	300-675	0.396-2.62	0.0796-0.135
Ravigururajan-Bergles (1986)	5×10^3-25×10^4	0.66-38	0.1-7.0	0.01-0.2
Chiou (1987)	600-10^4	90	0.333-1.0	0.084-0.24
Prasad-Brown (1988)	4×10^4-108×10^3	5.1-5.4	0.2-0.605	0.058-0.11
Zhang *et al.* (1991)	6000-8×10^4	0.7	0.35-2.48	0.037-0.09
Yang *et al.* (1992)	3800-42×10^3	5.7-7.9	0.783-2.087	0.0404-0.0848
Garcı´a *et al.* (2005)	80-90000	2.5-150	1.17-2.68	0.07-0.10

1- Experimental setup

The experimental setup schematically shown in Fig. 2a, used to study potential benefits of the tube inserts on heat transfer enhancement and fouling mitigation. It is used two test sections very similar because the fouling experiments were run a feed with the same operating condition for two states, one fills with tube insert and the other is as plain tube. The inner tube is carbon steel (St 35.8), with a 3/4-in OD diameter (BWG 14) and a 80-cm long that a 50-cm long of it placed in a carbon steel cylinder with a 10-cm diameter and a 50-cm long (fig. 2b). Two bond heaters, rated at 2000 W each, are continuously wrapped around carbon steel cylinder and bonded to the surface. Temperature of inlet surface of tube (and so heat duty of heaters) is controlled by a thermocouple from nine thermocouples that are placed in carbon steel cylinder as at three different length (L=5, 10, 20 cm) and at three different radiuses (fig. 2b). They are used to calculate the heat flux and inner surface temperature of the tube. Two band heaters surround for heating. Carbon steel cylinder placed for:

1- Uniformly heat distribution on outer surface of inner tube.
2- Calculation of heat flux and surface temperature using of temperature profile at different radius.

The system equipped with thermocouples (type K) to measure mixed mean inlet and outlet temperatures and transmitters to measure inlet-to-outlet differential pressure losses within a range of 0-1.2 bar; a rotameter flowmeter for range 140-1400 lit/hr. The rotameter flowmeters were gravimetrically calibrated across their respective flow ranges to ensure very precise flow measurement. All data were collected using a data acquisition system, to allow a proper time to reach to steady state condition at each increment. The heat flux calculated by data obtained from nine thermocouples which are placed in carbon steel cylinder.

3- Experimental Program

The temperature profile versus radius is obtained by averaging of three temperatures in each radius at different lengths (fig. 3),

$$T_i = S\,Ln(r_i) + T_I \qquad (4)$$

T_I is temperature in outer surface of tube (or inner surface of carbon steel cylinder). The heat transfer rate can be calculated from:

$$Q = K_b A_I \left(\frac{dT_i}{dr_i}\right)_{r=r_I} \qquad (5)$$

With,

$$A_I = p\, d_I\, L \qquad (6)$$

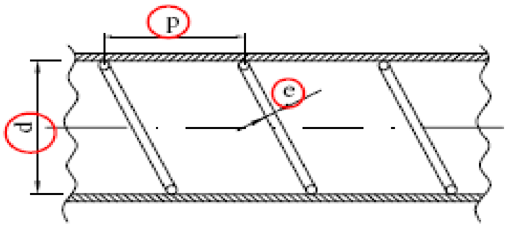

Figure 1 Sketch of a helical-wire-coil tube insert fitted inside a smooth tube

$\left(\frac{dT_i}{dr_i}\right)_{r_i=r_I}$ is calculated by temperature profile (Eq. 3):

$$\left(\frac{dT_i}{dr_i}\right) = \frac{S}{r_i} \quad \Rightarrow \quad \left(\frac{dT_i}{dr_i}\right)_{r=r_I} = \frac{S}{r_I} \qquad (7)$$

that,

$$Q = K_b (p\, d_I\, L)\left(\frac{S}{r_I}\right) \qquad (8)$$

The inside wall temperatures and local heat transfer coefficient can be calculated by:

$$T_s = T_I - Q \ln\left({d_I}/{d_S} \right) / \left(2p\, k_{pipe} L\right) \qquad (9)$$

$$h_{\exp} = Q / (L\, d_s p\, (T_s - T_b)) \qquad (10)$$

and finally, fouling resistance is calculated from:

$$R_f = \left(\frac{1}{h}\right)_{t=t} - \left(\frac{1}{h}\right)_{t=0} \qquad (11)$$

that $h_{t=0}$ is heat transfer coefficient at start of the experiments.

In above, we explained experiment method for design state. In these experiments, we encountered to problems. For example, there is a contact resistance between outlet surface tube and inlet surface carbon steel block, although for building of test sections, the carbon steel block heated to a high temperature and tube inserted into it and by contraction of tube, it was fixed permanently over inlet surface carbon steel block. However in fact, the contact resistance can be never eliminated, so it is spotted its error.

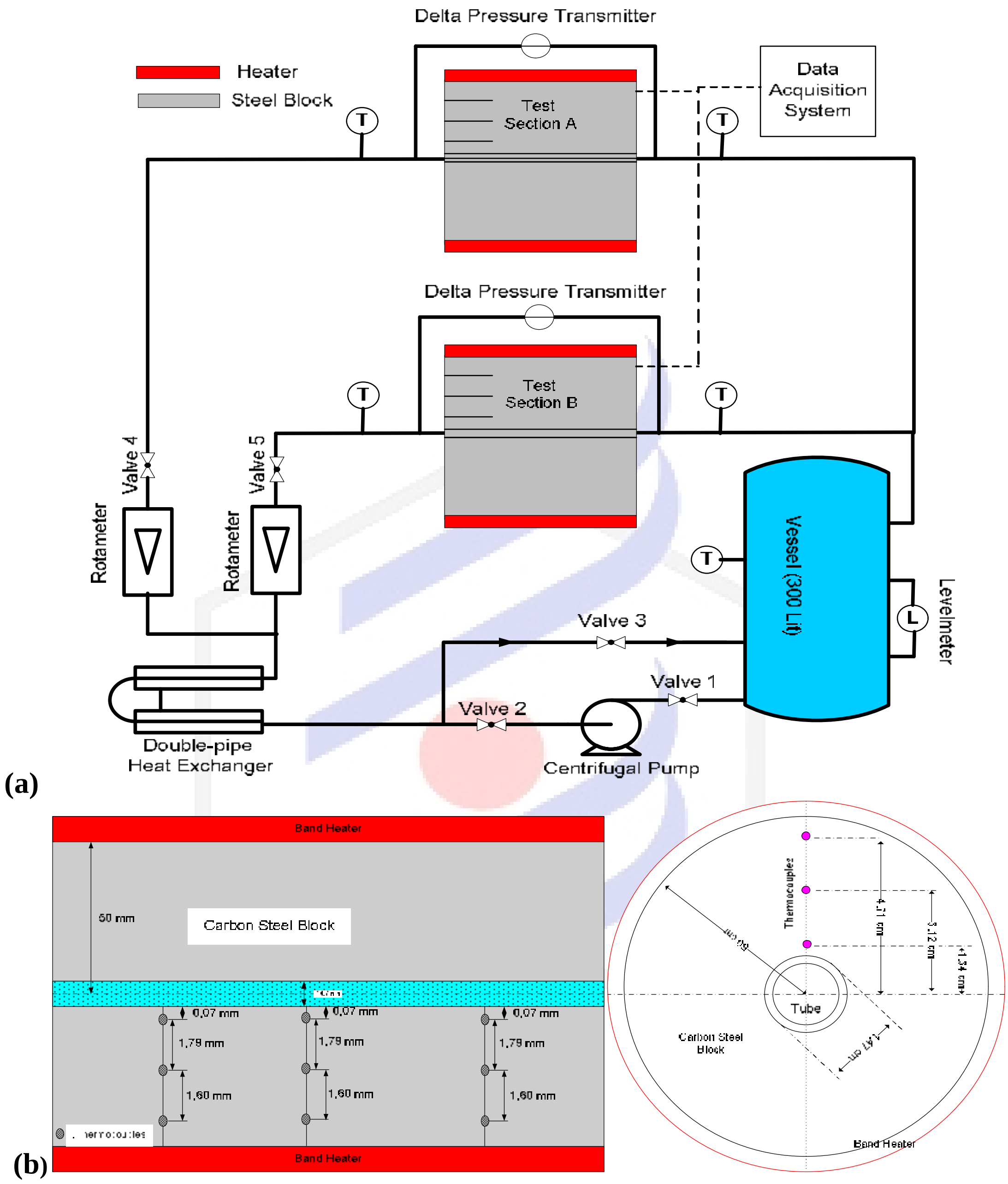

Figure 2 Experimental set-up and the schematic of the test sections

4-wire coils tested

Table 2 represents three wire coil inserts that are used in these experiments. The reason of this selection is focus on fouling mitigation in this study, so their diameter is lesser than tube diameter for wire coil 1, 2 and 3 that it caused vibrate in tube and remove scale regard to wire diameter.

5- Experimental results and discussion

5-1- Fouling mitigation

The fouling experiments were conducted by continuously circulating solution of calcium carbonate in a closed-loop system schematically shown in Fig. 2a. The experiments were performed with the Reynolds number set at 12,824 corresponding to 0.66 m/s flow velocity in the test section. The average total hardness was 245 and inlet bulk temperature was 39 ^{o}C. Also, the experiments were performed with plain tube to get the times for adding hardness to recycled water that achieved average hardness equal to 245. The calcium chloride ($CaCl_2$) and bicarbonate sodium ($NaHCO_3$) were added continuously to water tank because the average total hardness keeps almost constant. Calcium carbonate is an inverse solubility salt while bicarbonate sodium is a normal solubility salt. Under the stated conditions the solubility of calcium carbonate would decrease towards the heated plate and expected to crystallize and form deposits on the surface. Depend on characteristic dimensions of the helical wire coils, they can mitigate or increase scaling rate in tube. Fig 4 shows wire coil type 1 after fouling experiment. Fig 5 shows the fouling resistance for plain tube wire coil type 1, 2,3 and 4 (table 2). The wire coil type 4 is fixed in tube because its diameter is equal to tube diameter so fouling resistance increased compared to plain tube. Although in first, R_f decreased than plain tube because of turbulency, but it was more at final hours of experiment because in this time, crystal nucleus formed and produced turbulency isn't sufficient for removing of scaling. Also, the wire coils type 2 and 3 mitigate fouling than plain tube in first but it didn't generally change in final hours of experiments. The characteristic dimensions of wire coil type 1 (p/d and e/d) were as it vibrated in tube and scraped and removed formed scale in tube wall.

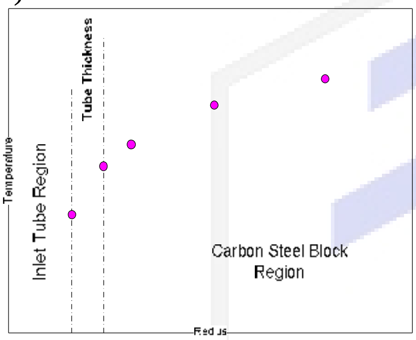

Figure 3 Temperature profile in carbon steel cylinder


Fig. 4 Tube insert tested in experiments (wire coil Type 1)

Fouling in a heat exchanger is generally modeled using Kern and Seaton approach [14] where the fouling rate is represented as a net effect of two separate processes:

$$\text{fouling rate} = \text{deposition rate} - \text{removal rate} \qquad (12)$$

A large number of studies are reported in literature dealing with different aspects of crystallization fouling. It is usually observed that there is no deposition for some time after a new or clean heat exchanger has been commissioned. This period is called the ‘initiation period’ or ‘time delay’. Kern and Seaton proposed a simple model to explain the fouling process [14].

$$R_f = R_{f\infty}(1 - e^{bt}) \qquad (13)$$

where R_{ft} is the fouling thermal resistance at time t, $R_{f\infty}$ is the fouling thermal resistance at infinite time- the asymptotic value and β is a constant dependent on the system properties. The model is essentially a mathematically interpretation of the asymptotic fouling curve that it doesn't predict the initiation time. We proposed a mathematical restatement of Kern and Seaton model that it could predict the initiation time as it observed in our experimental data.

$$R_f = R_{f\infty}(1 - e^{bt^3}) \qquad (14)$$

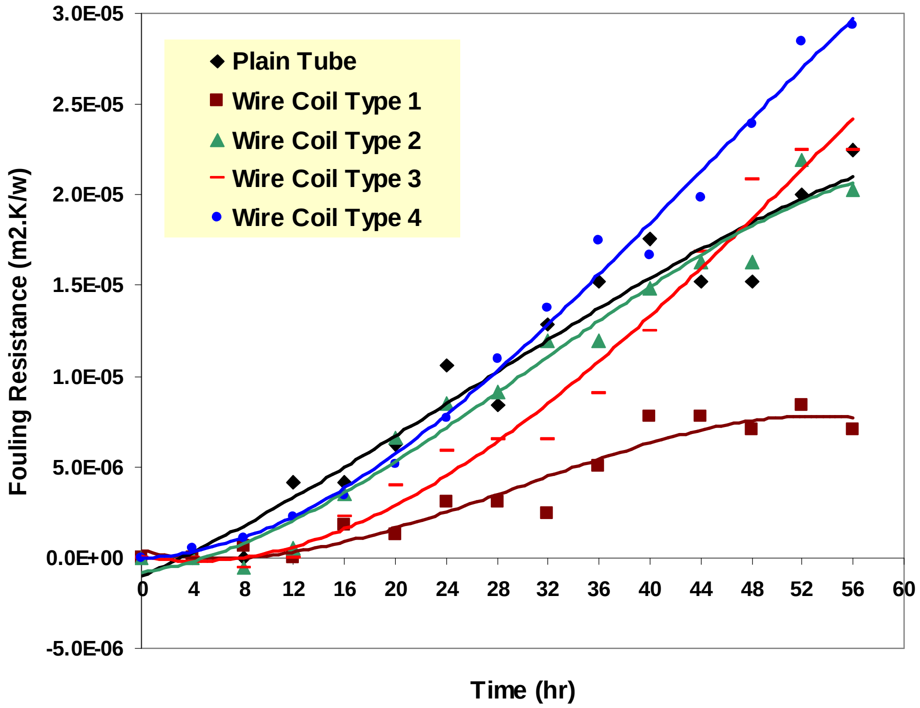

Figure 5 Fouling resistance versus testing time relationship (typical CaCO3 fouling process) for plain and enhanced tube with wire coils (types 1, 2, 3 and 4)

The $R_{f\infty}$ and β has been obtained through curve-fitting of fouling thermal resistance results (fig. 6) used by MATLAB software. For plain tube and wire coils 1, 2 and 3, the time of experiment (56 hr) wasn't enough to reach to asymptotic conditions, although we don't observed the asymptotic condition when we increased the time of experiment to 120 hr for plain tube. The slope of curve was 4×10^{-7} for plain tube in the first 40 hours of experiment. For enhanced tube with wire coil type 1 they obtained $R_{f\infty}= 8.0522\times 10^{-6}$ [$m^2.^oK/w$] and $\beta=2.4222\times 10^{-5}$ [hr^{-3}].

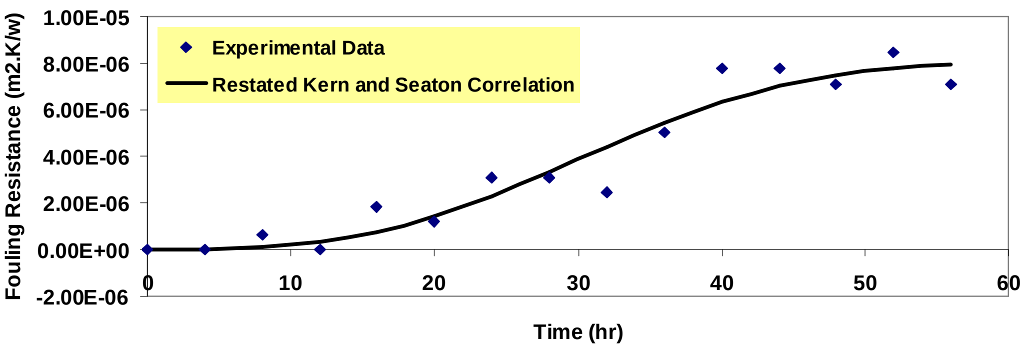

Figure 6 Evalution restated Kern and Seaton correlation with experimental data of fouling resistance for enhanced tube with wire coil type 1.

5-2- Heat transfer Enhancement

Heat transfer tests under the constant wall temperature condition were carried out in a plain tube and in the same tube with 3 wire coil inserts (table 2). Following the procedure described in Section 3 this paper, a range of flow conditions was covered: Re= 3000–20,000 and Pr=3.15-4.58. Fig 7 shows the experimental results of Nusselt number for plain tube and enhanced tubes with wire coil inserts (table 2) that All of wire coils increased the Nusselt number about 1.53-3.65 times for enhanced tube than plain tube. Also the set of tests started with the plain tube. These experiments allowed to check the experimental setup and to verify the procedure and determining the calculated uncertainties. Experimental results for plain tube shows that experimental data of Nusselt number are slightly lower (5.21–6.31% above) than those predicted by Petkhov equation (Equ. 15) and slightly lower (-0.87–16.89% above) than those predicted by Dittus and Boelter equation (Equ. 16).

$$Nu = \frac{\left(f/8\right)\mathrm{Re}\,\mathrm{Pr}}{1.07 + 12.7\left(f/8\right)^{1/2}(\mathrm{Pr}^{2/3}-1)}\left(m/m_w\right)^n \quad that \quad \begin{cases} n = 0.11 & if\ T_w > T_b \\ n = 0.25 & if\ T_w < T_b \end{cases} \tag{15}$$

and,
$$f = (1.82\log\mathrm{Re} - 1.64)^{-2} \tag{16}$$

$$Nu = 0.027\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}\left(m/m_w\right)^{0.14} \tag{17}$$

A Nusselt number equation in the form Nu = Nu (Re, Pr, e/d, p/d) has been obtained through curve-fitting of heat transfer results used by MATLAB software.

$$Nu = 1.003\,\mathrm{Re}^{0.5120}\,\mathrm{Pr}^{0.4379}\left(p/d\right)^{-0.1108}\left(e/d\right)^{0.1096} \tag{18}$$

The wire coil inserts is mainly influenced by the reduced pitch and the increased wire-diameter on Nusselt number. The results have shown that wire coil type 1 that makes a more fouling mitigation than other wire coils (types 2 and 3), makes only hardly ever lower enhancement than other wire coils because of the its lower pitch.

5-3- Friction factor

The pressure drop experiments were carried out by employing isothermal water fluid. The friction factors (based on Darcy friction factor) have been obtained in a continuous Reynolds number ranged from 3000 to 52,000.

Fig 8 shows the experimental results of friction factor for plain tube and enhanced tubes with wire coil inserts (table 2). Wire coil type 1 that makes a more fouling mitigation and lesser heat transfer enhancement than other wire coils (types 2, 3 and 4), it can leads to lower friction factor other wire coils at Re>10000 than other wire coils. The reason of the almost equally friction factor for all wire coils is decrease of pitch (p) contrary of wire diameter (e) of these wire coils. A friction factor equation in the form f= f (Re, e/d, p/d) has been obtained through curve-fitting of friction factor results used by MATLAB software.

$$f = 18.6098\,\mathrm{Re}^{-0.4134}\left(p/d\right)^{-1.8225}\left(e/d\right)^{1.4522} \tag{19}$$

Equ. (19) shows friction factor (such as Nusselt number, also with different factors) for wire coil inserts is mainly influenced by the reduced pitch (p/d) and the increased wire-diameter (e/d).

6- Conclusions

The present experimental study investigated the effects of wire coil inserts on the heat transfer, pressure drop and fouling in a concentric-tube heat exchanger. Based on the obtained results, the following conclusions can be drawn:

1. Vibration of wire coils that is caused by its characteristic dimensions, has an irrefutable effect on fouling mitigation in enhanced tubes with wire coil inserts.
2. The wire coil that it doesn't vibrate refer to its dimensions (e/d and p/d), may decrease fouling resistance rate more than plain tube in initial times because of

produced turbulence, but after 15-20 hours (also in experiment condition in this study) that initial crystals form in tube surface, it has reverse effect on fouling mitigation.

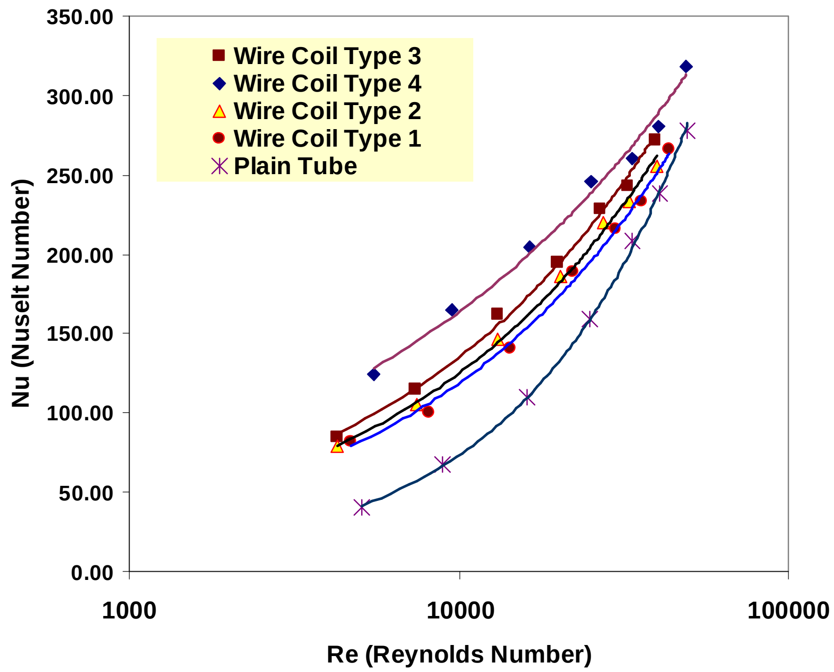

Figure 7 Nusselt Number vs. Reynolds number for plain and enhanced tubes with three wire coils (types 1, 2,3 and 4).

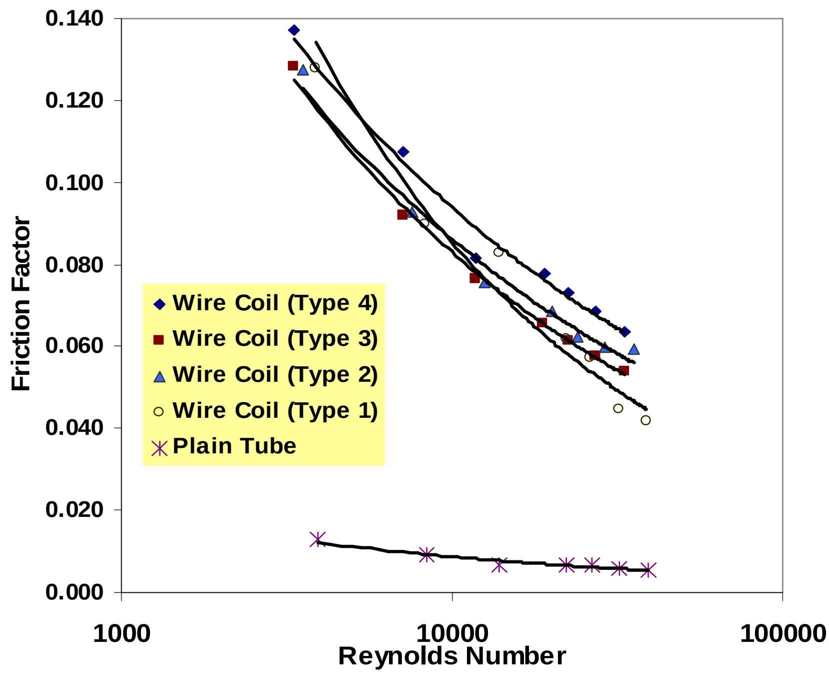

Figure 8 Friction factor vs. Reynolds number for plain and enhanced tube with three wire coils (types 1, 2, 3 and 4).

7- Recommendations

The development of performance criteria for comparison of heat transfer enhancement, fouling mitigation and pressure drop effects is necessary for the finding of optimum values e/d and p/d that it should survey in future studies. Also there are several important points at design of setup for the fouling study,

i. The long time of fouling experiments that it could be decrease by supersaturation solutions. Although there are usually problems occurred, for example: scaling in vessel and non-constant concentration of foulant in solution.

ii. The bulk temperature, wall temperature and velocity are the important factors that influenced on scaling rate, so it is necessary that study their effects on fouling resistance in enhanced tubes with wire coils.

iii. The mixing of $NaHCO_3$ and $CaCl_2$ strictly before test section can prevent from scaling in vessel and lines and solution circulating in short path with lesser diameter than test section's tube, cause almost constant concentration of foulant in solution.

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References

[1] Sultankhan, M., Budair, M. O., Zubair, S. M., "A parametric study of $CaCO_3$ scaling in AISI 316 stainless steel tubes", Heat and mass transfer, 38, 115-121, (2001).

[2] Mwaba, M.G., Golriz, M. R., Gu, J., "A semi-empirical correlation for crystallization fouling on heat exchange surfaces", Applied Thermal Engineering, 26, 440–447, (2006).

[3] Yanga, Q., Liub, Y., "Investigation of induction period and morphology of $CaCO_3$ fouling on heated surface", Chemical Engineering Science 57, 921 – 931, (2002).

[4] Andritsos, N., Karabelas, A. J., "Calcium carbonate scaling in a plate heat exchanger in the presence of particles", Int. Journal of Heat and Mass Transfer 46, 4613–4627, (2003).

[5] T. R. Bott, "Aspects of crystallization fouling", Experimental Thermal and Fluid Science 14, 356–360, (1997).

[6] Zdaniuk, G. J., Chamra, L. M., Mago, P. J., "A literature survey of water-side fouling applicable to cooling tower condensers", 220, 815-827, (2006).

[7] Hasson, D., Sherman, H., and Biton, M., "Prediction of calcium carbonate scaling rates", National Safety News, 2, 193–199, (1978).

[8] Webb, R. L., Li, W., "Fouling in enhanced tubes using cooling tower water, art I: long-term fouling data", Int. Journal of Heat and Mass Transfer 43, 3567-3578 (2000).

[9] A. Garcia , P. G. Vicente, A. Viedma, "Experimental study of heat transfer enhancement with wire coil inserts in laminar-transition-turbulent regimes at different Prandtl numbers", Internatioanal Journal of Heat and Mass Transfer 48, 4640–4651, (2005).

[10] S. Eiamsa-ard, C. Thianpong, P. Promvonge, "Experimental investigation of heat transfer and flow friction in a circular tube fitted with regularly spaced twisted tape elements", International Communications in Heat and Mass Transfer 33, 1225–1233, (2006).

[11] M. R. Jafari Nasr, G. T. Polley, "Should you use enhanced tubes?", Chemical Engineering Progress, 44-50, April (2002).

[12] R. M. Manglik, A. E. Bergles, "Heat transfer and pressure drop correlations for twisted-tape inserts in isothermal tubes", Journal of Heat Transfer 115, 323–334, (2003).

[13] Jafari Nasr, M. R., "Identification and application of the benefit of heat transfer enhancement", PhD thesis, University of Manchester institute of science and technology (UMIST), Manchester, 1977.

[14] Bott, T. R., Fouling Heat Exchangers, Elsevier Science, Amesterdam, The Netherlands, p.524, 1995.