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HITRAN® WIRE MATRIX INSERTS IN FOULING APPLICATIONS

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ABSTRACT

Fouling characteristics are dictated largely by the properties of the thermal and hydrodynamic boundary layers. As a result, fouling mitigation strategies must take into account the conditions in this region. hiTRAN® wire matrix tube inserts are a useful tool in altering the conditions near the tube wall, especially in the laminar and transition flow regions. This review paper considers Particle Image Velocimetry (PIV) and Laser Doppler Velocimetry (LDV) measurements, which were employed in order to show the hydrodynamic differences between plain tubes and those containing inserts. Measurements indicate that the wall shear rate in tubes containing hiTRAN® inserts operating in the laminar flow regime is similar to that for plain bore tubes operating in the turbulent flow regime. Moreover, the increased tube side heat transfer coefficient which results from the reduction of the thermal boundary layer allows operation with smaller EMTDs. This enables the designer to reduce the tube wall temperature to a level below the fouling threshold temperature, e.g. to combat crude oil fouling.

The results from the laser analyses into the hydrodynamic boundary layer are backed up by recent research data investigating the effect of hiTRAN® inserts on sedimentation and particulate fouling. The thickness of the fouling layer was measured by applying a combination of photographic and laser measurement techniques. The results are compared to plain tube data and are reported as a function of both flow rate and hiTRAN® insert packing density. The impact of altering the hydrodynamic and thermal conditions near to the wall is subsequently demonstrated for different fouling mechanisms. Studies of the impact of hiTRAN® inserts on biological and chemical reaction fouling in crude oil processing are also reviewed.

A better understanding of the threshold shear rates and wall temperatures for different fouling mechanisms is required for any study into the impact of fouling. Combining this knowledge with the principles outlined in this paper clearly emphasises the benefit of using hiTRAN® wire matrix inserts as a powerful tool to mitigate fouling.

INTRODUCTION

Heat transfer enhancement devices have become widely accepted as a method of enhancing exchanger performance and changing duties to either improve output or meet new operating requirements. The commercial uptake of these devices depends on more than the reported improvement in duty, however, and users of enhancement technologies are reluctant to adopt them if there is a significantly increased risk of long-term failure due to fouling. In the case of using inserts to reduce tube-side heat transfer resistance, it is not unreasonable for a potential user to suppose that the increase in surface area of metal inside the tube will result in an increase in the available sites for fouling to build up, and so an increase in fouling. This fallacious notion, coupled with an unenhanced system that is already prone to fouling, makes many plant engineers reluctant to even consider the use of tube-side inserts. In reality, the effect of many heat transfer enhancement devices on both the thermal and hydrodynamic boundary layers can result in significant mitigation of fouling and so further performance benefits over their use.

BACKGROUND

hiTRAN® wire matrix inserts work by continually mixing fluid from the tube wall into the bulk flow and vice-versa. This disrupts the laminar boundary layer that dominates in low Reynolds number flows, removing this inhibitor to heat transfer and resulting in significantly higher heat transfer coefficients on the tube side. Figure 1 shows this effect, with a dye visualisation experiment. In this test, dye was injected into the flow at the top and bottom of a glass tube wall. In the control tests, conducted without an insert present, the dye streams remained on the tube wall for the entire length of the test section, as is the case upstream of the insert in figure 1 (at point A). On reaching the first loop, however, the dye stream is lifted from the wall and gradually dispersed into the bulk flow, as at point B.

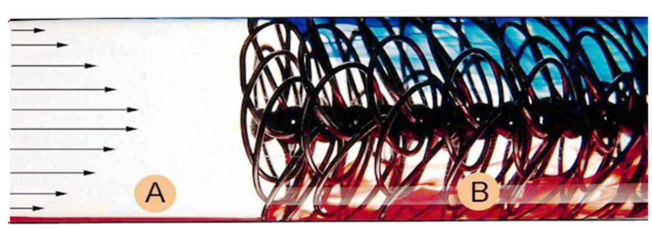

Fig. 1 Dye stream injection at a Reynolds number of 500, on a 22mm diameter tube

The use of hiTRAN® inserts can result in significant improvements in the tube-side heat transfer coefficient and hence overall heat transfer in tube-side controlled systems. Figure 2 shows how the heat transfer factor varies with the Reynolds number for plain tubes and for those fitted with hiTRAN® inserts. The hatched area indicates the heat transfer performance that one may expect from inserts of a range of different densities, with the lower lines representing correlations for various plain tubes. It can be seen from this plot that the increase in heat transfer factor is most pronounced in the laminar and transition regimes, with up to twenty-fold increases in heat transfer possible at a constant Reynolds number.

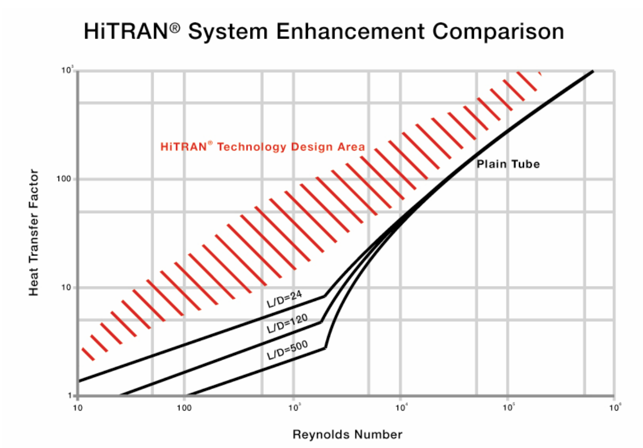

Fig. 2 Relationship between heat transfer factor and Reynolds number showing plain tube heat transfer and that achievable with the inclusion of hiTRAN® inserts, with heat transfer factor, $jH = Nu.Pr^{-1/3}$

When the hiTRAN®-enhanced exchanger is operated at the same flow velocity as the conventional exchanger, improvement in heat transfer comes with an increased pressure drop. In general hiTRAN®-enhanced exchangers operate at lower flow velocities. By reducing the number of passes in new exchanger designs or in revamp scenarios it is possible to reduce the total exchanger tube side pressure drop to below the pressure drop one would normally expect from a plain tube design, but maintaining the improvement of heat transfer.

The effects indicated by figure 1 are clearly of interest not only with regards to heat transfer enhancement, but also in fouling mitigation.

EXPERIMENTAL STUDIES

Various experimental studies have been conducted on hiTRAN® inserts, some of which are qualitative studies designed to indicate the effect of the inserts on a particular foulant or fouling method, though the most widely relevant experimental study relates to the effect of inserts on the velocity profile.

Fluid dynamics of hiTRAN®

Smeethe *et al* (2004) conducted experiments using Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV) to determine the velocity profile immediately downstream of a hiTRAN® insert. The LDV method involved dispersing very small particles within the flow and subjecting those particles to a dual-beam laser setup, which determined the velocity at that point. Smeethe *et al* also used the PIV method to take velocity measurements. The PIV method worked by use of a double-pulsed laser technique. In these experiments, a laser light sheet illuminated a plane in the flow, with the position of particles being recorded at that instant using a camera. Approximately 500 ms later, another pulse illuminated the same plane, which created a second particle image. From cross-correlation of those two images using a Fast Fourier Transform analysis, it was possible to obtain particle displacements for the entire flow region, and hence give velocity vectors for the entire imaged flow region.

The axial flow velocity results were obtained for both the LDV and PIV methods, and were in close agreement with each other. An example, showing the LDV results for a high-density insert at a Reynolds number of 500 is shown in figure 3.

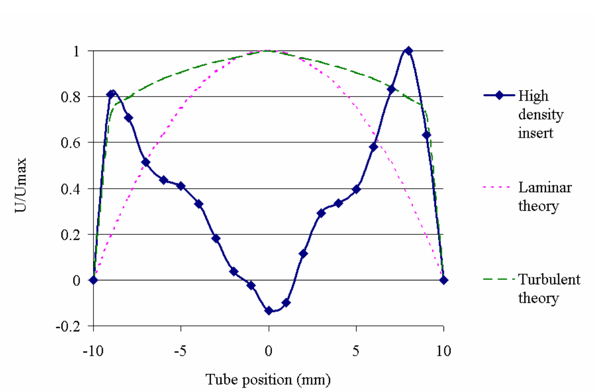

Fig. 3 LDV results at a Reynolds number of 500, showing normalized velocity immediately downstream of a high-density hiTRAN® insert.

These results appear to indicate a velocity near the wall that resembles a turbulent profile, despite the flow being clearly laminar. Moreover, there is a clear dead zone in the centre of the flow profile, which may be easily accounted for in the presence of the substantial core wire, which holds the insert loops together and which runs through the centre

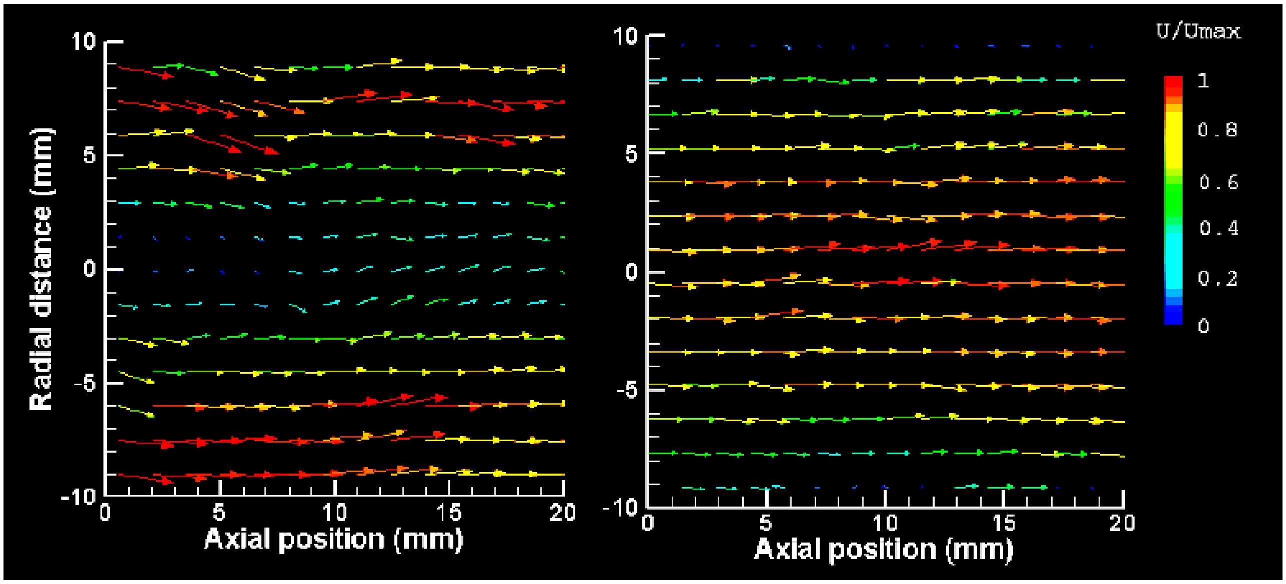

Fig. 4 PIV results at a Reynolds number of 2000, showing normalized velocity vectors immediately downstream of a high-density hiTRAN® insert on the left, with a plain-tube velocity profile on the right.

of the tube. Smeethe *et al* point out that, for a Reynolds number of 500, the velocity gradient near the wall closely matches that of turbulent flow at a Reynolds number of 10,000.

Figure 4 shows the PIV results for the same insert at a Reynolds number of 2000. These results have the extra benefit of including a radial component to the velocity profile, hence results are shown as vectors across a 20mm axial section, immediately downstream of the insert. These results appear to support and exemplify those shown in figure 3. On figure 4, the normalized velocity is indicated, with a red vector indicating a high relative velocity and a blue vector representing a low or no relative velocity. The results presented on the left graph indicate the profile downstream of an insert, with the plain tube results being shown on the right. The high velocity can still be observed around the wall in the hiTRAN®-enhanced case, as shown by vectors indicating the movement of fluid away from the wall and towards the bulk flow. This effect is clearly not apparent in the plain tube case, where the flow appears to be in clearly-defined laminae. The other major difference between the two graphs is the velocity through the centre, which again substantiates the results shown in figure 3, indicating little or no flow at the centre of the tube, due to the presence of the core wire.

The relevance of this change in the velocity profile across the tube will be considered in the discussion section, later in this paper.

Qualitative studies with hiTRAN®

A number of qualitative studies have been conducted into the effect of hiTRAN® inserts on fouling mitigation. Gough and Rogers (1992) reported, based on site reports collated from measurements over a number of years, that the use of matrix elements can significantly reduce and in some cases eliminate fouling. They assert that cases of chemical reaction, crystallization and particulate fouling are the mechanisms that are most likely to benefit from the use of matrix inserts. This section will, in addition, consider some qualitative studies of hiTRAN® inserts in biofouling systems.

Particulate fouling forming sediment. Small (2004) considered the effect of hiTRAN® inserts on sedimentation fouling at low Reynolds numbers, using a water-flour solution. It was concluded that these inserts have a beneficial effect in the reduction of such fouling. To measure the fouling layer thickness, Small expanded on the methods originally suggested by Hamachi and Mietton-Peuchot (1999 and 2001), and used a reflective laser technique as depicted in figure 5. The apparatus was constructed by machining flat notches into a tube so that the laser light could pass into the tube at a flat surface. As is suggested in figure 5, this method works by measuring the intensity of the light incident on the light sensor, which is a function of the original light absorbed by the fouling layer.

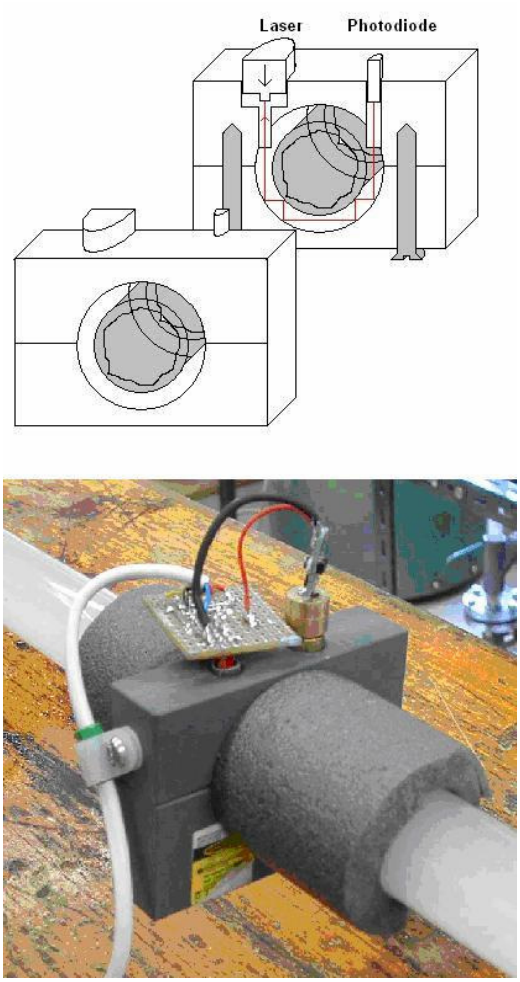

Fig. 5 Laser apparatus to determine fouling layer thickness

These measurements were combined with time-lapsed photographs to give a strong, though qualitative, indication of the impact of hiTRAN® inserts on fouling layer thickness. Figure 6 shows one set of results from the research. The upper line on the graph depicts the proportion of light apparently absorbed by the foulant layer in the case of an empty control tube, with the lower line showing the proportion of light absorbed in the section containing an insert. Applying the principle that the fouling layer is responsible for absorbing a proportion of the emitted laser light, it can be seen that the hiTRAN®-enhanced results appear to indicate a degree of mitigated fouling.

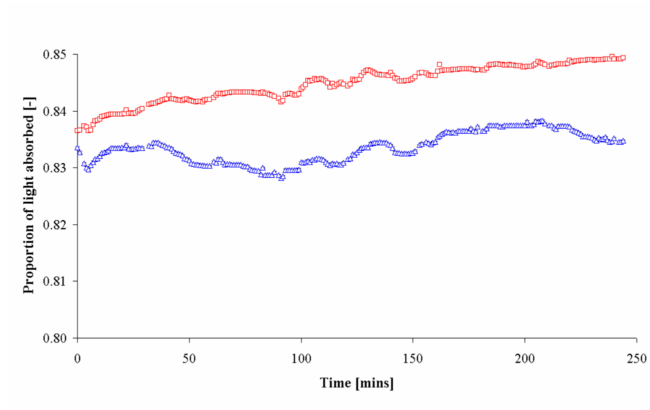

Fig. 6 Graph showing the proportion of light absorbed against time for a high density insert at Re = 520. The upper (red) line shows light absorbed in the empty control tube and the bottom (blue) line shows light absorbed in the tube containing an insert.

The time-lapsed photography results, shown in figure 7, appear to substantiate this assertion. It can be seen that, in the empty-tube control case (top photographs), there appears to be a steady buildup of sediment. Where an insert is fitted, however (the presence of which can be seen clearly in the bottom section), there appears to be a significant reduction in the sediment layer.

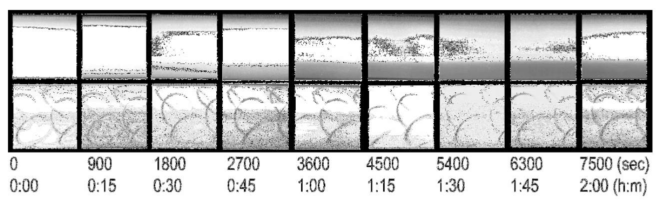

Fig. 7 Time-lapsed photographic results showing the effect of a low-density insert, at Re = 750.

Small also showed that both increasing insert density and increasing fluid velocity reduced the rate of fouling accumulation and the final height of the sediment.

Particulate fouling causing adhesion. Sleight (2006) expanded on the work of Small (2004) and considered adhesion fouling in the presence of hiTRAN® inserts, using dyed xanthan gum, at Reynolds numbers of 250 and 950. The fouling process was followed using the same laser absorption technique outlined in figure 5. It was found that hiTRAN inserts appeared to reduce fouling significantly at both Reynolds numbers tested. A sample of the results for a medium density insert at Re = 250 is shown in figure 8. It indicates a falling rate increase in absorbance (and hence foulant thickness) which apparently tends to an asymptote in the empty tube control section, but a much steadier levelling-off at significantly lower absorbance for the section containing a hiTRAN insert. Similar to the results of Small in fig. 6, Sleight reported these results in terms of the proportion of light apparently absorbed by the fouling layer (1-[V/V_0]).

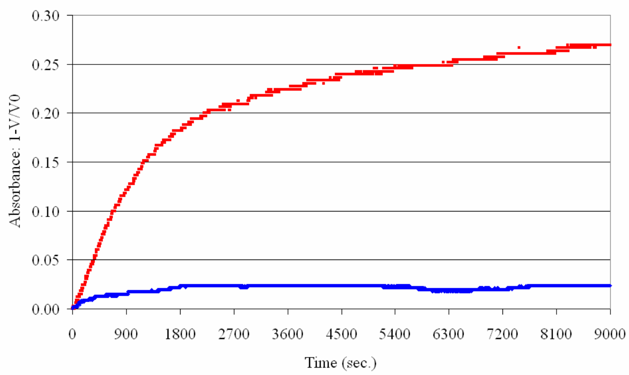

Fig. 8 Graph showing proportion of light apparently absorbed by fouling layer for a high density insert at Re = 250 (lower blue line) and for the control empty-tube section (upper red line)

Sleight also attempted to use time-lapsed photography, but found the results inconclusive due to the difficulty of observing the low-contrast deposit in the dyed solution. Despite this, the results presented from the laser absorption method strongly supported the findings of Small (2004) in showing that the presence of these inserts has a significant mitigating effect in the buildup of fouling.

Biofouling. Bott (2001) used a non-intrusive infrared absorbance technique to measure biofilm accumulation. Infrared radiation was passed directly through a tube to a receiver. The absorbed radiation is dependent on the amount of biofilm deposited, although it was noted that correlations obtained for the biofilm thickness using this method were dependent on the experimental conditions. Flow velocity, for example, was said to affect the biofilm density, therefore a given absorbance would have a different thickness for different velocities.

Wills *et al* (2000) considered the effect of hiTRAN® inserts on biofilm accumulation using the technique just described. Their apparatus consisted of a recirculation loop containing contaminated water, with microbes being fed the nutrients required for bacterial growth. The water temperature was kept to approximately 20°C, that of typical cooling water. The infrared measurement passed directly through the tube centre; in the case of the tubes containing inserts, the inserts were modified to allow light to pass through an eyelet in the core wire. Taking heed of the cautionary note of Bott (2001), results were compared for similar operating conditions between the tubes fitted with inserts and those without. In comparing tubes with and without inserts, at equal flow velocity, a 50% reduction in absorbance of infrared radiation was discovered for those tubes containing inserts.

Chemical reaction fouling. Although the experimental studies outlined above have considered fouling effects qualitatively in terms of a perceived thickness of foulant, without use of heat transfer equipment, Crittenden *et al* (1993) considered fouling in terms of heat transfer resistances. This research investigated the fouling of a heat exchanger pipe with a mixture of crude oil that contained additional waxy residue, using two parallel-pipe sections, one of which contained a hiTRAN® insert. It was reported that the extent of fouling was reduced substantially by the presence of an insert. This was attributed to both the reduction in temperature at the tube wall due to improved mixing, as well as better removal of deposits due to enhanced shear and the reduced residence time at the wall. This appeared to explain the better performance of higher-density inserts.

Figure 9 shows a comparison of a plain (bare) tube and one fitted with a low-density hiTRAN® insert. In this case, the presence of the insert increased the film heat transfer coefficient from 1,030 W/m^{2}K for the plain tube (with a wall temperature of 216°C) to 2,380 W/m2K (and a significantly-reduced wall temperature of 198°C) for the tube fitted with a low-density insert.

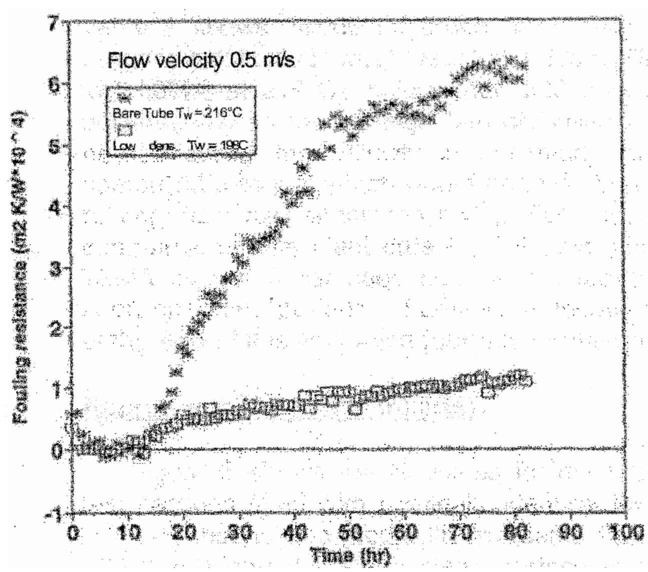

Fig. 9 Graph showing variation of tube fouling resistance with time for both a plain tube, and one fitted with a low-density hiTRAN® insert, with a flow velocity of 0.5 m/s.

CASE STUDIES

Gough *et al* (1995) present a number of case studies in which hiTRAN® inserts have been used to enhance tube side heat transfer and mitigate fouling. The case studies presented cover a number of different fouling mechanisms, and a selection are given in this section.

Case study 1, particulate fouling – Debottlenecking of a stabilizer reboiler

This case concerns the debottlenecking of a reboiler used to drive a crude stabilizer column, which removed C3/C4 components, prior to a splitter column. The tubeside fluid in this case was atmospheric residues and the shellside fluid stabilizer bottoms.

The fouling problem was that the plant was experiencing a failure to control bottoms temperature from the reboiler. This was due to poor reboiler performance associated with "sludge" buildup on the tube side of the unit (sedimentation-type fouling). This, in turn, was considered to be due to low tube side velocity. At 20% shell side fluid bypass (valve at minimum position) and 80% through the exchanger, control was not possible.

Analysis showed that with only the inlet pass of this two-pass unit fitted with inserts, control could be achieved at bypass fractions of up to 60%.

After two years of production, evaluation showed that control could be achieved at "greater than 50% bypass." The system remained in service with only one change of inserts following an exchanger inspection, The benefits of implementing hiTRAN® in this case include the achievement of a cost-effective upgrade, extended run time at maintained performance, increased crude pre-heat downstream, as well as low maintenance costs.

Case study 2, solidification/freeze fouling – Debottlenecking of an air cooler handling pitch

In this case, the tubeside fluid was fluxed pitch (a mixture of pitch, crude oil and residual oil). Increased feed temperature and reduced outlet temperature requirements resulted in increased duty from 815 kW to 2,036 kW. The existing unit was fitted with an air recirculation system. The degree of recirculation was to be reduced in order to meet the increased duty. However, with a minimum ambient temperature of -42.8°C in this Canadian plant, and a fluid pour point of 21°C, the result was wall temperatures below the pour point.

Operating experience prior to the revamp included difficulties in achieving the required outlet temperature in summer and tube plugging from solidification of product in winter.

By fitting inserts into the unit, the overall heat transfer coefficient was increased from 110.7 to 282 W/m^{2}K. The 4-row bundle was converted from a six-pass arrangement to a two-pass unit in order to keep the pressure loss within pump capability.

The project was chosen as the most cost-effective revamp option. Refinery reports confirmed that the enhanced performance remained constant since installation and fouling was considered to have been mitigated.

Case study 3, polymerization/reaction fouling – debottlenecking of a tar acid flash preheater/vaporizer.

In this case, the tube side fluid was tar acid and the shell side fluid was steam. The horizontally-mounted exchanger used to preheat and vaporize the feed to a flash drum was underperforming, despite the heat transfer area being considered "more than adequate." The large shell diameter and low pressure loss in the tubeside resulted in the tubes being only partially submerged. The high viscosity of the tubeside fluid limited the coefficient achievable. Operation of the unit at elevated steam temperature in order to achieve an acceptable level of vaporization caused the product to polymerize on the the tube surface.

A tube insert system was designed to overcome the maldistribution by forcing the fluid to pass through the upper tube rows of the unit. Multiple inserts were connected in series and installed in each tube. The arrangement involved the use of a high density insert in the inlet (to enhance the single-phase heat transfer), progressing to a low-density insert at the outlet (to enhance vaporization at low pressure drop). The overall pressure drop was within the base case allowance.

Under the original operating conditions, the recovery of vaporized "light" product was restricted to 60%. Increasing the steam temperature to 155°C to obtain a recovery of 85% resulted in serious polymerization.

The revamped unit achieved 85% recovery at a steam temperature of just 135°C. No polymerization occurred, yet higher recovery without polymerization may now be possible.

DISCUSSION

As a commercial product, the research commissioned into hiTRAN® inserts has largely followed qualitative studies as outlined above, which give a useful indication of the effect of the presence of an insert, but give little in the way of findings that may contribute to a model to deal specifically with fouling in tubes equipped with these inserts. A number of other studies have been conducted, however, which give some theoretical basis to the findings presented in this paper. The recent experimental research in this paper has largely considered particulate fouling, and this brief analysis of the presented results will call on previous studies into particulate fouling.

Webb and Kim (2005), citing Taborek *et al* (1972), proposed the following fouling removal rate model:

$$\dot{m}_r = \frac{m_f \tau_w}{\xi} = \frac{\rho_f x_f \tau_w}{\xi} \qquad (1)$$

It can be seen that the removal rate is assumed to be proportional to the both the fouling layer thickness and shear stress at the surface, as well as inversely proportional to the deposit bond strength factor. The deposition rate is given by equation (2):

$$\dot{m}_d = SK_m(C_b - C_w) \qquad (2)$$

As originally suggested by Kern and Seaton (1959), equations (1) and (2) may be combined to give a differential equation for a fouling system:

$$\frac{dR_f}{dt} = SK_m C_b - BR_f \qquad (3)$$

where,

$$B = \frac{\rho_f \tau_w k_f}{\xi} \qquad (4)$$

It is clear, therefore, that the fouling resistance R_f may be predicted if S, K_m, τ_w and ξ are known. In applying this principle to the case of hiTRAN® inserts, it is helpful to consider how the impact of the previous research impacts upon these variables. Papavergos and Hedley (1984) define the three regimes for particle deposition as the diffusion, inertia and impaction regimes, and define these regimes by a dimensionless particle relaxation time. As the particle deposition results presented in this paper are qualitative, the definition of this is not particularly pertinent to this discussion, other than to say that for lower values of the dimensionless particle relaxation time, the process is diffusion controlled, and the mass transfer coefficient above may be predicted from heat transfer data, using the classical analogy between heat and mass transfer:

$$\frac{K_m}{u} Sc^{\frac{2}{3}} = \frac{h}{\rho u c_p} \Pr^{\frac{2}{3}} \qquad (5)$$

It should be noted that, in these circumstances, eq. (5) would indicate that because an enhanced surface by its very nature gives an increased heat transfer coefficient, one should expect an accompanying increase in mass transfer coefficient and hence rate of deposit of fouling material. Based on this variable alone, heat transfer enhancement devices would appear to cause increased fouling deposition rates. However, equation (1) indicates that the fouling material removal rate is directly proportional to the surface shear stress. Considering the findings of Smeethe *et al* (2004), presented in fig. 4, showing significantly higher wall shear rates for tubes equipped with hiTRAN® inserts, one might expect that the significantly higher shear rates may at least compensate for the possibility of higher mass transfer rates as a result of improved heat transfer coefficients.

Indeed, Webb and Kim (2005) state that the net effect of deposition and removal is defined by the asymptotic fouling resistance, given by equation (6):

$$R_f^* = \frac{SK_m C_b}{B} \qquad (6)$$

Equation (6) shows that $R_f^* \propto \dot{m}_d / \tau_w \propto K_m / \tau_w$, hence in cases where $K_m / \tau_w > 1$, one should expect the enhanced surface to have a higher asymptotic fouling resistance than a plain surface. In the case of hiTRAN® inserts in particulate fouling, the results of Sleight (2006), an example of which is shown in fig. 8, would appear to indicate the converse to be the case. These results seem to give a clear indication that, using hiTRAN® inserts in these conditions, the shear effects at the wall significantly overcome the mass transfer effects, resulting in a significantly lower asymptote, as is demonstrated in fig. 8.

Various research has been conducted into determining the asymptotic fouling rate for a range of enhancement devices. Kim and Webb (1990), for example, established that transverse rib-roughened tubes of a certain geometry give an asymptotic fouling rate that is proportional to $u^{-3.9}$. This is in comparison to the plain tube model proposed by Chamra and Webb (1993), which predicted the asymptotic fouling rate to be proportional to $u^{-2.94}$. In any case, it is clear that the presence of this enhancement results in an increased inverse dependency of the flow velocity and hence significant reduction in fouling buildup with increased flow velocity. Whilst this enhancement device is quite different from the hiTRAN® insert, both in principal and geometry, there is evidence to suggest, even from the qualitative results, that a similar principal applies. Indeed, considering the conclusions of the recent particulate fouling studies outlined earlier in this paper, i.e. that increased flow appeared to decrease the rate of fouling accumulation, there is every reason to believe that a quantitative study into the effect of hiTRAN® inserts would lead to a relationship indicating the asymptotic fouling rate is indeed inversely proportional to a significantly higher power of the flow velocity.

It should be noted that the wall shear stress, being the only useful variable for which we have quantitative and reliable data, forms relationships in many of the published models for fouling in enhanced tubes. Considering again the work of Chamra and Webb (1993), for a fixed geometry and given particle size and concentration in enhanced tubes (in this case, GEWA-NW and Korodense tubes), the ratio of factors for enhanced and plain empty tubes are given by:

$$\frac{S_{enh}}{S_{ref}} \propto \tau_w^{-0.721} \qquad (7)$$

and

$$\frac{\xi_{enh}}{\xi_{ref}} \propto \tau_w^{-0.435} \qquad (8)$$

Again, although these values apply to a quite different enhancement method from hiTRAN®, from the qualitative results it is possible to draw some comparisons between the relationships drawn by Chamra and Webb, and the observations made from the hiTRAN® results. The decrease in the sticking probability and deposit bond strength factor as the wall shear rate increases (as indicated by equations (7) and (8)) appear to reflect the phenomenon observed by Small (2004), in that increasing insert density (hence increasing shear rate) results in a decrease in the buildup of fouling material. In these circumstances, as shear rates increase, there will be less probability that a particle transported to the wall will actually stick to the wall (so decreasing the deposition rate, indicated by eq. (2)), as well as decreasing the deposit strength factor in eq. (1), hence increasing the removal rate of fouling material.

Whilst this discussion appears to indicate similarities with the results of other researchers in terms of the dependence of wall shear rate, it should be noted that the success of an enhancement device is, of course, significantly dependent upon the other process variables (not least C_b and d_p in determining the sticking probability and deposit strength factor, but also the enhanced heat transfer coefficient, which will have a significant impact on the mass transfer coefficient and so the deposition rate of the fouling material.

CONCLUSIONS

This paper has demonstrated:

1. The impact of hiTRAN® inserts on tube fluid dynamics by means of LDV and PIV analysis, and the significant increase in wall shear rate that occurs as a result of the presence of an enhancement device.
2. By review of qualitative experimental studies, that fouling appears to be mitigated as a result of the presence of an insert in the case of particulate fouling.
3. Fouling affects are also mitigated in cases of both biofouling and chemical reaction fouling – this is demonstrated further by use of case studies.
4. The significance of the wall shear stress in the buildup of fouling, and how previous experimental studies have indicated the mitigating effect of enhancement devices by inducing an increased shear stress.
5. The presence of an enhancement device, whilst increasing the tube side coefficient and bringing the wall temperature closer to the bulk, also increases, by analogy, the mass transfer coefficient and hence potential buildup of fouling material. In the case of the results given in figure 8, however, it would appear that the wall shear effects of hiTRAN® inserts compensate for this increase in mass transfer coefficient.
6. That the result of increased wall shear stress on other systems appears to be effectively demonstrated by the qualitative experimental results from the hiTRAN® testing.
7. There appears to be some promise for determining a model for fouling of heat transfer surfaces containing hiTRAN® inserts if further quantitative experimental studies are conducted.

NOMENCLATURE

c_p specific heat capacity, kJ/kg K
C_b particulate concentration in bulk fluid, ppm
C_w particulate concentration at all, ppm
d tube inner diameter, m
d_p particle diameter, m
D diffusion coefficient, m^2/s
G mass velocity based on minimum flow area, kg/m^2s
h heat transfer coefficient, W/m^2 K
k_f fouling material layer thermal conductivity, W/m K
K_m mass transfer coefficient, kg/m^2s
m_f fouling material mass per unit area, kg/m^2

$\dot{m}_d$ fouling material deposition rate, kg/m^{2}s
$\dot{m}_r$ fouling material removal rate, kg/m^{2}s
Pr Prandtl number, $c_p\mu/k$, dimensionless
Re Reynolds number based on the tube inner diameter, Gd/μ, dimensionless
R_f fouling resistance, m^{2}K/W
R_f^* asymptotic fouling resistance, m^{2}K/W
S Sticking probability, dimensionless
Sc Schmidt number, ν/D, dimensionless
u flow velocity, m/s
V Photodiode voltage of light absorbed, volts
x_f fouling layer thickness, m

Greek letters

μ dynamic viscosity, Pa s
ν kinematic viscosity, m^2/s
ξ deposit bond strength factor, N s/m^2
ρ fluid density, kg/m^3
ρ_f density of fouling layer, kg/m^3
τ_w wall shear stress, N/m^2

Subscripts

$_0$ initial
$_{enh}$ enhanced
$_{ref}$ reference (plain tube)

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