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# INCREASED SHEAR, REDUCED WALL TEMPERATURES, USE OF hiTRAN WIRE MATRIX INSERTS IN SYSTEMS SUBJECT TO FOULING

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## ABSTRACT

Fouling characteristics are influenced largely by the properties of the thermal and hydrodynamic boundary layers. This paper demonstrates that tube side heat transfer enhancement devices such as hiTRAN thermal systems can be used as a tool to influence both wall temperatures and wall shear stress. Experimental results from Laser Doppler Velocimetry experiments and direct wall shear measurements with hiTRAN Wire Matrix inserts are presented. These measurements were verified by CFD simulations. The results are comparable in good agreement and indicate an increase in wall shear forces when applying this insert type. The main driving force for the use of hiTRAN Elements in heat exchanger design is the substantial increase in tube side heat transfer performance. As a direct consequence of increasing the rate of heat transfer, the resulting tube wall temperature is changed and therefore the fouling behaviour. In a real case crude oil fouling scenario hiTRAN is used in order to improve the overall duty of the unit with increased wall shear and reduced wall temperatures.

## INTRODUCTION

A body of research has been undertaken to identify the parameters which determine fouling behaviour. As a result semi empirical fouling rate models have been developed. To describe crude oil fouling behaviour over time, the Ebert and Panchal Model (Ebert and Panchal 1997) and its variants have been successfully applied. These models are developed to describe chemical reaction fouling in tube side flows (Wilson *et al.*, 2012). Some research also takes into account the use of tube internals in order to achieve threshold conditions (Mengyan *et al.*, 2012). Common to these types of model is a deposition and a suppression term.
Since crude oil fouling downstream from the desalter can be characterized by chemical reaction fouling the reaction rate of the foulant will increase with higher temperatures. The deposition term is strongly influenced by the film temperature of the fluid. The suppression term describes how the influence of wall shear forces counteracts the buildup of foulant and supresses further build up of fouling deposit:

$$\frac{dR_f}{dt} = \alpha Re^{\beta} \exp\left(-\frac{E_a}{RT_f}\right) - \gamma\tau_W \qquad (1)$$

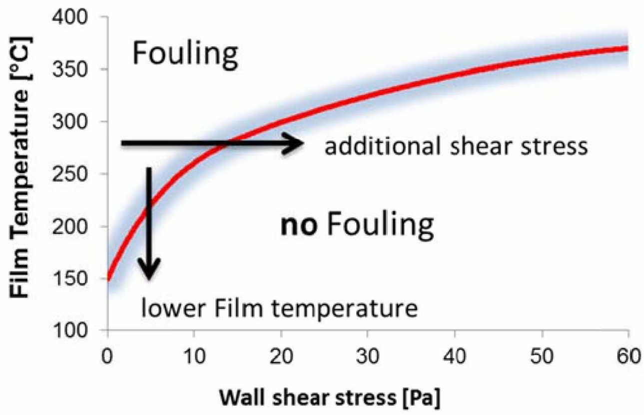


Fig. 1: Threshold model and implication of additional shear stress and lower film (wall) temperatures.

By default this type of model implies that in a technical process film temperatures and wall shear stress can be found to suppress fouling entirely as shown in fig. 1. The fouling model parameters α,β,γ as well as the Activation Energy Ea have to be determined by experiments from laboratory or process data.

In a plain empty tube exchanger design, the parameters for wall temperature and wall shear are determined by the process, geometry and property conditions. hiTRAN tube inserts can be used in order to beneficially influence these two parameters.

## hiTRAN WIRE MATRIX ELEMENTS

hiTRAN technology (fig. 2) is used effectively to increase the turbulence of tube side flow. Main applications are in laminar and transitional flow regimes, but hiTRAN elements are also used in turbulent flow in cases were additional pressure drop is available within the system. Pressure drop and heat transfer characteristics are adapted to the process requirement by changing the packing density of the inserts. This insert type has been applied successfully in fouling applications (Gough *et al.*,1995, Ritchie *et al.*, 2007).

Fig. 2: Typical hiTRAN Wire Matrix element.

## INFLUENCE OF HEAT TRANSFER ON WALL TEMPERATURES

Tube side heat transfer measurements at a single phase test facility were conducted in order to measure the tube side performance for a wide range of hiTRAN insert geometries with varying packing densities.

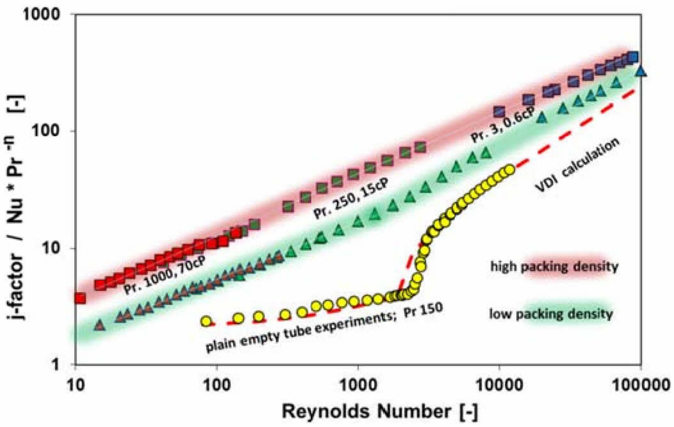


Fig. 3: Typical heat transfer performance of two hiTRAN geometries.

In figure 3 the measured heat transfer results for two hiTRAN insert geometries with low and high packing densities as a function of Reynolds are shown. Thermal and hydraulic performance data for heat transfer and pressure drop for the full range of hiTRAN geometries are implemented in the Software hiTRAN.SP distributed by Cal Gavin LTD. It can be seen that increases of up to 16 times heat transfer rate in laminar flow and 2 to 4 times the heat transfer rate in turbulent flow are measured. Neglecting wall resistance and any fouling layer, the wall temperature can be expressed as follows:

$$T_w = T_o - \left( \frac{h_i}{h_i + h_o} \right) \cdot \left( T_o - T_i \right) \qquad (2)$$

For an increased tube side heat transfer coefficient the wall temperature approaches the tube side bulk temperature. In case the tube side flow is heated a lower wall temperature is achieved. The increased tube side heat transfer can be utilized in order to move into the area of no fouling in figure 1

## WALL SHEAR STRESS WITH hiTRAN

In plain empty tubes the wall shear stress $\tau_W$ is directly linked to the pressure drop $\Delta p$:

$$\tau_W = \frac{4\,\Delta p\, D}{L} \qquad (3)$$

When applying tube inserts a substantial amount of pressure drop is generated by drag and shear forces at the insert geometry. These forces have to be known in order to determine the wall shear stress based on pressure drop measurements. This paper describes three independent methods to measure and also simulate the tube side wall shear stress in the presence of hiTRAN inserts.

### Wall shear stress calculation by measurement of the velocity field

Wall shear stress is directly associated with the velocity field near to the tube wall:

$$\tau_W = \eta \frac{du}{dy} \qquad (4)$$

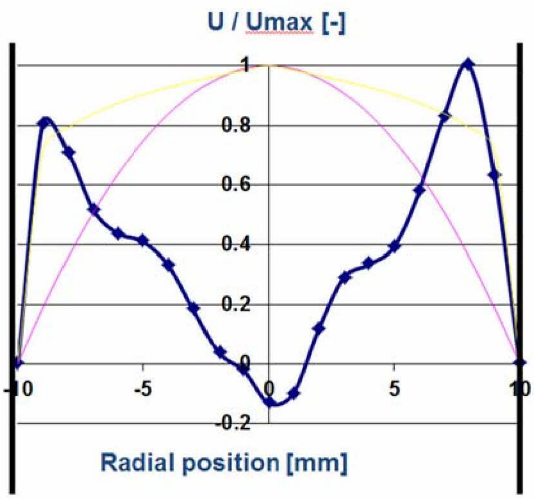


Fig.. 4: Normalized velocity profile at Reynolds Number 500 just after hiTRAN insert. For plain tube comparison Yellow line - turbulent profile, pink line –laminar profile are shown

Laser Doppler Velocimetry (LDV) data from Smeethe et al (2004) were re-evaluated. He measured the velocity profile immediately downstream of hiTRAN inserts. Aluminum tracer particles were added to the flow without slip and subjected to a dual beam laser. With this technique the velocity of the tracer particles and therefore the flow profile was measured. The velocity profile indicates a much steeper velocity gradient du/dy at the wall compared to a laminar profile at the measured Reynolds number (fig. 4). In fact at a Reynolds number 500 the velocity gradient near to the wall with hiTRAN was similar to a profile expected for turbulent flow conditions.

Near to the wall detailed measurements were carried out at different Reynolds numbers for the plain empty tube and medium dense insert geometry. The results are shown in figure 5

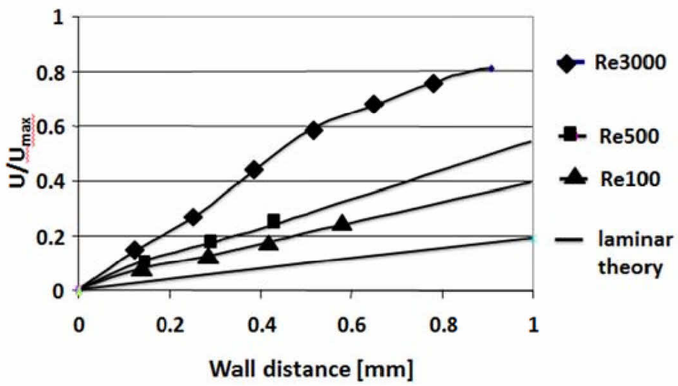


Fig. 5.: Near wall velocity profile for different Reynolds numbers compared to plain empty tube theory for a constant insert geometry

For the plain empty tube a normalized velocity gradient du/dy of ~0.2 1/s is measured and calculated in laminar flow. For transitional flow at Reynolds 3000 this value is about 0.275 1/s. With hiTRAN this gradient is steeper, generating up to 2.9 times higher wall shear forces compared to the plain empty tubes as seen in table 1.

Tab. 1: Shear force multiplier when using one particular insert geometry

| Reynolds | du / dy [1/s] | Multiplier [-] |
|---|---|---|
| 100 | 0.4 | 2 |
| 500 | 0.55 | 2.75 |
| 3000 | 0.8 | 2.9 |

**Wall shear stress calculations by measuring the forces impacting on the insert**

In a separate experimental setup the wall shear forces were measured directly over the whole insert length.

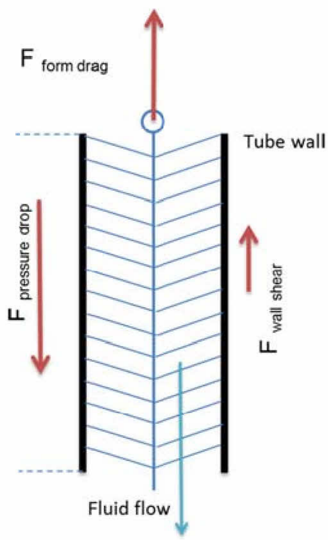


Fig..6: Measurement principle to determine the increased wall shear force created with the addition of hiTRAN insert

In this setup the insert is installed in a tube in such a way that the loops are just touching the tube wall, without exerting any pressure. In order to measure a large range of fluid conditions water and water-glycerin mixtures were used. A load cell measures the form drag inflicted by the fluid flow on the insert (fig. 6). In addition the pressure drop over the installed insert length is measured. The overall wall shear force can then calculated as shown in Equation (5).

$$F_{\text{wall shear}} = \Delta p \cdot A_{\text{cross section}} - F_{\text{form drag}} \tag{5}$$

The wall shear stress ($\tau_{Wall}$) is calculated by dividing the measured shear force ($F_{\text{wall shear}}$) with the tube surface area occupied by the insert. The dimensionless "wall" friction factor for a particular insert geometry can then be calculated as follows:

$$f_W = \frac{2\,\tau_W}{\rho\, u^2} \tag{6}$$

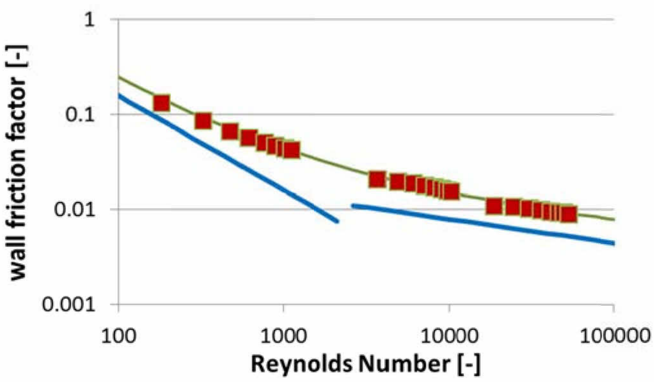


Fig. 7: Measured wall fanning friction factor for a particular hiTRAN geometry compared with plain empty tube data as function of Reynolds number

Using this approach the dimensionless wall friction factor for hiTRAN inserts can be measured and compared with the plain empty friction factor as demonstrated in figure 7.

By connecting the data points, correlation of the wall friction factor for each insert geometry, can be found. In figure 8 the increase in wall shear force compared to a plain empty tube is shown and expressed as multiplier. The area between the blue and red line represents the hiTRAN operation area with low and high density inserts.

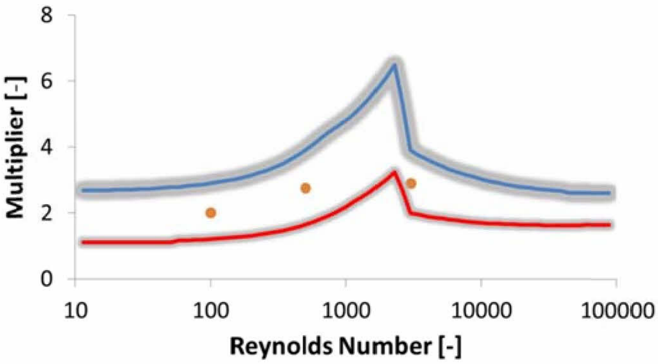


Fig. 8: Shear stress multiplier when using hiTRAN inserts. Bottom line (Red) low dense insert. Top line (blue) high dense insert, yellow points data from LDV experiments

As seen in figure 8 the highest increase can be found just before the transition from laminar to turbulent flow. Here up to 7 times higher shear stress is measured by comparison to the plain empty tube. The measured data for a medium dense insert from the Laser experiments in table 1 are also shown and indicate good agreement with the results.

**Wall shear stress simulations with CFD**

Apart from the two experimental methods CFD was employed to simulate the flow behaviour with inserts. The CFD package ANSYS CFX was used to carry out the simulations presented in this paper. The insert geometries were drawn using ANSYS DesignModeler. Some simplifications were made to the insert geometries to make them easier to mesh. The geometries were then meshed using the ANSYS meshing software. A mesh independence study was carried out on each of the geometries to ensure that the mesh was of high enough quality to accurately model each of the inserts. The Shear Stress Transport (SST) turbulence model was used for the turbulent regime, since it gave more accurate near wall values compared to the k-ε turbulence model.

The calculations were performed under isothermal flow conditions and with property, geometry and process conditions similar to the shear force experiments. Figure 9 shows a typical simulated velocity profile in laminar flow, which resembles very much the LDV measured flow profile (fig 4), with steep velocity gradient near to the wall.

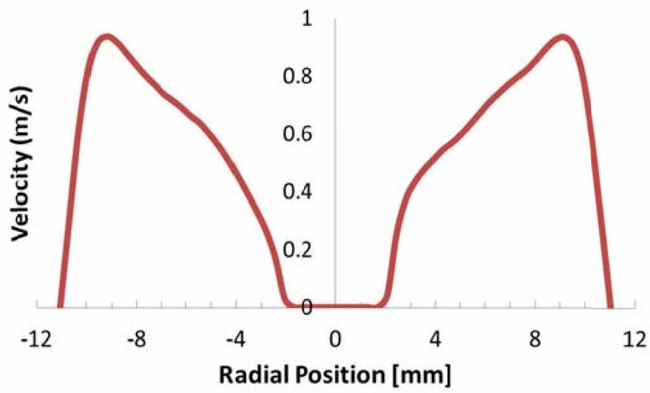


Fig. 9: Velocity profile with CFD simulation, Reynolds 1000

To compare the simulated results with the measured data the local wall shear stress values is integrated over the whole tube surface area. The results then indicate the average CFD simulated shear stress. In figure 10 the measured correlated wall shear stress is compared for different Reynolds numbers with the CFD simulated data for discrete data points.

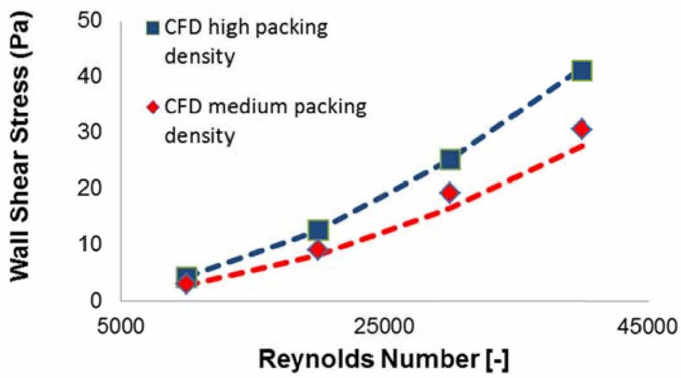


Fig. 10: Wall shear stress correlations from measured data for medium dense (red dashed line) and high dense (blue dashed line) hiTRAN inserts with CFD simulations

For the dense inserts the CFD simulated values are in very good agreement with the correlated measurement data. CFD simulated shear stress values are slightly higher compared to the measured data for the medium dense insert. Having validated the CFD simulation against the measured data, in a next step the local shear stress can be investigated. In contrast to a plain empty tube the wall shear stress in a hiTRAN enhanced tube varies along the tube wall. This is shown in figure 11 were for a medium dense insert the shear stress is shown between two adjacent loops.

The shear stress peaks directly above the loop wire and is at its lowest just after the wire. This can be confirmed when doing experiments with water particle suspension. In figure 12 it is evident that some particles are settling out in low shear areas behind the loops but principally in the plain empty tube section.

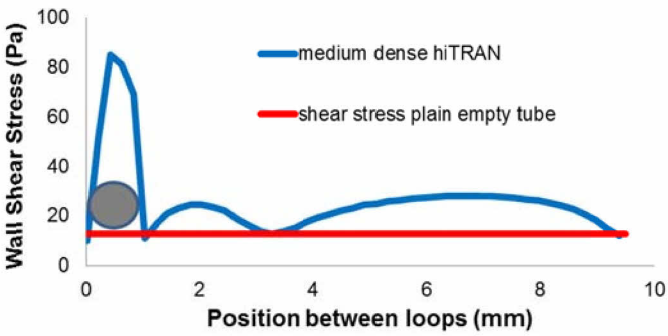


Fig. 11: Shear stress distribution between adjacent hiTRAN loops. Water, flow velocity 2.06m/sec Reynolds number 30000

Fig. 12: Water flow suspension. Average particle size 50µm, density 2420kg/m3

The simulation also shows that the lowest shear stress calculated just behind the loop wire is of the same magnitude as the plain empty tube value (red line in fig. 11)

## CASE STUDY; VDU FEED EXCHANGER

The findings show that hiTRAN inserts influence tube wall temperatures and tube wall shear rates and can be used in order to change fouling behaviour.

In a retrofit application hiTRAN wire matrix elements were installed in a two in series AES type Feed / Effluent Exchanger. In these exchangers the tube side fluid (VDU feed) is heated, before entering the fired heater at about 300°C. Under design conditions the exchanger operates in the transitional flow regime of Re ~6000. The overall heat transfer rate of the exchanger is tube side controlled. On the shell side Vacuum Residue is cooled from 350°C, to preheat the VDU feed.

The exchanger was suffering from very low tube side design velocities of around 0.4m/s, resulting in low tube side coefficients with high wall temperatures, long fluid residence time and low wall shear stress. The low tube side frictional pressure drop also increases the risk of fluid mal distribution within the bundle.

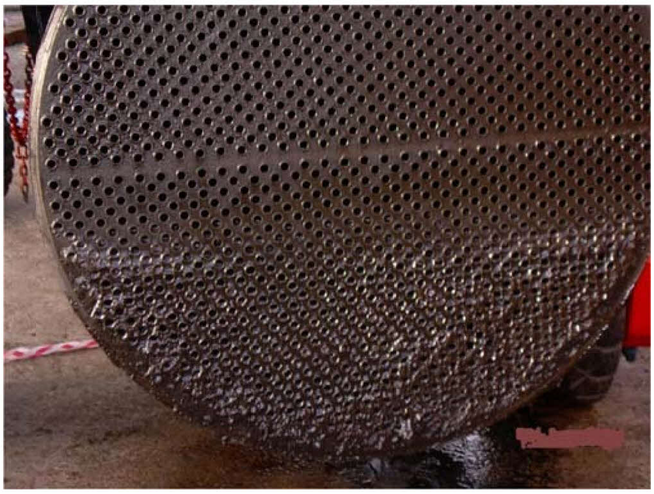

Fig. 13: Investigation of fouled AES VDU / Feed heat exchanger.

Figure 13 shows the fouled plain empty tube exchanger after operation of 1130days. Fouling on the tube side and the shell side was observed. Before installing a hiTRAN Thermal System the exchanger was cleaned. After installing hiTRAN the calculated tube side pressure drop increased within the allowable limit to about 70mbar.. The induced wall shear increase from 0.43Pa to about 0.75Pa. More importantly the tube side heat transfer rate increased by about four times from 312W/m$^2$K to 1132W/m$^2$K. As a result, the main heat transfer resistance shifts to the shell side. Process information with hiTRAN installed, was taken over a period of 10 month. In order to compare both setups only the initial period of 300 days were used for evaluation. The initial setup was tube side controlled and was in an area where hiTRAN Systems can improve the heat transfer substantially. The measured overall coefficient for the exchangers was increased by about 40% (fig. 14).

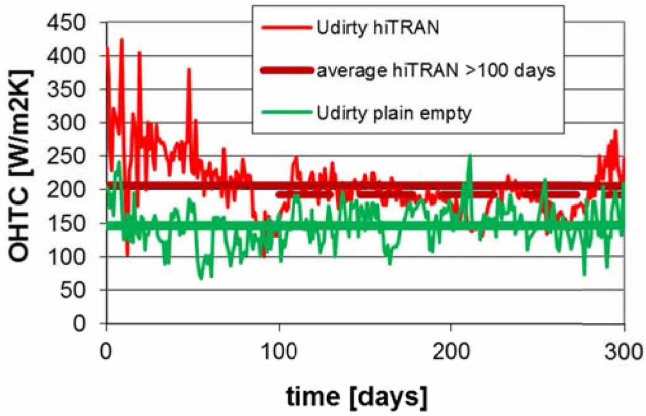


Fig. 14: Overall heat transfer coefficient over time for plain empty tube and hiTRAN System

Since the tube side heat transfer was increased there was also an expected reduction in tube side wall temperature.

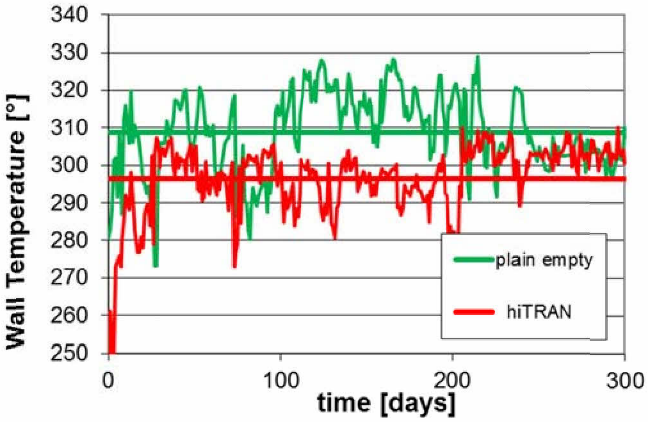


Fig.15: Tube wall temperatures before and after installation of hiTRAN

The average wall temperature was about 13°C lower compared to the plain empty tube measurements. Even greater was the reduction in peak values from 330°C to 310°C (fig. 15).

Tab. 2: Conditions before and after installing hiTRAN

| Geometry | Plain empty | hiTRAN |
|---|---|---|
| TEMA Type | AES | |
| Shells in Series | 2 | |
| Tube geometry | 1416 x 19.05mm OD x 6096mm | |
| No of tube passes | 2 | |
| **Process** | | |
| **Averages over time [days]** | **1130** | **300** |
| Shell side flow [kg/s] | 28.6 | 25.6 |
| Tube side flow [kg/s] | 33.4 | 30 |
| Shell side in/out Temp [°C] | 347 / 293 | 343 / 286 |
| Tube side in/out Temp [°C] | 256 /294 | 268 /309 |
| Duty [MW] | 3.79 | 3.54 |
| EMTD [°C] | **41.2** | **18.3** |
| Average tube wall temp. [°C] | **309** | **296** |
| Tube side HTC [W/m2K] | 312 | 1132 |
| Shell side HTC [W/m2K] | 647 | 602 |
| Tube side velocity [m/s] | 0.34 | 0.31 |
| Overall coefficient [W/m2K] | **147** | **206** |
| Tube side Reynolds [-] | 4842 | 5018 |
| dp calculated [bar] | 0.09 | 0.7 |
| Wall shear [Pa] | 0.43 | 0.75 |

Over a period of 300 days the fouling factor was calculated and compared to the longer runtime prior to the installation of hiTRAN inserts. In figure 16 it can be seen that the initial fouling is similar to the plain empty tube behaviour. It will be interesting to see whether a jump in fouling as experienced after about two years, can be avoided with the installed hiTRAN Elements. For the runtime so far the benefit can be seen in the increased duty of the exchanger, reducing the load on the fired heater.

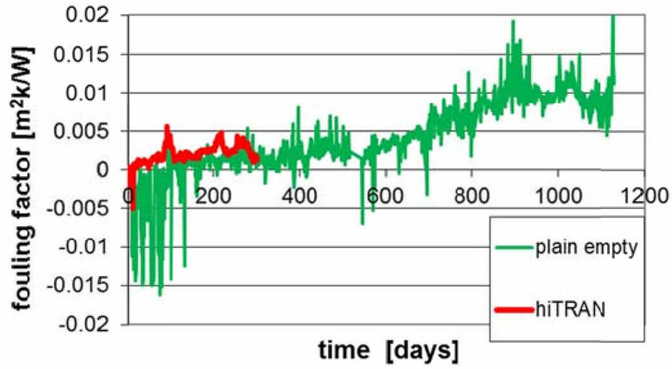


Fig. 16: Fouling factor for plain empty tube and hiTRAN operation

## CONCLUSION

This paper discusses the possibility of altering the plain empty tube conditions concerning wall temperature and wall shear stress by using hiTRAN tube inserts. For fouling threshold models, the knowledge of these two variables is necessary in order to determine the expected fouling rate.

It is shown that the wall shear stress can be increased by up to 7 times depending on the flow regime. Different experimental set ups to measure wall shear forces directly are presented and show good agreement. The measured results give similar results to the CFD simulations. Those simulations are ideal to investigate the local shear stress distribution between the insert loops; again a qualitative agreement with experimental results in particulate fouling was found.

The impact on exchanger performance is demonstrated in a heat exchanger revamp scenario. The overall operation time evaluated with hiTRAN is too short in order to draw definite conclusion on the impact of the fouling behaviour with enhancement installed. Nevertheless it is clear that the process benefits from the increased overall heat transfer.

For turbulent flow hiTRAN Systems can be a viable option in cases where the exchanger operates at low flow velocities and does not utilize all available pressure drop, for example using a single pass arrangements to achieve small driving temperature differences. Sufficient research has been completed to provide confidence in applying hiTRAN Systems in many fouling duties. More research will be needed in order to verify whether there are additional effects to consider when modeling the fouling rate behaviour in the presence of tube internals.

## NOMENCLATURE

| | |
|---|---|
| A | Area, $m^2$ |
| D | diameter, m |
| $E_a$ | fouling model activation energy, J/mol |
| $F_{drag}$ | drag force, N |
| $F_{shear}$ | shear force, N |
| h | heat transfer coefficient, $W/m^2K$ |
| L | length, m |
| Nu | Nusselt, dimensionless number |
| n | Prandtl exponent |
| $\Delta p$ | pressure drop, $N/m^2$ |
| Pr | Prandtl, dimensionless number |
| R | gas constant, J/mol K |
| $R_f$ | fouling resistance, $m^2K/W$ |
| t | time, s |
| $T_f$ | film temperature, K |
| T | temperature, K |
| u | velocity, m/s |
| y | coordinate, m |

### Greek letters

| | |
|---|---|
| $\alpha$ | fouling model parameter, $m^2K/J$ |
| $\beta$ | fouling model parameter, dimensionless |
| $\gamma$ | fouling model parameter, $m^2K/J$ Pa |
| $f$ | fanning friction factor, dimensionless |
| $\tau$ | shear stress, Pa |
| $\eta$ | dynamic viscosity, Pa s |
| $\rho$ | density, $kg/m^3$ |

### Subscript

| | |
|---|---|
| i | inner |
| o | outer |
| w | wall |

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