ECI Symposium Series, Volume RP5: Proceedings of 7th International Conference on Heat Exchanger Fouling and Cleaning - Challenges and Opportunities, Editors Hans Müller-Steinhagen, M. Reza Malayeri, and A. Paul Watkinson, Engineering Conferences International, Tomar, Portugal, July 1 - 6, 2007

TOWARDS AN UNDERSTANDING OF HOW TUBE INSERTS MITIGATE FOULING IN HEAT EXCHANGERS

B. Aquino[1], C. Derouin[2] and G.T.Polley[3]

[1] TOTAL, Centre de Recherche de Gonfreville, Le Havre, France E-mail: brice.aquino@total.com
[2] TOTAL, Centre de Recherche de Gonfreville, Le Havre, France E-mail: celine.derouin@total.com
[3] Universidad de Guanajuato, Mexico E-mail: gtpolley@aol.com

ABSTRACT

A number of studies undertaken by Total have measured the improvement that can be expected when Turbotal™ inserts are installed in heat exchangers. These studies have fully established that Turbotal™ both improve heat transfer coefficient and mitigate fouling. It has been found that fouling levels vary with application. Consequently, economics of installing inserts are difficult to quantify. Gains must be estimated through specific tests. A model that predicts fouling development solves this problem.

In this paper first steps towards the understanding of how Turbotal™ limits the fouling rate are described. Authors suggest that the calculation of both pressure drop and heat transfer coefficient in a tube equipped with insert can be used to extend the Ebert & Panchal fouling model to predict the fouling rate in tube equipped with Turbotal™.

This extension of the Ebert-Panchal Model requires adjustment of both the deposition term and the removal term. The deposition term can be adjusted by multiplying by the ratio of plain to enhanced heat transfer coefficients and the removal term can be based on the pressure drop imposed by the insert.

This modified model is then compared with operating cases to verify its reliability. Further issues that require consideration are a mechanical effect that gives rise to limiting growth of the fouling deposit, and total suppression of fouling in parts of the exchanger into account.

INTRODUCTION

In recent years Total have undertaken a number of studies aimed at measuring the improvement in performance that can be expected when Turbotal™ are installed within tubes. It has been found that the inserts provide a significant improvement in heat transfer coefficient [1] and a marked reduction in fouling rates [2].

The effect of the inserts is dramatically demonstrated in the experimental results shown in Figure 1.

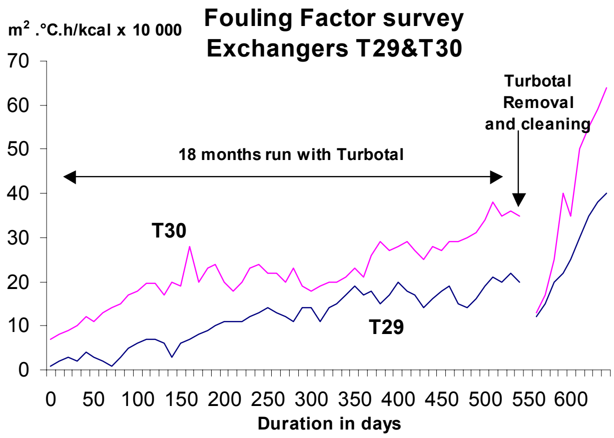

Fig. 1 Test Results showing fouling reduction achieved using Turbotal

In these tests heat exchangers forming part of a pre-heat train in a refinery were fitted with Turbotal inserts. Their performance was monitored over a period of eighteen months. At the end of the period the inserts were removed and the exchangers cleaned. The performance of the units was then monitored for a further eighty days.
Chemical additives were also used during the full trial period. [3]. These tests will be referred to as Study A.

In a separate test (Study B) the performance of exchangers were monitored before and after the installation of inserts. The use of inserts resulted in reductions in rates of fouling of between 70 and 97%. However, the subsequently fouling levels varied with application. The lowest rate observed was 0.86e-7 $m^2C/kcal$ and the highest was 3e-6 $m^2C/kcal$. Such variation means that the economics of installing inserts are difficult to determine without specific tests. This situation can be resolved if a model that predicts fouling development can be developed.

RESULTS AND DISCUSSION

Fouling in plain tube

Recent work [4,5] has demonstrated that fouling in pre-heat trains is reasonably well predicted by the Ebert-Panchal Model [6].

In 1995 Ebert and Panchal proposed a semi-empirical approach to quantify the effect of flow velocity and wall temperature on tube-side fouling in crude oils at high temperatures. Using data reported by Scarborough *et al.* [7] they observed:

(i) Fouling rates increased with increasing temperature – initially interpreted as film temperature, elsewhere as wall/deposit temperature.

(ii) Fouling rates decreased with increasing flow velocity.

They went on to propose a model where the rate of fouling is presented as a competition between deposition and removal, as shown in equation (1)

$$\frac{dR_f}{dt} = \overbrace{A_I \mathrm{Re}^{-\beta} \exp\left(\frac{-E_A}{RT_f}\right)}^{\text{deposition}} - \overbrace{C_I \tau_w}^{\text{removal}} \tag{1}$$

This model has been used within Total to successfully correlate data obtained from the monitoring of pre-heat train exchangers [4].

This model has been applied to the exchangers involved Study A. Exchanger T29 operates at a velocity of 1.4 m/s and initially had a wall temperature (at the tube exit) of 230°C. Exchanger T30 operated at a velocity of 1.25 m/s and initially had a wall temperature of 290°C. The Ebert-Panchal Model (following determination of Activation Energy and Removal Constant that best fitted the data) provided excellent agreement between predicted and measured fouling rates (e.g. Fig. 2 and 3) and accounted for the effect of the difference in wall temperature on fouling rates very well.

In these comparisons the upper line shows the fouling expected at the tube exit. The lower line shows the fouling expected at the tube inlet. The Middle line (covering the full time-scale) is the predicted 'integral' mean fouling rate [4]. The short line lying on the integral line in the case of T29 and close to it in the case of T30 show the measured fouling rates.

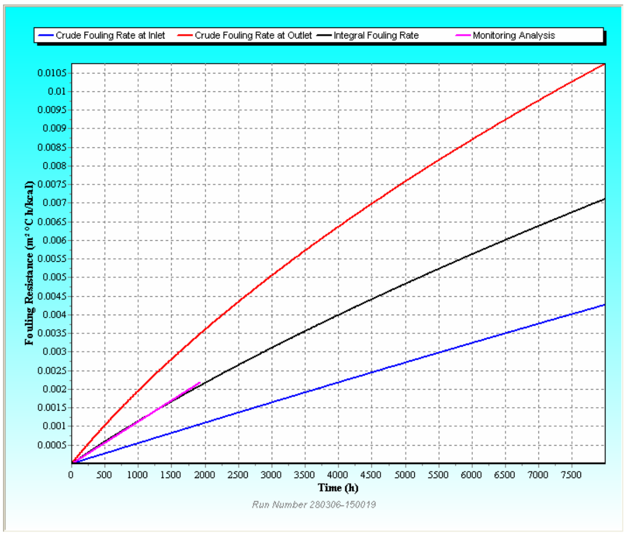

Fig. 2 Predicted Fouling Rates for Exchanger T29

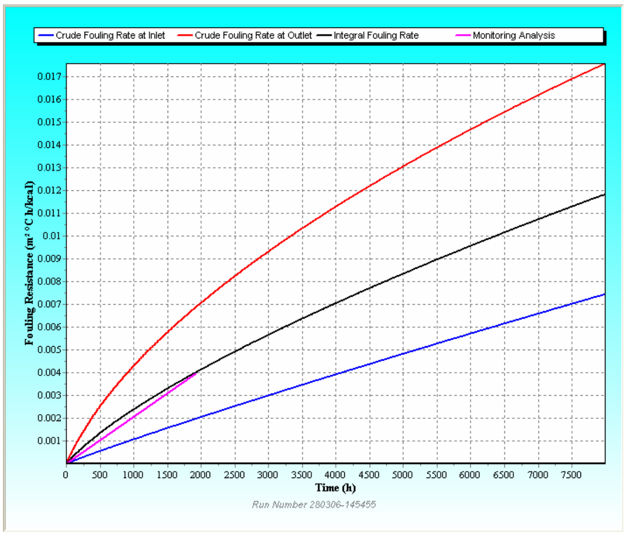

Fig. 3 Predicted Fouling Rate for Exchanger T30

The fouling behaviour observed in Study B also follows the Ebert-Panchal Model. The Removal Constant used in this analysis was identical to that used for T29 and T30. The Activation Energy providing best fit to the data was lower for the second study (however, the feedstock was different and chemical were not being added). Comparison between predicted and measured fouling for each of the five exchangers is given in Table 1.

Table 1. Plain Tube Performance (Study B)

Unit	Velocity m/s	T_{wall} C	Predicted rate	Measured rate	Ratio
1	1.0	218	1.52e-6	1.52e-6	1.00
2	0.84	213	2.26e-6	3.01e-6	0.75
3	1.0	264	4.75e-6	7.68e-6	0.62
4	1.15	266	2.50e-6	2.34e-6	1.07
5	1.7	263	3.20e-6	3.27e-6	0.98

Table 2. Clean Performance (Study B)

Unit	Plain h.t.c.	Insert h.t.c.	Plain P.D.	Insert P.D.	P.D. Ratio	Expected Ratio	Factor
1	893	2074	0.049	0.442	9.02	6.33	0.7
2	989	2127	0.061	0.468	7.67	5.35	0.7
3	1050	2239	0.07	0.524	7.49	5.25	0.7
4	1084	2858	0.075	0.926	12.35	8.36	0.68
5	1516	3020	0.153	1.057	6.91	4.52	0.655

Extension of Ebert-Panchal model to predict insert performance

The Ebert-Panchal Model has two basic terms; a deposition term based upon a reaction volume and rate set by the Activation Energy (E_A) and a removal term that is a linear function of shear stress characterised by a removal constant (C_I).

The presence of an insert could be expected to reduce the reaction volume. This effect can be calculated by dividing the deposition rate for a plain tube by the ratio of the enhanced tube and plain tube heat transfer coefficients.

The insert will also result in increased wall shear and therefore increased removal rate. However, when an insert is installed the pressure drop has two components: wall friction and form drag. So, it would be incorrect to base the wall shear on the full pressure drop encountered during the presence an insert.

We can use the change in heat transfer coefficient as a guide of the amount of pressure drop forming wall friction. With a plain tube the heat transfer coefficient varies with velocity to an exponent of 0.8. So, the plain tube velocity relates to heat transfer coefficient raised to a power of 1.25. The plain tube pressure drop is dependant upon velocity raised to a power of 1.75. Thus, pressure drop is related to heat transfer coefficient raised to an exponent of 2.19. If all of the pressure drop for an insert was wall friction the increase in pressure drop over that occurring in a plain tube operating at the same velocity would equate with the ratio of the heat transfer coefficients raised to a power 2.19. Given the presence of form drag, the observed pressure drop will be greater than this. The ratio of this predicted increase to the observed value provides an indication of the fraction of pressure drop actually contributing to wall friction.

Examination of the clean performance of the exchangers involved in the second study yields the following:

This analysis suggests that around 0.7 of the absorbed pressure drop is associated with increased wall shear.

An alternative is to use the total pressure drop in the calculation of the wall shear and multiply the removal constant by 0.7. That is the practice adopted below.

Finally, we need to consider the mechanical action of the insert on the deposits formed within the exchanger tubes. The clearance between the rotating coil and the inside wall of a clean tube is around 2 mm. If the deposit exceeds this thickness the coil will no longer rotate. Therefore, either the coil controls the deposit thickness or the insert fails to operate.

The limiting fouling resistance equates with the coil clearance divided by the thermal conductivity of the deposit. The thermal conductivity of the deposit can be assumed to take one of the following values [8]:

Option	Value W/m.K	kcal/h.m.C
Crude Oil	0.122	0.105
Asphaltene	0.2	0.17
Coke	1.7	1.46
Value suggested from Pressure Drop (smooth layer model) reported by Watkinson	0.46	0.4

With the corresponding limiting resistances being:

Option	Value W/m²K	h.m^{2}C/kcal
Crude Oil	0.0164	0.0191
Asphaltene	0.01	0.0117
Coke	0.0012	0.0013
Value suggested from Pressure Drop (smooth layer model) reported by Watkinson	0.0043	0.0050

The conclusion is that the insert can have three effects:

1. A mechanical effect that gives rise to a 'limiting resistance' (a resistance that will not be exceeded).
2. A reduction in deposition rate due to a reduction in 'reaction volume'
3. An increase in removal rate due to increased wall shear.

Evidence for limiting resistance

The Ebert-Panchal Model has been modified in the manner described above and its predictions compared with measured performance.
A typical result (for unit 3, Study B) is shown in Figure 3. The rate of fouling at the tube exit is seen to be very high. The time taken to reach a resistance of 0.005 at the tube exit is just 1200 hours. It would take around 3300 hours to reach a value of 0.01 and 7000 hours to reach a value of 0.015 h.m^{2}C/kcal.

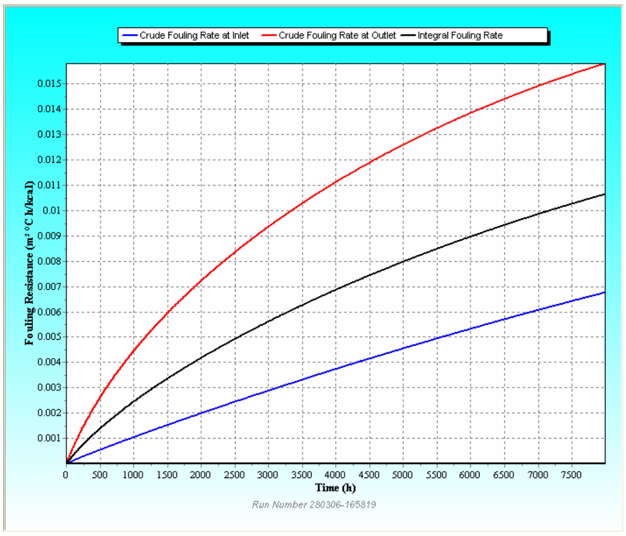

Fig. 3 Fouling Rates Predicted When Insert Used

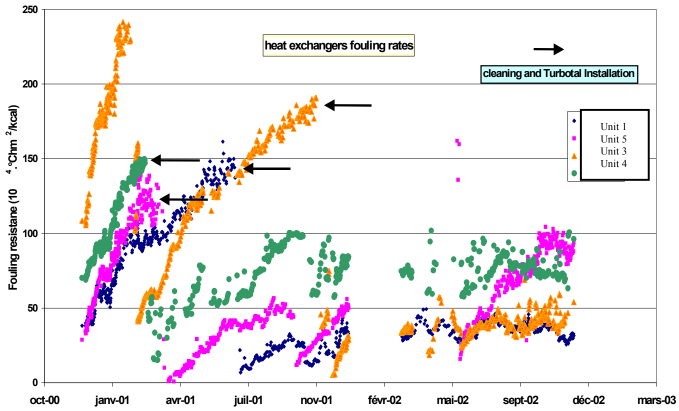

Fig. 4 Full Operating Period for Test Series 2

The extended test period covers around 8000 hours.

If the inserts do not control the deposit thickness those in the last tube pass would stop rotating once the fouling resistance had reached its critical value. The result would be that the fouling in this pass would become close to that observed for the plain tube. Unit 3 has two exchangers in series with each exchanger having two tube passes. The affect would have been quite marked.

Unit 3 corresponds to orange plots in Figure 4. The initial fouling rate (period December 2001, January 2002) is seen to be quite high. However, this rate does not last long and the unit does not exhibit progressive fouling. The fouling resistance appears to become constant at a value of around 0.0045 h.m^{2}C/kcal (based on O.D., equivalent to 0.0035 when based on ID – the base used for the modelling).
Fouling in two other units, 1 (blue plots) and 4 (green plots), appear to settle about constant values (in one case at a value of around 0.0045, in the other case a value of around 0.007).

Analysis of fouling data

The presence of a limiting resistance complicates the integration of the Ebert-Panchal Model. In its current form the 'integral model' can only be applied to initial fouling rates (that is, to fouling levels below the point at which the limiting resistance is reached at the tube exit).

Two series of tests were conducted on Unit 3 (first one from Dec. 01 to Jan. 02; second one from April 02 to Nov. 02). Comparisons between these fouling rates and predictions of the modified Ebert-Panchal Model are made in Figures 5 and 6.

(In the modified model the deposition term has been multiplied by the ratio of the plain tube to enhanced tube heat transfer coefficients, the shear stress is based upon the full pressure drop and the removal constant has been multiplied by 0.7. Values of removal constant and activation energy are equal to those determined with plain tube fouling rates).

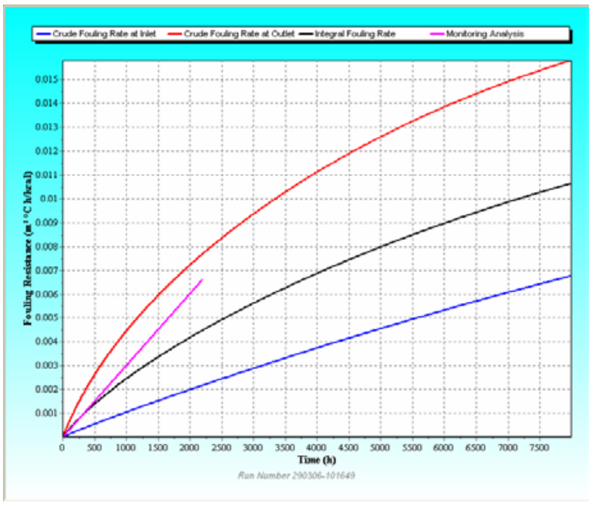

Fig. 5 First Insert Test on Unit 3

In the first test the measured fouling rate is significantly higher than the predicted values (e.g. Fig. 5).

In the second test the measured fouling rate is just below the predicted value (e.g. Fig. 6).

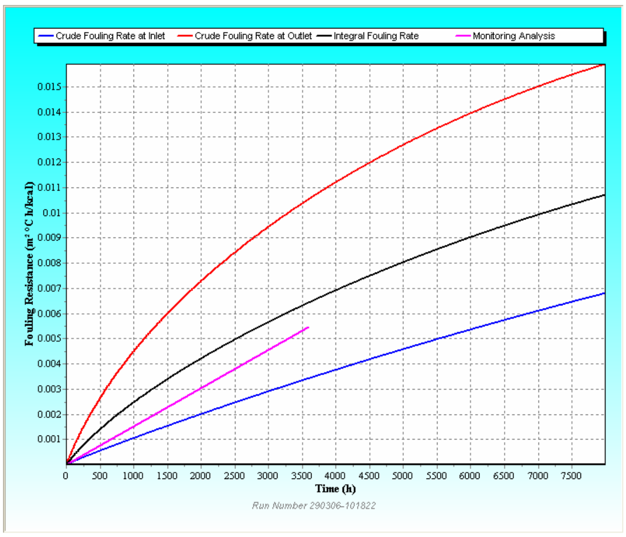

Fig. 6 Second Insert Test on Unit 3

Comparisons for all of the exchangers covered in the series given in Table 3.

Table 3. Predictions of Modified Ebert-Panchal Model

Unit	Predicted Rate	Measured Rate	Ratio
1	4.0e-7	3.6e-7	1.11
2	6.0e-7	8.6e-7	0.7
3 (test 1)	2.1e-6	3.0e-6	0.69
3 (test 2)	2.1e-6	1.5e-6	1.39
4	1.2e-6	2.8e-6	0.44
5	9.4e-7	1.04e-6	0.9

These comparisons are encouraging.

Justification for adjusting the deposition term can be tested by examining how a model without this adjustment and without any adjustment to the removal constant (so the affect of increased shear stress is maximised) compares with the measurements.

The following results were obtained:

Table 4. Effect of Ignoring Change to Deposition Term

Unit	Predicted Rate	Measured Rate	Ratio
1	1.0e-6	3.6e-7	2.78
2	1.1e-6	8.6e-7	1.28
3 (test 1)	3.6e-6	3.0e-6	1.2
3 (test 2)	3.6e-6	1.5e-6	2.4
4	2.5e-6	2.8e-6	0.89
5	1.8e-6	1.04e-6	1.73

With the exception of the data for unit 4, the comparisons clearly indicate that the adjustment to the deposition term is both justified and required.

The need for using a reduced removal constant can be gauged by examining predicted rates when the deposition term is reduced, removal term is based on wall stress computed from total pressure drop.

The following results were obtained:

Table 5. Effect of Ignoring Change to Removal Constant

Unit	Predicted Rate	Measured Rate	Ratio
1	0 asymptote 0.0004	3.6e-7	0.0
2	6e-7	8.6e-7	0.69
3 (test 1)	2e-6	3.0e-6	0.66
3 (test 2)	2e-6	1.5e-6	1.33
4	1e-6	2.8e-6	0.36
5	5.3e-7	1.04e-6	0.51

These comparisons support the reduction in the removal constant.

Returning Study A the predictions of the modified model are compared with the test results in Figures 7 and 8.

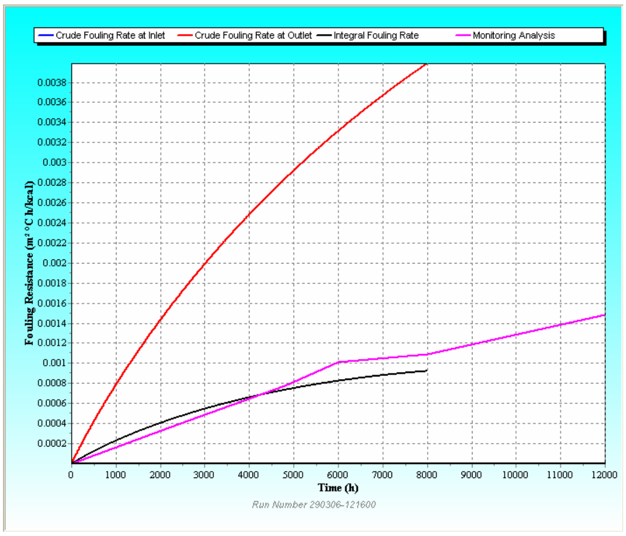

Fig. 7 Predicted Fouling for T29 when fitted with Turbotal

Given the very low fouling rates (compared with those found for the original exchangers) observed in these exchangers these comparisons are again encouraging.

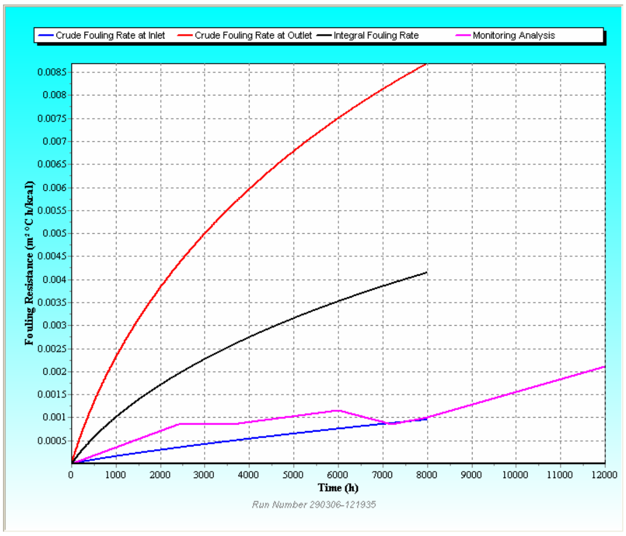

Fig. 8. Predicted Fouling for T29 when fitted with Turbotal

However, it can be seen that in the case of T29 fouling is totally suppressed at the exchanger inlet. Under these circumstances the integral model may not be reliable.

CONCLUSIONS

1. Turbotal inserts are an effective way of reducing fouling in heat exchangers processing crude oil.
2. The analysis of the data for the exchangers not fitted with inserts gives further support to the Ebert-Panchal Model.
3. An extension of the Ebert-Panchal Model to cover inserts requires adjustment of both the deposition term and the removal term.
4. The deposition term can be adjusted by multiplying by the ratio of plain to enhanced heat transfer coefficients.
5. The removal term can be based on the total pressure drop imposed by the insert provided the removal constant is reduced.
6. Consideration of heat transfer effects suggests that the reduction in removal constant should be one third.
7. There is evidence to indicate that Turbotal inserts control the thickness of the deposit.
8. Given a limit on deposit growth the Ebert-Panchal Model can only be applied to the initial fouling rate.
9. Installation of inserts can result in total suppression of fouling at the entry to the exchanger. Under these circumstances the 'integral' model may become unreliable.
10. The fouling model should be further developed to take into account limits on deposit growth and total suppression of fouling in parts of the exchanger.

NOMENCLATURE

A_I Deposition constant, m² K / J
C_I Removal constant, m² K / J.Pa
E_A Activation energy, J / mol
R Gas constant, 8.314 J / mol.K
Re Reynolds number
R_f Fouling resistance, m² K / W
T_f Fluid temperature, K
β Reynolds number exponent
τ_w Wall shear stress, Pa

ACKNOWLEDGEMENT

The EXPRESS program developed by ESDU International was used throughout the conduct of this study.

REFERENCES

1. Petitjean E., Aquino B. & Polley G.T., 2007, Observations on the Use of Tube Inserts to Suppress

Fouling in Heat Exchangers, *Hydrocarbon World 2007,* Ed. Touch Briefings, pp 47-51

2. Bories, M. and Patureaux, T., 2003, Preheat train crude distillation fouling propensity evaluation by Ebert and Panchal model, *Proc. Heat Exchanger Fouling & Cleaning: Fundamentals & Applications,* Santa Fe, July 2003.

3. Pouponnot F. & Krueger A.W., 2004, Heat Transfer Enhancement and fouling mitigation by heat exchanger tube inserts, *Int. Conf. On Heavy Organic Depositions*, Los Cabos, Mexico

4. Polley G.T., Wilson D.I., Pugh S.J. & Petitjean E., 2005, Extraction of parameters for use in fouling models from results of exchanger monitoring, *Engng. Int. Conf.*, Iresee

5. Wilson D.I. and Polley G.T., 2005, Ten Years of Ebert, Panchal and the Threshold Fouling Concept, *Engng. Int. Conf.*, Iresee

6. Ebert, W. and Panchal, C.B., 1997, Analysis of Exxon crude-oil slip stream coking data, in Fouling Mitigation of Industrial Heat Exchange Equipment, Panchal, C.B., Bott, T.R., Somerscales, E.F.C. and Toyama, S.. (eds.), Begell House, NY, 451-460.

7. Scarborough, C.E., Cherrington, D.C., Diener, R. and Golan, L.P., 1979, Coking of crude oil at high heat flux levels, Chem. Eng. Proc., Vol. 75, 41-46.

8. Watkinson A.P., 1988, Critical Review of Organic Fluid Fouling, Argonne National Laboratory, ANL/CNSV-TM-208